

Chapter 2

Neutron Halo and Breakup Reactions

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Abstract Characteristic features of neutron halos in the context of breakup experiments at intermediate/high energies are discussed. Neutron halos have been found for light neutron rich nuclei along the neutron drip line, as intense radioactive nuclear beams have become available in recent years. A neutron halo nucleus is composed of a tightly bound core surrounded by one or two neutrons which extend outside of the mean field potential due to quantum tunneling. Coulomb breakup of halo nuclei shows extremely enhanced cross sections for such systems, originating from the characteristic electric dipole response of halo nuclei at low excitation energies, called soft $E1$ excitation. Such features are shown for one-neutron halo nuclei by Coulomb breakup experiments of ^{11}Be on Pb at about 70 MeV/nucleon, performed at RIKEN, where it was found that the direct breakup mechanism is responsible for this excitation. We then show how the $E1$ excitation spectrum can be related to properties of the halo distribution, and hence that the method of Coulomb breakup is a powerful spectroscopic tool. As such, applications of the Coulomb breakup of ^{15}C and ^{19}C are shown. The ^{19}C case is valuable for extracting the microscopic structure of ^{19}C , which has only recently been clarified. The ^{15}C case can be used to extract the radiative capture cross section of the $^{14}\text{C}(n, \gamma)^{15}\text{C}$ reaction. We then demonstrate recent applications of the “inclusive” Coulomb breakup method to a new-region of loosely bound nuclei near the island of inversion ($N \sim 20$). There, evidence obtained, of the $1n$ halo structure in ^{31}Ne , is presented. In the $2n$ halo case the Coulomb breakup of ^{11}Li at 70 MeV/nucleon, measured at RIKEN, is shown. This reaction has provided evidence of dineutron-like structure, revealed by the strong enhancement of the soft $E1$ excitation. For nuclear dominated breakup, where a light target is used, the momentum distribution of the core fragment has key information on the halo

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distribution, and the single-particle properties of the valence neutron. Here we show an example of a spectroscopic study of ^{13}Be , populated by removing one neutron from the two neutron halo nucleus ^{14}Be . These results show that the breakup reactions play significant roles in elucidating the structures along the neutron drip line. This feature will be very important for further investigations of the drip-line nuclei towards the heavier region, as will be produced using the new-generation RI (Rare-Isotope) beam facilities, as has just been completed in RIKEN (RIBF) in Japan. Such enhanced RI-beam facilities are soon to be commissioned in Europe (SPIRAL2, FAIR etc.), in Asia (KoRIA), and in the US (FRIB).

2.1 Introduction

In 1985, the anomalously large matter radius of the most neutron-rich Li isotope, ^{11}Li , significantly beyond the conventional $r_0 A^{1/3}$ law, was discovered from a measurement of its interaction cross section with a carbon target at 790 MeV/nucleon [1]. Soon after this epoch-changing finding, an extremely narrow transverse momentum distribution of ^9Li , following the breakup of ^{11}Li on a carbon target, was observed [2]. This was later confirmed by the measurement of the corresponding longitudinal component [3]. Combined with the large matter radius, the narrow momentum width of the core fragment was interpreted as a manifestation of a “halo”, an extended density distribution of two valence neutrons spilling out of the densely-packed ^9Li core. This basic concept was discussed in Ref. [4]. The third important finding of this nucleus was made by observing its anomalously large Coulomb breakup (CB, or electromagnetic dissociation EMD) cross section [5], which was interpreted as evidence of an enhanced electric dipole response at low excitation energies, known as “soft $E1$ excitation”. These features are all related to the cluster-like structure of ^{11}Li , i.e., a three-body $^9\text{Li}+n+n$ structure appearing near the breakup threshold.

This chapter focuses on “breakup reactions” of halo nuclei. Breakup reactions have played significant roles since the early days of halo physics. After about two decades from the first experimental confirmation of halo structure in ^{11}Li , many experimental methods and techniques related to breakup reactions of halo nuclei have made very significant progress.

It should also be noted that several RI-beam facilities have been upgraded, commissioned, or are expected to soon be commissioned, to improve the quality and intensity of the secondary beams. In 2007, the new-generation RI-beam facility RIBF (RI beam Factory) at RIKEN in Japan has been commissioned [6, 7]. This facility enhances capabilities of drip-line physics thanks to its extraordinary improvement in intensities of exotic nuclei, by more than three orders of magnitude for most nuclei, compared to those available at the pre-existing facilities. The power of the RIBF facility was demonstrated recently by the discovery of about 50 new neutron-rich isotopes near the predicted astrophysical r -process path [8, 9]. Later in this chapter, we show results of breakup measurement of ^{31}Ne performed in this facility [10]. Other new-generation facilities include FAIR at GSI in Germany [11], SPIRAL2 at

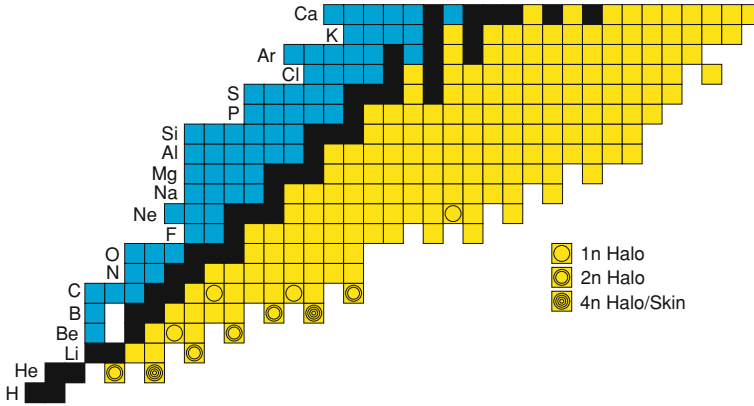


Fig. 2.1 Nuclear chart up to $Z = 20$ (Ca), whose drip-lines are based on the identified bound nuclei. The known neutron halo nuclei are indicated. Evidence for halo structures of ^{22}C and ^{31}Ne have recently been obtained experimentally [10, 14]

GANIL in France [12], FRIB at MSU in the USA [13], which will be in operation in 3–10 years.

As in ^{11}Li , neutron halo nuclei have been discovered at the limit of nuclear stability on the neutron-rich side (neutron drip line) in the lower mass part of the nuclear chart, as shown in Fig. 2.1. A neutron halo nucleus is composed of a tightly bound core surrounded by a low-density neutron cloud, called a halo, which contains one or two neutrons. Halo phenomena occur basically due to the quantum tunneling effect for weakly bound neutron(s) which extend outside of the surface of nuclear mean-field potential due to the core. Since the halo neutron(s) are spatially decoupled from the core, a halo nucleus has a cluster-like property, and a $1n$ halo nucleus is regarded as a two-body system composed of a core+ $1n$, and a $2n$ halo nucleus as a three-body system composed of a core+ $n+n$.

As discussed in the review articles [15–19], and references therein, the main issues in halo physics are summarized as follows:

1. Microscopic structure of $1n$ halo nuclei: A key issue is the single-particle configuration of the valence neutron relative to the core. The condition of $1n$ -halo formation is that a nucleus should have small S_n ($1n$ separation energy), typically $S_n < 1$ MeV. Another important requirement is that the valence neutron has low (or no) orbital angular momentum to avoid the hindrance of the tunneling effect due to the centrifugal barrier ($\ell(\ell + 1)\hbar^2/(2\mu r^2)$). It is suggested that the orbital angular momentum should be $\ell = 0$ or 1 for halo formation. In fact, only when $\ell = 0, 1$ can one obtain a divergent r.m.s. radius ($\sqrt{\langle r^2 \rangle}$) of the tail density distribution in the limit that $S_n \rightarrow 0$ [18, 20, 21].
2. Microscopic structure of $2n$ halo nuclei: A $2n$ -halo nucleus has a three-body structure, called Borromean, where the two-body subsystems are weakly unbound but the three-body system is bound. Recently, a possible strong dineutron correlation,

where the two neutrons at the low-density nuclear surface take a spatially compact configuration [22], has attracted special interest since this may happen for $2n$ halo nuclei or neutron-skin nuclei [23]. The dineutron correlation is different from the BCS-type long range correlation which arises for normal nuclei [24]. If such a correlation is evidenced by $2n$ halo nuclei, we may expect similar correlations in heavier neutron-skin nuclei, or even in the inner crust of a neutron star. The possibility of the revelation of Efimov states in three-body halo nuclei has also been discussed [25–27], but whose evidence has yet to be provided.

3. Interplay between shell evolution and halo formation: In most halo nuclei the lowering of a low- ℓ single-particle orbital, compared to the conventional shell order is suggested. A famous example is the intruder $1/2^+$ ground state below the $1/2^-$ state in ^{11}Be (parity inversion), as was identified 50 years ago [28] well before the discovery of its $1n$ halo structure. Such a shell evolution enhances the halo formation due to the appearance of a low- ℓ orbital. In turn, we should note that low kinetic energy of halo neutron(s) may cause the lowering of ℓ .
4. Interplay between deformation and the halo: Deformation can influence the lowering of a low- ℓ orbital in some cases, which could cause formation of a halo structure [29, 30].
5. Other many-body correlations as a cause of halo formation: The possibility that tensor correlations enhance s - p degeneracy of the two valence neutrons in ^{11}Li is discussed [31, 32].
6. Characteristic nuclear responses of halo nuclei: “Soft $E1$ excitation” is a unique response of halo nuclei to an electric dipole operator. Such exotic excitation modes may appear in different responses, such as $E0$, $E2$ [33], and spin-isospin excitations [34].
7. Halo formation in heavier nuclei: So far, halo nuclei have been found in the mass region less than $A \sim 20$, except for the newly-found $1n$ halo nucleus ^{31}Ne (see Fig. 2.1)[10]. We thus raise the question: can we observe many halo cases in heavier nuclei?; how? In what form can halo states appear in heavier nuclei? The anti-halo effect predicted theoretically [35, 36], where neutron halo formation is suppressed due to the pairing correlation, may limit the number of $2n$ halo cases. It is also suggested that the dominance of larger ℓ orbits for heavier nuclei may restrict the cases of neutron halo to limited regions where s or p shells are located near the Fermi surface. On the other hand, deformation and shell evolution effects may increase the possibility of halo cases along the neutron drip line. In heavier regions, we may expect more complex halo structure due to a mixture of different shell configurations. For example, Meng and Ring have predicted the existence of giant halo structure, involving about 6 neutrons for neutron-rich Zr isotopes [37].
8. Understanding of possible $4n$ halo systems (among other multi-neutron halos): ^8He and ^{19}B are the $4n$ halo candidates, whose structures are not well known. These systems could provide the first step to understand multi-neutron halos expected in heavier neutron rich nuclei.
9. Finally, we would like to raise the following questions:

- a. Where is the neutron drip line located in heavier nuclei?
- b. Does the existence of halo states change the location of the drip line? (*i.e.*, will the existence of halo structures change the nuclear stability?)

Such questions are fundamental to understand many-body nucleonic systems and their stability at the limit of extreme isospin asymmetry.

Breakup reactions of halo nuclei play important roles in solving many of the above issues. Breakup reactions are categorized into two processes, (1) Coulomb Breakup, and (2) Nuclear Breakup, depending on the primary interaction involved. The breakup on a heavy target, such as Pb or U, is dominated by Coulomb breakup, while the breakup with a light target, such as proton, Be, and C, is dominated by nuclear breakup. Both reaction processes are important in the spectroscopy of halo nuclei since the observables in breakup reactions are strongly correlated to the microscopic structures of the ground and continuum states of halo nuclei; as described later.

In what follows, we show the characteristic features of breakup reactions by illustrating recent experimental results. [Section 2.2](#) describes the Coulomb breakup method in general. [Section 2.3](#) describes the characteristic features of Coulomb breakup and soft $E1$ excitation of “ $1n$ ” halo nuclei. There, we explain the mechanism of soft $E1$ excitation and how the single-particle configuration of a $1n$ halo nucleus can be studied. The examples shown there are for exclusive Coulomb breakup of ^{11}Be [38–40], ^{19}C [41], ^{15}C [42–44], and recent inclusive Coulomb breakup of ^{31}Ne measured at RIBF [10]. [Section 2.4](#) describes examples for “ $2n$ ” halo nuclei, showing ^{11}Li [45–50]. There we discuss the possible application to probe the dineutron correlation in $2n$ halo nuclei. In [Sect. 2.5](#), we discuss the use of nuclear breakup experiments on ^{14}Be to study the spectroscopic information on the unbound nucleus ^{13}Be [51]. In [Sect. 2.6](#), we summarize and provide an outlook of the potential of breakup reactions on halo nuclei for the future.

2.2 Coulomb Breakup at Intermediate/High Energies

Coulomb excitation has been a powerful spectroscopic tool in nuclear physics for many years. In earlier days, heavy ion beams of low-energy, below the Coulomb barrier, were primarily used. Recently, Coulomb excitation has been applied successfully to neutron-rich/proton-rich nuclei at intermediate/high energies. When Coulomb excitation is applied to drip line nuclei, such as halo nuclei, the Coulomb excitation leads to a breakup channel, associated with 1–2 nucleon removals, called Coulomb breakup or equivalently electromagnetic dissociation, due to their weak binding.

In Coulomb breakup, a projectile is excited by an impulse due to the Coulomb field of a high- Z target as shown schematically in [Fig. 2.2](#). Here Lorentz-contracted electric field acts on the projectile as it passes the high- Z target with a relativistic velocity at an impact parameter b . For relativistic speeds, the magnetic field also becomes effective, so the more general term electromagnetic dissociation (EMD) is also used. In fact, for a relativistic incident velocity $\beta = v/c$ of a projectile, the

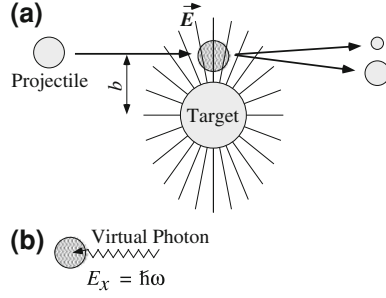


Fig. 2.2 **a** The Coulomb breakup process is shown schematically. When a relativistic projectile passes a high- Z target at an impact parameter b , it experiences an impulse due to the Lorentz-contracted electromagnetic field. When the intermediate excited state is above the particle decay threshold, as is often the case for halo nuclei, the projectile breaks up into the core fragment and nucleon(s). **b** The Coulomb breakup process can be regarded as the absorption of a virtual photon

electric field $\mathbf{E}$ and magnetic field $\mathbf{B}$ are almost perpendicular to each other, related by $|\mathbf{B}| = \beta|\mathbf{E}|$ [52]. This implies that the EM field approximates a real electromagnetic wave as $\beta \rightarrow 1$.

Hence, Coulomb breakup can be expressed as a photo-absorption process induced by a virtual photon, as shown schematically in Fig. 2.2b. Such a treatment is called the equivalent-photon [52, 53] or Weizsäcker-Williams method of virtual quanta. There, the Coulomb excitation cross section at an excitation energy E_x is expressed simply as a product of the photo-absorption cross section $\sigma_\gamma^{E\lambda}(E_x)$ and the virtual photon number $N_{E\lambda}(E_x)$. The latter is obtained by integrating $N_{E\lambda}(E_x, b)$ (the photon flux at an impact parameter b) from the cutoff impact parameter b_0 to infinity or, equivalently, by integrating the angle differential photon number with respect to the scattering angle from 0 to the grazing angle θ_{gr} ,

$$\frac{d\sigma(E\lambda)}{dE_x} = \int_{b_0}^{\infty} 2\pi b db N_{E\lambda}(E_x, b) \frac{\sigma_\gamma^{E\lambda}(E_x)}{E_x} \quad (2.1)$$

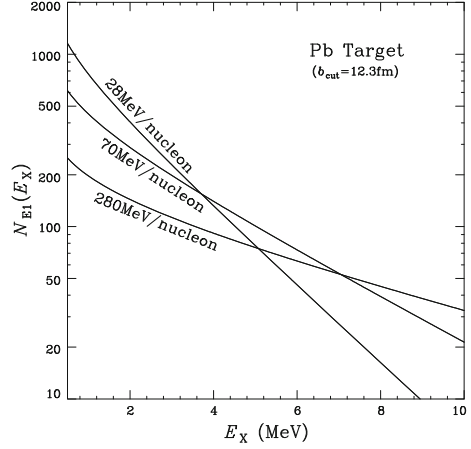
$$= \int_0^{\theta_{\text{gr}}} d\Omega \frac{dN_{E\lambda}(E_x, \theta)}{d\Omega} \frac{\sigma_\gamma^{E\lambda}(E_x)}{E_x} \quad (2.2)$$

$$= N_{E\lambda}(E_x) \frac{\sigma_\gamma^{E\lambda}(E_x)}{E_x}. \quad (2.3)$$

Here, λ represents a multipolarity of the transition, and E identifies an electric transition (M is used for the magnetic transitions). The photo-absorption cross section is related to the reduced transition probability $B(E\lambda)$ as in,

$$\sigma_\gamma^{E\lambda}(E_x) = \frac{(2\pi)^3(\lambda+1)}{\lambda[(2\lambda+1)!!]^2} \left(\frac{E_x}{\hbar c}\right)^{2\lambda-1} \frac{dB(E\lambda)}{dE_x}. \quad (2.4)$$

Fig. 2.3 $E1$ virtual photon spectra as a function of the energy of a virtual photon ($E_\gamma = E_x$). Three cases, for incident energies of 28, 70, and 280 MeV/nucleon on a Pb target are shown. These incident energies are those for the Coulomb breakup experiments of ^{11}Li in Refs. [45, 46], [50], and [49], respectively



Since $N_{E1}(E_x)$ is provided in an analytical form, a measurement of $d\sigma/dE_x$ can be used to extract $dB(E1)/dE_x$ directly.

For neutron halo nuclei, the electric dipole ($E1$) transition is dominant. For $E1$ excitation, Eqs. (2.3) and (2.4) can be combined as,

$$\frac{d\sigma(E1)}{dE_x} = \frac{16\pi^3}{9\hbar c} N_{E1}(E_x) \frac{dB(E1)}{dE_x}, \quad (2.5)$$

where $N_{E1}(E_x)$ is the number of $E1$ virtual photons with photon energy E_x . When we measure the scattering angle, as in the example of the ^{11}Be Coulomb breakup experiment shown later [40], the formula for the corresponding double differential cross section is also useful.

$$\frac{d^2\sigma}{d\Omega dE_x} = \frac{16\pi^3}{9\hbar c} \frac{dN_{E1}(E_x, \theta)}{d\Omega} \frac{dB(E1)}{dE_x}. \quad (2.6)$$

Note that in the semiclassical approach the center of mass (c.m.) of the projectile and that of the outgoing particles after the breakup approximately follows a Rutherford trajectory. Hence, there is a one-to-one correspondence between b and θ , stated as $b = a \cot(\theta/2) \simeq 2a/\theta$, where a is half the distance of the closest approach in the classical Rutherford scattering.

The typical $E1$ virtual photon spectra (photon flux) as a function of γ -ray energy ($E_\gamma = E_x$) are shown in Fig. 2.3. The electric field experienced by the projectile, as a function of time, is bell-shaped, with a width of $b/(\beta\gamma)$. Hence, the energy spectrum, which is the Fourier transform of the time spectrum, extends to higher excitation energy (higher frequency) for projectiles with higher incident energy, as detailed in Ref. [52].

2.3 Coulomb Breakup and Soft $E1$ Excitation of $1n$ Halo Nuclei

A large EMD cross section (0.89 ± 0.10 b) was observed for ^{11}Li at 0.8 GeV/nucleon, which was associated with the large enhancement of the $E1$ strength at low excitation energies [5]. As the virtual-photon flux falls rapidly with energy, as shown in Fig. 2.3, such a large cross section can only be explained by the concentration of significant $E1$ strength at low excitation energies of 1–2 MeV; which we now call soft $E1$ excitation. Such a picture is contrary to the conventional picture of the $E1$ response of nuclei where most of the $E1$ strength is exhausted by the giant dipole resonance (GDR), located at $E_x \sim 80A^{-1/3}$ MeV or $31.2A^{-1/3} + 20.6A^{-1/6}$ MeV [54].

Ikeda predicted that such a low-energy $E1$ transition is caused by the low-frequency motion of the charged core nucleus against the low-density neutron halo, which is called a soft dipole resonance (SDR) [32, 54]. On the other hand, it has been known that the enhancement occurs due to a direct breakup mechanism, where the halo nucleus breaks up without forming any intermediate resonances, and that the enhancement occurs due to the spatially-decoupled nature of the halo, whose detail is shown later.

Three earlier exclusive Coulomb breakup experiments on ^{11}Li , in the 1990s [45–49], failed to clarify the mechanism of the soft $E1$ excitation, since the $B(E1)$ strength distributions obtained from the three experiments were inconsistent (see Sect. 2.4). In addition, theoretical interpretation of the soft $E1$ excitation of ^{11}Li is difficult due to the correlations of the two neutrons. Hence, the Coulomb breakup of the $1n$ halo nucleus ^{11}Be was of great importance for understanding the underlying mechanism of soft $E1$ excitation due to its simpler structure. This section is devoted to the Coulomb breakup of a $1n$ halo nucleus, to clarify the mechanism and characteristic features of the soft $E1$ response of a $1n$ halo nucleus.

2.3.1 Coulomb Breakup of ^{11}Be and Characteristic Feature of Soft $E1$ Excitation of One-Neutron Halo Nuclei

The $1n$ halo structure of ^{11}Be was first suggested by the enhancement of its reaction cross section at a high incident energy of 790 MeV/nucleon at LBL [56], and at a lower incident energy of 33 MeV/nucleon at RIKEN [57]. A narrow momentum distribution of ^{10}Be following the breakup of ^{11}Be on a light target was observed [58], and later investigated further with γ ray coincidences with the ^{10}Be fragment [59] at MSU. These measurements show clearly the one neutron halo structure of ^{11}Be . The first exclusive Coulomb breakup experiment was studied at 72 MeV/nucleon at RIKEN [38]. Later, Coulomb breakup was studied at 520 MeV/nucleon at GSI [39], and was investigated in more detail at 69 MeV/nucleon at RIKEN [40]. In this section, we show the characteristic features of Coulomb breakup of $1n$ halo nuclei by showing these experimental results for ^{11}Be .

The wave function of the ground state of $^{11}\text{Be}(J^\pi = 1/2^+)$ can be written as,

$$|^{11}\text{Be}(1/2^+; \text{gs})\rangle = \alpha |^{10}\text{Be}(0^+) \otimes 2s_{1/2}\rangle + \beta |^{10}\text{Be}(2^+) \otimes 1d_{5/2}\rangle + \dots \quad (2.7)$$

Here, the main issue is the occupancy of the halo configuration in the ground state, namely, the spectroscopic factor for the first term involving the s -wave neutron. Already in the 1970s, although the halo structure was not known, there were some spectroscopic studies of ^{11}Be by using the transfer reaction, $^{10}\text{Be}(d, p)^{11}\text{Be}$, from which the dominance of $2s_{1/2}$ neutron in the ground state ($\alpha^2 (= C^2 S) = 0.73$ [60], 0.77 [61]) was extracted. The one-neutron separation energy is known very precisely as 504 ± 5 keV. Since its ground state property is better established, Coulomb breakup of ^{11}Be is better suited for investigating the mechanism of soft $E1$ excitation, compared to the $2n$ halo nucleus ^{11}Li .

2.3.1.1 Typical Experimental Setup and the Invariant Mass Method

The three exclusive Coulomb breakup experiments used to map the $B(E1)$ distribution of ^{11}Be [38–40] were largely consistent with each other. Hence, hereafter, we mainly show the result from Ref. [40].

To extract the $B(E1)$ distribution, an exclusive (kinematically complete) measurement is required, where momentum vectors of all the outgoing particles, in this case ^{10}Be and the neutron, are measured. The experimental setup used in the experiment of Ref. [40] is shown in Fig. 2.4. In this experiment, the ^{11}Be secondary beam, produced by fragmentation of an ^{18}O beam at 100 MeV/nucleon at RIPS at RIKEN, bombarded a Pb target at an average energy of 68.7 MeV/nucleon. The momentum vectors of the beam ($\mathbf{P}^{(11)\text{Be}}$) as well as those of the outgoing ^{10}Be fragment ($\mathbf{P}^{(10)\text{Be}}$) and the neutron ($\mathbf{P}(n)$) were measured in coincidence.

The excitation energy of the projectile can be extracted by reconstructing the invariant mass $M(^{11}\text{Be}^*)$ of the intermediate excited state of ^{11}Be as follows.

$$M(^{11}\text{Be}^*) = \sqrt{\left(\sum_i E_i\right)^2 - \left(\sum_i \mathbf{P}_i\right)^2} \quad (2.8)$$

$$= \sqrt{(E(^{10}\text{Be}) + E(n))^2 - (\mathbf{P}^{(10)\text{Be}} + \mathbf{P}(n))^2}, \quad (2.9)$$

where $E(^{10}\text{Be})$ and $E(n)$ are the total energy of the ^{10}Be fragment and that of the neutron, respectively. The relative energy E_{rel} between ^{10}Be and the neutron is then related to $M(^{11}\text{Be}^*)$ as,

$$E_{\text{rel}} = M(^{11}\text{Be}^*) - M(^{10}\text{Be}) - m_n. \quad (2.10)$$

Here $M(^{10}\text{Be})$ and m_n denote the mass of ^{10}Be and of the neutron, respectively. The excitation energy E_x is related to the relative energy by $E_x = E_{\text{rel}} + S_n$.

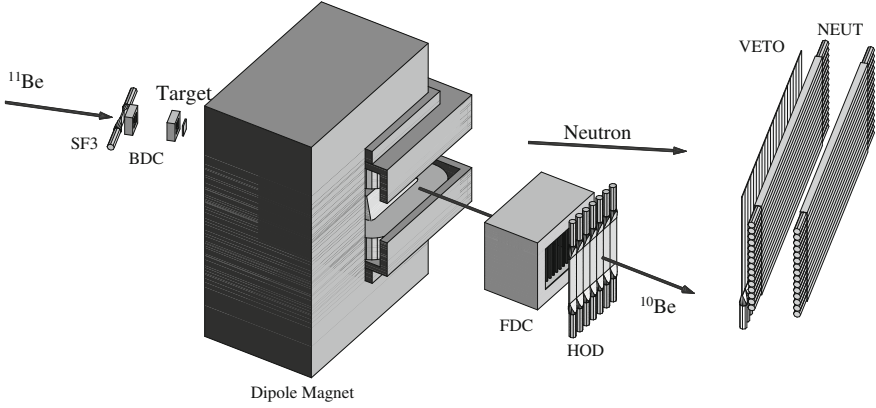


Fig. 2.4 Experimental setup used in the exclusive Coulomb breakup experiment of ^{11}Be at RIPS at RIKEN. The figure is from Ref. [40]

It is useful to note approximate forms of E_{rel} . In the non-relativistic limit, E_{rel} can be written as,

$$E_{\text{rel}} = \frac{\mu}{2} \left[\mathbf{v}(^{10}\text{Be}) - \mathbf{v}(n) \right]^2, \quad (2.11)$$

where μ stands for the reduced mass of ^{10}Be and the neutron, and $\mathbf{v}(^{10}\text{Be})$ and $\mathbf{v}(n)$ the velocities of the outgoing particles. When these velocities are transformed to the projectile rest frame, this result is a good approximation. This can be also approximately written as

$$E_{\text{rel}} = \frac{\mu}{2} \left[\left(v(^{10}\text{Be}) - v(n) \right)^2 + (\bar{v}\theta_{12})^2 \right], \quad (2.12)$$

where $\bar{v}$ and θ_{12} represent the mean velocity and the opening angle between the two outgoing particles. This approximate form implies that the measurement of the relative energy is primarily determined by the difference of the velocities (first term) and the opening angle (second term) of the two outgoing particles. An approximate formula of the energy resolution can then be given as,

$$\Delta E_{\text{rel}} \cong \sqrt{2 \cdot \frac{E}{A} \frac{A_1 A_2}{A_1 + A_2} \cdot E_{\text{rel}}} \cdot \sqrt{\left(\frac{\Delta v_1}{v_1} \right)^2 + \left(\frac{\Delta v_2}{v_2} \right)^2 + \Delta \theta_{12}^2}, \quad (2.13)$$

where E and A denote the kinetic energy and mass number of the projectile. In the case of 70 MeV/u ^{11}Be , decaying into ^{10}Be and a neutron with a relative energy of 1 MeV, a resolution of 190 keV(r.m.s.) is achieved for the condition of $\Delta v_1/v_1 = \Delta v_2/v_2 = 1\%$, and $\Delta \theta_{12} = 10$ mrad. In the experiment of Ref. [40], the same resolution value was obtained by a detailed Monte Carlo analysis including the known velocity

and angular resolutions. Note that the energy resolution is proportional to $\sqrt{E_{\text{rel}}}$ and $\sqrt{E/A}$. Because of this dependence, one can achieve better energy resolution in the invariant mass method compared to the missing mass method where the resolution is determined by the order of E instead of $\sqrt{E/A}$. It is also noted that in the invariant mass method, energy resolution is independent of the angular and energy spreads of the beam, the source of one of the major uncertainties for missing mass spectroscopy.

2.3.1.2 Breakup Cross Sections and the $B(E1)$ Spectrum

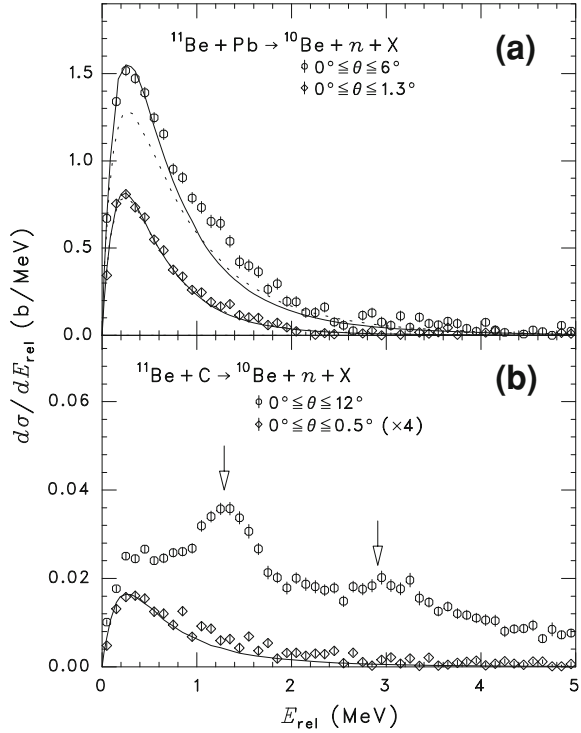
The breakup cross sections of ^{11}Be on lead and carbon targets are shown in Figs. 2.5a and b, respectively. The breakup data on the carbon target, where nuclear breakup is expected to be dominant, is used to investigate the characteristic features of target dependence. The cross sections are plotted for the different scattering angular ranges shown. Here, the scattering angle θ is that in the c.m. frame of the target+projectile. This was extracted from the difference of the incoming, $\mathbf{P}(^{11}\text{Be})$, and the sum of the outgoing, $\mathbf{P}(^{10}\text{Be}) + \mathbf{P}(n)$, momentum vectors. The angular ranges, $0 \leq \theta \leq 6^\circ$ for the Pb target and $0 \leq \theta \leq 12^\circ$ for the C target, are almost identical in the laboratory frame, corresponding to the acceptance range in this experiment. We call these angular ranges the “whole acceptance”. All the spectra shown in these figures are corrected for the acceptance.

One can see clearly the distinctive difference between the spectra for the two targets. The total breakup cross section into $^{10}\text{Be} + n$ for the Pb target (whole acceptance, $E_{\text{rel}} \leq 5 \text{ MeV}$) is 1790 ± 20 (stat.) ± 110 (syst.) mb, which is larger by a factor of about 20 than that for the C target (93.3 ± 0.8 (stat.) $^{+5.6}_{-10.3}$ (syst.) mb). Such a big difference is due to the fact that the reaction on the Pb target is dominated by Coulomb breakup, which is of the order of one barn for the soft $E1$ excitation. On the other hand, reaction with the C target is dominated by nuclear breakup. Note that if only nuclear breakup were to occur on both for C and Pb targets, the ratio of the cross sections for these two targets would be about 2, roughly equal to the ratio of the target+projectile radii [40].

The second remarkable difference is the spectral shape. The spectra for the Pb target, both for the whole acceptance and the angular-selected one, have an asymmetric peak at very low E_{rel} , while that for the carbon target for the whole acceptance shows two resonance peaks ($E_x = 1.78 \text{ MeV}$, $5/2^+$, and $E_x = 3.41 \text{ MeV}$, $3/2^+$) superimposed on the continuum. It is interesting to note that the angular-selected spectrum for the C target has a similar asymmetric peak as for the Pb target.

This asymmetric shape of the peaks is in good agreement of the direct breakup mechanism shown by the solid curves. Namely, the direct breakup mechanism explains how the soft $E1$ excitation occurs for a $1n$ halo nucleus. The detailed explanation of the direct breakup mechanism, and its characteristic features, is described in the next subsection. We find that the agreement with the direct breakup mechanism is perfect for the angular selected data for Pb, and approximately so for the whole acceptance data. The selection of the most forward angles, well within the grazing angle ($\theta_{gr} = 3.8^\circ$), has been found useful to extract almost purely the “Coulomb”

Fig. 2.5 Breakup cross sections as a function of E_{rel} of ^{10}Be and the neutron in the breakup of $^{11}\text{Be} + \text{Pb}$ at 69 MeV/nucleon (a) and $^{11}\text{Be} + \text{C}$ at 67 MeV/nucleon (b). See text and Ref. [40] for details. (The figure is from Fukuda et al. [40])



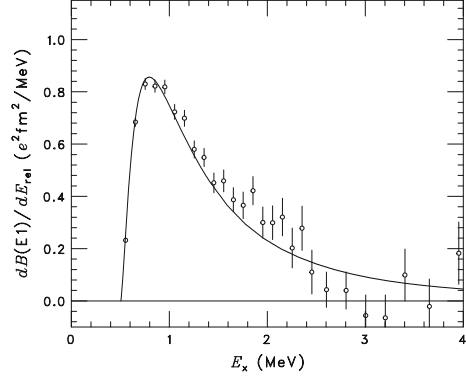
component of the breakup as was demonstrated in this experiment and later by detailed reaction theories [62–64]. For the whole acceptance data, we see a slight deviation which is attributed to nuclear breakup and higher order Coulomb breakup effects. Even for the C target data, when we select sufficiently forward angles, we find the direct Coulomb breakup dominates. These features were also seen in the angular distributions shown in Ref. [40].

The $B(E1)$ distribution was extracted from the angular-selected data. In this case, it is useful to adopt the double differential cross section of Eq. (2.6), integrated over the selected angular range. The resultant $B(E1)$ spectrum is shown in Fig. 2.6, which is again explained by the direct breakup mechanism shown in the solid curve. The integrated $B(E1)$ obtained from the data selected for the forward angles amounts to $1.05 \pm 0.06 \text{ e}^2 \text{ fm}^2$ corresponding to $3.29 \pm 0.19 \text{ W.u.}$ (Weisskopf unit) for $E_x \leq 4 \text{ MeV}$, which is huge, considering that the $E1$ strength in this energy region for normal nuclei is negligible (below 0.1 W.u.).

2.3.1.3 Direct Breakup Mechanism

We now explain the direct breakup mechanism. As demonstrated by the comparison with the Coulomb breakup data of ^{11}Be , the direct breakup mechanism explains well the soft $E1$ excitation of $1n$ halo nuclei. In the direct breakup mechanism, the $1n$ -halo

Fig. 2.6 $B(E1)$ strength distribution for ^{11}Be as a function of E_x , obtained from the angle-selected Coulomb breakup data on a Pb target ($\theta < 1.3$ degrees). The solid curve is the result of a calculation with the direct breakup mechanism with $\alpha^2 = 0.72$



nucleus, in this case ^{11}Be , breaks up into ^{10}Be and a neutron without forming any intermediate resonances. The possibility of the soft dipole resonance (SDR) as a main mechanism of this large $E1$ strength is now rejected. Hence, it is more appropriate to call this phenomenon soft $E1$ “excitation”.

The direct breakup mechanism is explained simply by the following matrix element,

$$\frac{dB(E1)}{dE_{\text{rel}}} = |\langle \Phi_f(\mathbf{r}, \mathbf{q}) | e_{\text{eff}}^{E1} \hat{T}(E1) | \Phi_i(\mathbf{r}) \rangle|^2, \quad (2.14)$$

where $\Phi_i(\mathbf{r})$ and $\Phi_f(\mathbf{r}, \mathbf{q})$ represent the wave function of the ground state and the final state in the continuum of the neutron relative to the core, respectively. $\mathbf{r}$ is the relative coordinate of the valence neutron relative to the c.m. of the core. $\Phi_f(\mathbf{r}, \mathbf{q})$ is also a function of the relative momentum $q = \sqrt{2\mu E_{\text{rel}}/\hbar}$. The electric dipole operator is $\hat{T}(E1) (= rY^{(1)}(\Omega))$. For the case of ^{11}Be , Φ_i is $|^{11}\text{Be}(1/2^+; \text{g.s.})\rangle$.

For simplicity, we consider a pure single particle state and a spinless core, as in $|^{10}\text{Be}(0^+) \otimes \nu 2s_{1/2}\rangle$. The Eq. (2.14) can then be expressed in a simpler form as

$$\frac{dB(E1)}{dE_{\text{rel}}} = \frac{3}{4\pi} (e_{\text{eff}}^{E1})^2 \langle \ell_i 0 1 0 | \ell_f 0 \rangle^2 \left| \int dr r^2 \phi_f(r, q) r \phi_i(r) \right|^2, \quad (2.15)$$

where ℓ_i, ℓ_f are the orbital angular momenta of the valence neutron in the initial state, and the scattered neutron in the final state, respectively [65–67]. ϕ_i is the radial wave function involved in Φ_i , and ϕ_f is the radial component of the final scattering state of the neutron. The $E1$ effective charge e_{eff}^{E1} for the one-neutron halo nucleus is Ze/A . Although the actual analysis is performed with a distorted wave for ϕ_f , it is instructive to consider the plane wave approximation

$$\phi_f(r, q) = \sqrt{\frac{2\mu q}{\hbar^2 \pi}} j_{\ell_f}(qr), \quad (2.16)$$

where $j_{\ell_f}(qr)$ is the spherical Bessel function. With this approximation, it is found that the above equations (Eqs. (2.14) and (2.15)) have the form of the Fourier trans-

form of $r\phi_i(r)$. Hence, the $B(E1)$ distribution at low q (low E_{rel}) is the amplified Fourier image of the density distribution of the valence neutron (or halo). It should be noted that this image is amplified due to the factor “ r ” in the $E1$ operator. It is shown in Ref. [64] that due to this amplification, $B(E1)$ at low E_{rel} is almost solely determined by the density distribution outside of the range of the mean-field potential. That is, in the integration of Eq. (2.14), most of the contribution comes from the radial region outside of the range of the neutron-core binding potential.

This interpretation in terms of a Fourier transform also implies that the spatial decoupling of the halo and the core is important. The spatially decoupled halo state overlaps very well with the $E1$ operator which further emphasizes large separations of the valence neutron and the core. Such an intermediate state has a large overlap with the final scattering state where the outgoing neutron is by definition well separated from the core fragment. Conversely, since neutrons in ordinary nuclei are not spatially decoupled from the core, only a high energy $E1$ photon can separate the whole neutron fluid from the proton fluid as arises in the GDR.

Another instructive formula is obtained by further approximating Eq. (2.15), by replacing the ground state radial wave function by its asymptotic form at large distance. In general, $\phi_i(r)$ can be written

$$\phi_i(r) = Nh_{\ell_i}^{(1)}(i\eta r), \quad (2.17)$$

where N is the normalization factor, and $h_{\ell_i}^{(1)}$ is the spherical Hankel function with $\eta = \sqrt{2\mu S_n}/\hbar$. In particular, the s -wave state as in $|^{10}\text{Be}(0^+) \otimes \nu 2s_{1/2}\rangle$ is expressed by the Yukawa function,

$$\phi_i(r) = -N \frac{\exp(-\eta r)}{\eta r} \quad (2.18)$$

Then Eq. (2.15) leads to the following analytical form:

$$\frac{dB(E1)}{dE_{\text{rel}}} = N^2 \frac{3\hbar^2}{\pi^2\mu} \left(\frac{Ze}{A} \right)^2 \frac{\sqrt{S_n} E_{\text{rel}}^{3/2}}{(E_{\text{rel}} + S_n)^4}. \quad (2.19)$$

This formula shows the essence of the direct breakup of an s -wave halo state. We find that the peak of this analytical form appears at $E_{\text{rel}} = (3/5)S_n$ (i.e., $E_x = (8/5)S_n$), and the integrated strength is inversely proportional to S_n . Hence, the lower the separation energy, the stronger the soft $E1$ excitation is. Thus, the observable is dictated by S_n or the threshold energy. This is why the soft $E1$ excitation is considered as a threshold effect. However, we should note that S_n is simply the reflection of the halo distribution. Hence, the spatially decoupled nature of the halo nucleus is considered to be more essential. Such analytical forms, for different combinations of the initial and final states, were described in Ref. [66, 67] and their features are also discussed in Sect. 2.3.2

2.3.1.4 Spectroscopic Factor

The $B(E1)$ spectrum can be used to extract the spectroscopic information of the halo structure. Namely, for the two-component configuration, Eq. (2.14) can be rewritten as,

$$\begin{aligned} \frac{dB(E1)}{dE_{\text{rel}}} &= \alpha^2 \left| \langle \Phi_f \left| \frac{Ze}{A} \hat{T}(E1) \right| {}^{10}\text{Be}(0^+) \otimes \nu 2s_{1/2} \rangle \right|^2 + \\ &\quad \beta^2 \left| \langle \Phi_f^* \left| \frac{Ze}{A} \hat{T}(E1) \right| {}^{10}\text{Be}(2^+) \otimes \nu 1d_{5/2} \rangle \right|^2 \\ &\simeq \alpha^2 \left| \langle \Phi_f \left| \frac{Ze}{A} \hat{T}(E1) \right| {}^{10}\text{Be}(0^+) \otimes \nu 2s_{1/2} \rangle \right|^2, \end{aligned} \quad (2.20)$$

where Φ_f^* represents the scattering state between the excited state of ${}^{10}\text{Be}(2_1^+)$ and the neutron. Note that the interference term vanishes since the final state of ${}^{10}\text{Be}$ is definite.

As was mentioned the $B(E1)$ strength at low E_{rel} is only sensitive to the tail of the density distribution. Accordingly, only the amplitude for the $|{}^{10}\text{Be}(0^+) \otimes \nu 2s_{1/2}\rangle$ component, the halo configuration, survives as shown in Eq. (2.20). The spectroscopic factor α^2 of $|{}^{10}\text{Be}(0^+) \otimes \nu 2s_{1/2}\rangle$ can thus be extracted from the amplitude of the $B(E1)$ spectrum. In the experiment of Ref. [40], the spectroscopic factor for the halo configuration $\alpha^2 = 0.72 \pm 0.04$ was extracted. The spectroscopic factors from other experiments range from 0.6 to 0.9 (see Table II of Ref. [40]), which are over all consistent with the current result.

2.3.1.5 Sum Rules

There are two significant sum rules for the $E1$ response of a $1n$ halo nucleus; the non-energy weighted cluster sum rule [68–70] and the energy weighted cluster sum rule [71]. The non-energy weighted cluster sum rule is described as,

$$B(E1) = \int_{-\infty}^{+\infty} \frac{dB(E1)}{dE} dE = \frac{3}{4\pi} \left(\frac{Ze}{A} \right)^2 \langle r^2 \rangle, \quad (2.21)$$

which shows that the integrated $B(E1)$ is proportional to $\langle r^2 \rangle$, where r represents the distance of the halo neutron from the c.m. of the core. For ${}^{11}\text{Be}$, Ref. [40] estimated $\sqrt{\langle r^2 \rangle} = 5.77 \pm 0.16$ fm by summing the $E1$ strength up to $E_x = 4$ MeV, which is 1.05 ± 0.06 $e^2\text{fm}^2$. Note, however, the sum should be taken to infinity, and also take account of bound final states [68, 69]. The extrapolation to infinity amounts to $0.12e^2\text{fm}^2$, while for bound states, we should also add the $E1$ strength of $0.100(15)$ $e^2\text{fm}^2$ due to excitations of the 1st excited state at $E_x = 320$ keV ($J^\pi = 1/2^-$) [72] as well as other contributions ($1p_{3/2}$) calculated as $0.037e^2\text{fm}^2$ [70]. Then the sum of $E1$ strength amounts to $1.31 \pm 0.07e^2\text{fm}^2$, where the uncertainty is only statistical.

Considering the systematic errors arising from the model [69], the estimated $\sqrt{\langle r^2 \rangle}$ is 6.4 ± 0.5 fm, about 10% larger than the original estimate.

It is useful to investigate the other dependence on the integrated $B(E1)$ strength. Combined with the result of the previous section, for the case of the s -wave $1n$ halo, one can extract the following relations:

$$B(E1) \propto \alpha^2 / S_n \quad (2.22)$$

$$\propto \langle r^2 \rangle. \quad (2.23)$$

It is now evident that $B(E1)$ of the $1n$ halo is determined by and scales with S_n , α^2 , and is related to the size, $\langle r \rangle^2$, according to the non-energy weighted cluster sum rule.

Another important sum rule is the energy-weighted cluster sum rule [71], which is described as,

$$\int \sigma_\gamma(E1) dE_x = \int \frac{16\pi^3}{9\hbar c} E_x \frac{dB(E1)}{dE_x} dE_x = \frac{60NZ}{A} - \frac{60N_c Z_c}{A_c} \text{MeVmb}, \quad (2.24)$$

where A_c , N_c , and Z_c represent the mass-, neutron- and atomic number of the core fragment. For ^{11}Be , this means that the cluster sum rule exhausts 5.7% of the TRK (Thomas-Reich-Kuhn) sum rule. Ref. [40] extracted the value 4.0(5)%, which is about 70 % of the cluster sum. It is interesting to note that this value is consistent with the spectroscopic factor α^2 for the halo configuration.

2.3.2 Spectroscopy Using Coulomb Breakup of $1n$ Halo Nuclei - Application to ^{19}C

As was demonstrated for ^{11}Be , Coulomb breakup of a $1n$ halo nucleus occurs primarily by the direct breakup mechanism, as expressed by the matrix element shown in Eqs. (2.14) or (2.15). The $B(E1)$ distribution has a characteristic shape depending on S_n , ℓ (denoted by ℓ_i in this section) of the valence neutron, and the spectroscopic factor of the configuration. Here, the characteristic shapes and amplitude of $B(E1)$ spectra are discussed, whose characteristic differences can be used to clarify the shell configuration and spin-parity of the loosely bound state, in this case, the ground state of ^{19}C . The structure of ^{19}C was unknown for many years before the exclusive Coulomb breakup experiment [41] was performed. We also demonstrate that the angular distribution of the Coulomb breakup reaction is useful in the determination of S_n . These features provide the basis for the Coulomb breakup method offering a useful spectroscopic tool for a loosely-bound $1n$ nuclear system.

2.3.2.1 Issues with ^{19}C

The structure of ^{19}C has not been well known partially because of a large uncertainty in the four direct mass measurements: The Time-Of-Flight Isochronous (TOFI) at Los Alamos measured $S_n(^{19}\text{C})$ to be 700 ± 240 keV [73], and later 230 ± 120 keV [74], while at GANIL, the high-resolution spectrograph (SPEG) combined with the TOF measured $S_n(^{19}\text{C})$ to be 50 ± 420 keV [75], and later -70 ± 240 keV [76]. The mass evaluation in 1993 based on these direct mass measurements was 0.16 ± 0.11 MeV [77, 78]. Such a small S_n value, even smaller than that of ^{11}Be , suggests a significant halo state in ^{19}C , which has drawn much attention. However, we should note that the extracted S_n value ranged from almost 0 to 700 keV.

Since the 13th neutron in ^{19}C most-likely occupies an orbital in the sd shell, the following two possibilities for the ground state configuration should be examined:

$$|^{19}\text{C}(1/2^+)\rangle = \alpha|^{18}\text{C}(0^+) \otimes \nu 2s_{1/2}\rangle + \beta|^{18}\text{C}(2^+) \otimes \nu 1d_{5/2}\rangle, \quad (2.25)$$

$$|^{19}\text{C}(5/2^+)\rangle = \gamma|^{18}\text{C}(2^+) \otimes \nu 2s_{1/2}\rangle + \delta|^{18}\text{C}(0^+) \otimes \nu 1d_{5/2}\rangle, \quad (2.26)$$

where α, β, γ , and δ denote the spectroscopic amplitude for each configuration. The shell model calculations in Ref. [79, 80] also suggest such configurations, where these two states are almost degenerate in energy.

Before the exclusive Coulomb breakup measurement that we present here was performed, inclusive measurements of either ^{18}C [79–81] or the neutron [82] momentum components following ^{19}C breakup were performed. The momentum distribution of ^{18}C measured at 77 MeV/nucleon at MSU [79, 80] exhibited a narrow width of 42 ± 4 MeV/c, while that measured at 914 MeV/nucleon at GSI [81] had a broader width of 69 ± 3 MeV/c. Later, the semi-exclusive nuclear breakup on the ^9Be target was performed at MSU, where the γ -coincidence information was also incorporated. There, the inclusive ^{18}C momentum distribution is closer to the high energy result of Ref. [81].

Because of such ambiguities in the early inclusive measurements, the interpretation of the ground state of ^{19}C had long been controversial. Reference [79] suggested a $J^\pi = 1/2^+$ assignment for the ^{19}C ground state, and indicated halo formation arising from a large component of the $|^{18}\text{C}(0^+) \otimes \nu 2s_{1/2}\rangle$ configuration. However, the revised analysis [80] suggested the $J^\pi = 5/2^+$ assignment with a large portion of a $|^{18}\text{C}(2^+) \otimes \nu 2s_{1/2}\rangle$ configuration. A similar possibility was also suggested in the GSI paper [81]. The halo formation should be strongly suppressed for this configuration because of the effective increase of S_n by 1.62 MeV corresponding to the cost of the core excitation energy of the $^{18}\text{C}(2^+)$ state. As is later shown, this would affect the spectral shape of the Coulomb breakup spectrum as well.

2.3.2.2 Characteristic Features of Spectral Shape of Direct Breakup

Since the density distribution outside of the potential will vary strongly, depending on the orbital angular momentum of the valence neutron ℓ_i and the S_n value, the $B(E1)$

Table 2.1 Characteristics of the spectral shape of $dB(E1)/dE_{\text{rel}}$ depending on the orbital angular momentum of the valence neutron (ℓ_i) in the initial state, and that of the scattered neutron (ℓ_f) in the final state [21, 67]

$\ell_i \rightarrow \ell_f$	$dB(E1)/dE_{\text{rel}} \propto E_{\text{rel}}^{\ell_f+1/2}$ (for small E_{rel})	Peak of $dB(E1)/dE_{\text{rel}}$
$s \rightarrow p$	$\propto E_{\text{rel}}^{3/2}$	$E_{\text{rel}} = \frac{3}{5} S_n$
$p \rightarrow s$	$\propto E_{\text{rel}}^{1/2}$	$E_{\text{rel}} \simeq 0.18 S_n$
$p \rightarrow d$	$\propto E_{\text{rel}}^{5/2}$	$E_{\text{rel}} = \frac{5}{3} S_n$
$d \rightarrow p$	$\propto E_{\text{rel}}^{3/2}$	$E_{\text{rel}} = \frac{5}{3} S_n$

spectrum is also characterized by these values. There is also a dependence on ℓ_f , the orbital angular momentum of the dissociated neutron. In the realistic calculation of $dB(E1)/dE_{\text{rel}}$ based on the direct breakup mechanism, Eq. (2.14) or (2.15) are used. However, it is instructive to investigate the analytical forms when using a spherical Hankel function for the ground state, and a spherical Bessel function (plane wave) for the final state, as in Eq. (2.19) for the s -wave halo. One obtains a general form, for instance, in Eq. (2) of Ref. [67]. In this reference, the explicit analytical forms are presented for $p \rightarrow s$ and $p \rightarrow d$, in addition to that for $s \rightarrow p$ (Eq. (2.19)). It can also be shown that, for a very small E_{rel} value,

$$\frac{dB(E1)}{dE_{\text{rel}}} \propto E_{\text{rel}}^{\ell_f+1/2}, \quad (2.27)$$

and $dB(E1)/dE_{\text{rel}}$ reaches maximum at the value shown in Table 2.1, depending on ℓ_i and ℓ_f [21]. This table illustrates that the distinctive difference of spectral shape of $dB(E1)/dE_{\text{rel}}$ allows us to determine the ℓ_i value as well as to estimate S_n . For some cases, J^π of the ground state can be extracted. Therefore, the exclusive Coulomb breakup of a $1n+$ core system is a very powerful tool for investigating microscopic structure of such a weakly-bound nucleus.

2.3.2.3 Energy Spectrum and the Ground State Configuration of ^{19}C

Figure 2.7 shows the Coulomb breakup cross section as a function of E_{rel} , which was obtained by using the ^{19}C beam with an average energy of 67 MeV/nucleon at RIKEN [41]. Here, the nuclear breakup component was subtracted using the breakup spectra for a C target. The method of selecting only very forward angles, as was used in more recent ^{11}Be data [40], was not adopted in these data due to lower statistics. The Coulomb breakup spectrum in Fig. 2.7 shows a typical asymmetric shape with a large cross section of 1.19 ± 0.11 barn, a typical feature for a neutron halo nucleus.

Calculations were performed for the direct breakup mechanism for 4 different assumed ground state configurations, depending on the configuration in Eqs. (2.25) and (2.26). First of all, we have found that for $J^\pi = 5/2^+$, any mixture of the two components, $|^{18}\text{C}(2^+) \otimes \nu 2s_{1/2}\rangle$ and $|^{18}\text{C}(0^+) \otimes \nu 1d_{5/2}\rangle$ failed to reproduce the

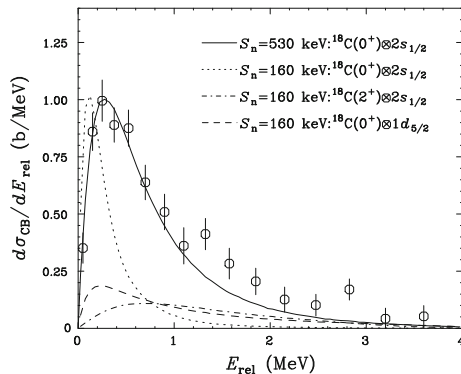


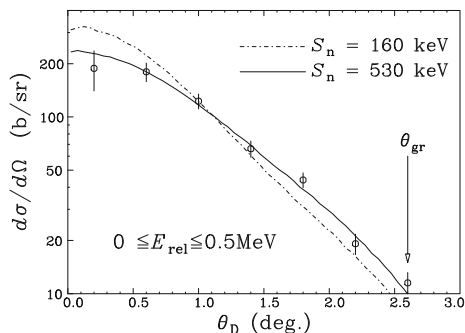
Fig. 2.7 Coulomb breakup cross sections for ^{19}C measured at 67 MeV/nucleon on a Pb target. The dot-dashed and dashed curves are calculations for the configurations, $|^{18}\text{C}(2^+) \otimes \nu 2s_{1/2}\rangle$ and $|^{18}\text{C}(0^+) \otimes \nu 1d_{5/2}\rangle$, respectively, of $J^\pi = 5/2^+$ assignment with unit spectroscopic factors and $S_n = 160$ keV. The dotted and solid curves are calculations for the configuration $|^{18}\text{C}(0^+) \otimes \nu 2s_{1/2}\rangle$ with $S_n = 160$ keV and $S_n = 530$ keV, respectively. The latter S_n value is from the angular distribution shown below

data with a former adopted S_n value of 160 keV. Varying S_n over a wide range (from 100 to 700 keV) was not able to reproduce the data, since the calculation could not explain the magnitude of the cross section.

For the $J^\pi = 1/2^+$ case, on the other hand, the peak height of the spectrum can be reproduced with $\alpha^2 = 0.064$ (dotted line) for $S_n = 160$ keV. However, a further tuning of the S_n value was required to obtain an overall fit to the spectrum. In fact, good agreement was obtained using a higher S_n value of 530 keV as shown by the solid line. This S_n value was obtained from an independent analysis using the angular distribution, as shown below. In this case a large spectroscopic factor of $\alpha^2 = 0.67$ was deduced. As for the $|^{18}\text{C}(2^+) \otimes \nu 1d_{5/2}\rangle$ configuration, only negligible contribution is obtained and thus this is not shown.

We concluded that the ground state of ^{19}C is $J^\pi = 1/2^+$, involving a dominant configuration of $|^{18}\text{C}(0^+) \otimes \nu 2s_{1/2}\rangle$ and the S_n value of about 500 keV. This configuration is rather close to that predicted by a shell model calculation with the WBP interaction [79, 83]. The large amplitude for an s -wave valence neutron with such a small S_n value shows that ^{19}C is a $1n$ halo nucleus. There are a number of theoretical work on dynamics and spectroscopic significance of Coulomb breakup of ^{19}C . S. Typel and R. Shyam used a time-dependent dynamical model of the breakup with a heavy target, which could explain well the energy spectrum of ^{19}C as well as that of ^{11}Be [84]. We also refer to Ref. [63] and references therein.

Fig.2.8 Angular distribution of the Coulomb breakup cross section of ^{19}C on a Pb target. (The figure is from T. Nakamura et al. [41])



2.3.2.4 Mass from the Angular Distribution of Coulomb Breakup

We now demonstrate that the S_n value can be determined from an analysis of the angular distribution of ^{19}C (i.e., of the $^{18}\text{C} + n$ c.m.). As was shown in the case of the Coulomb breakup of ^{11}Be [40], the scattering angle of the excited $^{19}\text{C}^*$ in the c.m. frame of the target+projectile can be extracted using the momentum vectors of the incident ^{19}C particle, and of the outgoing ^{18}C and the neutron. As in Eq. (2.6), the angular distribution of the cross section is proportional to that of the $E1$ virtual photon ($dN_{E1}/d\Omega$). The point is that the angular distribution of the photon is the function of E_x , which is related to S_n by $E_x = E_{\text{rel}} + S_n$. For a given E_{rel} , the angular distribution is then controlled by the parameter S_n , and is independent of the choice of the final state wave function. Hence, S_n can be extracted from the measured angular distribution. Note that the determination of S_n from the angular distribution is less model dependent compared to the determination of S_n from the peak position of the $B(E1)$ spectrum which may be affected by other $E1$ excitations.

Figure 2.8 shows the measured angular distribution, for $0 \leq E_{\text{rel}} \leq 0.5$ MeV, in comparison with the calculated spectra, where an angular resolution of 8.4 mrad (in 1σ) was incorporated. The angular distribution is best fitted with $S_n = 530 \pm 130$ keV as indicated by the solid curve, while the previously adopted value of $S_n = 160$ keV was unable to reproduce the angular distribution.

Such a higher S_n value was also extracted from the investigation of the momentum distribution of ^{18}C in coincidence with the de-excitation γ ray from the first excited state of ^{18}C at MSU [85]. Note that the newer mass evaluation $S_n(^{19}\text{C}) = 0.577 \pm 94$ MeV [86, 87]) now takes into account the angular distribution of this Coulomb breakup measurement as well as the momentum distribution in the γ -ray tag method.

In this section, we have shown that Coulomb breakup is a powerful spectroscopic tool to investigate otherwise unknown states of loosely bound nuclei. It is important that the technique of using the angular-distribution analysis for a $1n$ halo system was established through this work [41].

2.3.3 Application to the Radiative Capture Reaction $^{14}\text{C}(n, \gamma)^{15}\text{C}$ of Astrophysical Interest

Coulomb breakup associated with one neutron emission can be useful to extract the radiative neutron capture reaction (n, γ) , the latter being the inverse of the (γ, n) reaction. As such, Coulomb breakup is also a useful tool in application to nuclear astrophysics [88, 89]. Here, we show the case of the Coulomb breakup of ^{15}C whose inverse process is $^{14}\text{C}(n, \gamma)^{15}\text{C}$. The principle of detailed balance provides the relation between $\sigma_{\gamma n}$ (photo-absorption cross section: $\sigma_{\gamma n} = \sigma_{\gamma}$ in Eq. (2.4)) and the radiative neutron capture cross section $\sigma_{n\gamma}$ as in,

$$\sigma_{n\gamma}(E_{\text{c.m.}}) = \frac{2I_A + 1}{2I_{A-1} + 1} \frac{E_{\gamma}^2}{2\mu c^2 E_{\text{c.m.}}} \sigma_{\gamma n}(E_{\gamma}), \quad (2.28)$$

where $I_A = 1/2$, and $I_{A-1} = 0$ for the present case, and μ denotes the reduced mass of $^{14}\text{C} + n$, and $E_{\text{c.m.}}$ is the c.m. energy of $n + ^{14}\text{C}$ which is equivalent to E_{rel} . Due to the phase-space factor, the photo-absorption cross section is larger by 2–3 orders of magnitude. For instance, for the current case at $E_{\text{c.m.}} = 0.5$ MeV, $\sigma_{\gamma n}(E_{\gamma})/\sigma_{n\gamma}(E_{\text{c.m.}}) \simeq 150$. We also note that the photon numbers are further multiplied, which is of 2–3 orders of magnitude. Considering, in addition, the kinematic focusing and the possibility of using a thick target, of the order of 100 mg/cm^2 , Coulomb breakup is more advantageous, even using a weak radioactive beam, compared to the neutron capture experiment. In this particular experiment on the neutron capture on ^{14}C , there is an additional difficulty in preparing the ^{14}C target, which is radioactive, while Coulomb breakup is free from such a difficulty.

2.3.3.1 The Radiative Neutron Capture Reaction $^{14}\text{C}(n, \gamma)$

The neutron capture reaction on ^{14}C has drawn much attention due to its importance in several nucleosynthesis processes. There are three cases where this reaction may be of significance.

1. The neutron induced CNO cycle, $^{14}\text{C}(n, \gamma)^{15}\text{C}(\beta^-)^{15}\text{N}(n, \gamma)^{16}\text{N}(\beta^-)^{16}\text{O}(n, \gamma)^{17}\text{O}(n, \alpha)^{14}\text{C}$, which occurs in the burning zone of asymptotic giant branch (AGB) stars with $1\text{--}3 M_{\odot}$ [90]. The $^{14}\text{C}(n, \gamma)^{15}\text{C}$ reaction is the slowest in this reaction chain, and thus controls the cycle.
2. Synthesis of heavy elements: Terasawa [91, 92] proposed a new-type of r -process initiating from the lightest elements, and thus contains light neutron rich nuclei in the path. This r process was inferred from the similarity of the nuclear abundance pattern in metal-deficient halo stars to that of ordinary ones. The neutron capture on ^{14}C lies in one of the critical reaction flows of this process.
3. Inhomogeneous big bang models: In such models, the neutron-rich zone induces nucleosynthesis and reaction paths involving light neutron-rich nuclei can appear.

In this scenario, the $^{14}\text{C}(n, \gamma)^{15}\text{C}$ reaction is also considered to be one of the key reactions [93].

Due to these possible stellar reactions, the $^{14}\text{C}(n, \gamma)^{15}\text{C}$ reaction has attracted much attention.

2.3.3.2 Soft $E1$ Excitation and the p -Wave Direct Neutron Capture

From the nuclear structure point of view, the ground state of ^{15}C , i.e., the final state of the capture reaction, is intriguing because it has a moderate-sized neutron halo with a neutron separation energy S_n of only 1.218 MeV. Its main configuration is $|^{14}\text{C}(0^+) \otimes \nu 2s_{1/2}\rangle$. Therefore, Coulomb breakup of ^{15}C is expected to proceed via soft $E1$ excitation due to the direct breakup mechanism.

Then, the direct capture of a p -wave neutron [65] is considered to be a dominant process. This capture process is called direct neutron capture since the neutron in the continuum is captured onto the ^{14}C nucleus, just as in the inverse process where ^{15}C breaks up into its p -wave continuum by the Coulomb breakup (direct breakup). The p -wave capture process, as a stellar reaction, is exceptional, considering that the neutron capture of a low-energy s -wave neutron that obeys the $1/v$ law is usually dominant. The dominance of p -wave neutron capture has also been discussed for stable nuclei, although the final state in this case is an excited state in an s orbital as in $^{13}\text{C}(1/2^+)$ [94, 95].

2.3.3.3 Issues with ^{15}C Coulomb Breakup and Direct Capture Experiments on ^{14}C

There has been controversy over the previous experimental results for this neutron capture process. The pioneering experiment to extract the $^{14}\text{C}(n, \gamma)^{15}\text{C}$ reaction rate was made by a direct measurement of the neutron capture cross section on a ^{14}C radioactive target [96]. The extracted MACS (Maxwellian averaged capture cross section) of $1.72 \pm 0.43 \mu\text{b}$ at $kT=23$ keV was about a factor of 4-5 smaller than predicted by the p -wave direct neutron capture calculations [93, 97].

As for the Coulomb breakup approach, A. Horváth et al. measured ^{15}C Coulomb breakup at 35 MeV/nucleon at MSU [42]. There, the energy spectrum of the inverse capture cross section was very different from the expected p -wave behavior. Their extracted capture cross section was about twice as large as that from the above-mentioned direct measurement. More recently, Datta Pramanik et al. measured the Coulomb breakup at higher energies, 605 MeV/nucleon at GSI [98, 99]. The result showed a typical direct breakup spectrum, indicating the p -wave direct capture in the inverse process.

More recently, the direct capture measurement was performed for the second time by Reifarth et al. [100]. The result shows a significantly higher cross section compared to the first direct measurement. In this new measurement, an energy spectrum

ranging from ~ 10 keV to 800 keV was also obtained so that a direct comparison to the Coulomb breakup energy spectrum is now possible.

Here, we primarily show the result from the most recent Coulomb breakup experiment at RIKEN using a ^{15}C secondary beam at 68 MeV/nucleon on a Pb target [44]. It should be noted that the $^{14}\text{C}(n, \gamma)^{15}\text{C}$ case is a rare one, where both directions of the reactions, neutron capture and Coulomb breakup, can be measured, so that such data can be used to make a rigorous test of the Coulomb breakup method. Therefore, precise measurements in both directions are highly desirable. Recent reaction theories [101–103] for treating Coulomb breakup reactions can also be tested using such measurements.

2.3.3.4 Coulomb Breakup and Neutron-Capture Spectra

Figure 2.9 shows the relative energy spectrum of $^{14}\text{C} + n$ in the breakup of ^{15}C on a Pb target at 68 MeV/nucleon. To extract the Coulomb breakup component, we adopt the same procedure as in the Coulomb breakup of ^{11}Be [40], using the angular selection at forward angles. The solid squares show the breakup cross section integrated over the scattering angular range $0^\circ \leq \theta \leq 6.0^\circ$ which nearly corresponds to the whole acceptance. Open circles show the cross section for a selected angular range, $0^\circ \leq \theta \leq 2.1^\circ$, which corresponds to the impact parameter range $b > 20$ fm.

The breakup cross sections for $E_{\text{rel}} \leq 4$ MeV are 670 ± 14 (stat.) ± 40 (syst.) mb and 294 ± 12 (stat.) ± 18 (syst.) mb for the whole acceptance and the selected angular range, respectively. Such large breakup cross sections due to Coulomb breakup on a heavy target are typical for halo nuclei. We should note, however, that the ^{15}C breakup cross section is about $1/5 \sim 1/3$ of those for the conventional halo nuclei such as ^{11}Be [40], and ^{19}C [41], both of which were measured at about 70 MeV/nucleon. This indicates that the size of the halo in ^{15}C is not as extended as in those more weakly-bound halo nuclei. The $B(E1)$ spectrum, extracted from the spectrum for $0^\circ \leq \theta \leq 2.1^\circ$, is shown in Fig. 2.10, which is in excellent agreement with the direct breakup calculation, as shown in the solid curve (dot-dashed curve shows the calculation before folding the experimental resolutions).

2.3.3.5 Neutron Capture Cross Section

Figure 2.11 shows the neutron capture cross section $\sigma_{n\gamma}$ extracted from the $B(E1)$ spectrum by applying the principle of detailed balance (Eq. 2.28). An excellent agreement is obtained with the p -wave direct radiative capture model calculation [66]. This result is consistent with the consideration that the final state of the ^{14}C capture reaction (namely ^{15}C g.s.) is a halo state with a dominant s wave component. The result is also found to be consistent with the neutron capture measurement in Ref. [100], with only a slight deviation at around $E_{\text{c.m.}} \sim 0.5$ MeV. The overall agreement of the Coulomb breakup result with the direct capture measurement suggests that Coulomb breakup can be a good alternative for obtaining the neutron

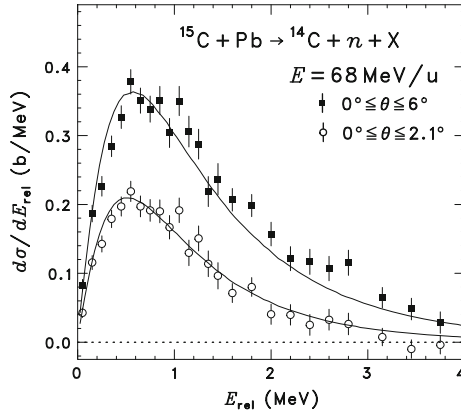


Fig. 2.9 Relative energy spectra for Coulomb breakup of ^{15}C . *Solid squares* represent the data for scattering angles up to 6° , and *open circles* represent the data for selected scattering angles up to 2.1° . The *solid curves* are calculations for a direct breakup model with a spectroscopic factor $\alpha^2 = 0.91$, for the halo configuration ($a = 0.5$ fm and $r_0 = 1.223$ fm) (The figure is from T. Nakamura et al. [44])

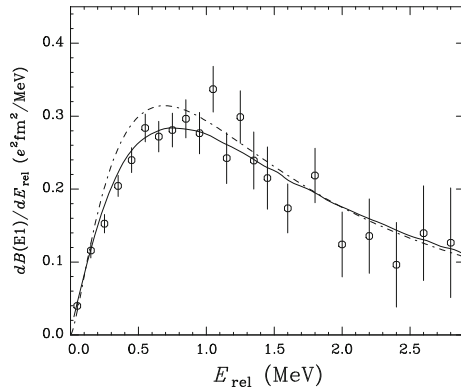


Fig. 2.10 $B(E1)$ spectrum for ^{15}C excitation. The *solid curve* corresponds to the direct breakup model calculation. The *dot-dashed curve* is the same calculation, before folding with the experimental resolution. (The figure is from T. Nakamura et al. [44])

capture cross sections involving radioactive nuclei. Note that in general the Coulomb breakup method can be applied to neutron-rich nuclei where the corresponding direct neutron capture measurement is not feasible.

As for the comparison with previous Coulomb breakup results, we find that only the data obtained from the Coulomb breakup measurement performed at GSI [98, 99] is consistent with the presented measurement. The neutron capture cross section derived from the Coulomb breakup experiment performed at MSU is significantly smaller (about $1\mu\text{b}$ at $E_{\text{c.m.}} = 23.3$ keV, and $4\mu\text{b}$ around $0.05\text{--}0.10$ MeV).

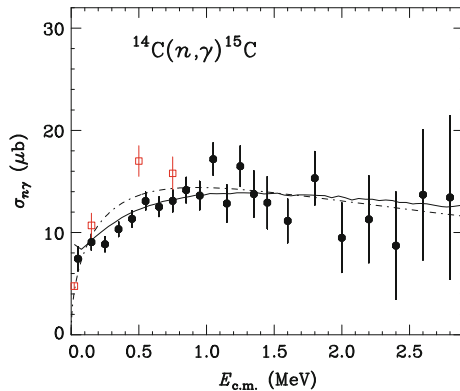


Fig. 2.11 Neutron capture cross section on ^{14}C leading to the ^{15}C ground state. *Solid circles* are the results of the current experiment, and *open squares* are those from the most recent direct capture measurement [97]. The *dot-dashed curve* is the calculation based on the direct radiative capture model, while the *solid curve* is the same one but includes experimental resolution. Both calculations were done using a spectroscopic factor $\alpha^2 = 0.91$ and with potential parameters $a = 0.5$ fm and $r_0 = 1.223$ fm (The figure is from T. Nakamura et al. [44])

Since our results are consistent with those of Reifarh et al. [100], the argument and implications in the nucleosynthesis scenario follows closely those of Ref. [100], where the role of the $^{14}\text{C}(n, \gamma)^{15}\text{C}$ in the neutron induced CNO cycles, and the impact of such a cycle on the neutron flux are discussed. The confirmation of the reciprocity between Coulomb breakup and the radiative neutron capture is encouraging for further studies of (n, γ) reactions in heavier neutron-rich nuclei. One should note, however, that in the inverse reaction of Coulomb breakup, one can restrict the reaction to the ground state. For the case of ^{15}C , there is only one excited state at 0.74 MeV, and the neutron capture to this state is found negligible from theories [93, 97]. Although, such fortunate situations may be scarce for heavier regions, we may expect lower level densities near closed shells, such as $N = 50$ and 82, where Coulomb breakup can be applicable. These nuclei may be relevant to the r -process, and thus also be of importance.

2.3.4 Inclusive Coulomb Breakup of ^{31}Ne

As was shown above, Coulomb breakup reaction is a powerful tool for investigating $1n$ halo nuclei when one can map the $dB(E1)/dE_{\text{rel}}$ function by a kinematically complete measurement (exclusive Coulomb breakup). Here, we show that “inclusive” Coulomb breakup can also be a useful tool. The case presented in this section is an inclusive Coulomb breakup measurement of ^{31}Ne [10], which was performed at the new-generation RI-beam facility, RIBF, at RIKEN as one of the day-one ^{48}Ca beam campaign experiments in Dec. 2008.

2.3.4.1 Issues with ^{31}Ne

For about a decade, the heaviest $1n$ halo nucleus experimentally known has been ^{19}C . Since the first observation of ^{31}Ne in the late 1990s [104], ^{31}Ne has been the next heavier candidate for a $1n$ halo nucleus due to the small $1n$ separation energy. According to the mass evaluation in 2003 [85, 86], S_n was theoretically estimated as 0.332 ± 1.069 MeV, while the recent direct mass measurement showed S_n to be 0.29 ± 1.64 MeV [105].

Experimental studies of ^{31}Ne are thus important as to how and in what form heavier halo nuclei appear, as raised in the questions in the Introduction. Once halo structure of ^{31}Ne is established, then we may obtain a key to understand how a single particle configuration plays a role in halo formation. ^{31}Ne ($N = 21$) could be inside “the island of inversion”, where shell model calculations showed that $N = 20$ magicity is lost and significant $2p$ - $2h$ configurations are mixed [106–108]. The neighboring nuclei ^{32}Mg [109], ^{32}Na [110], $^{30,32}\text{Ne}$ [111, 112] were found within this island, experimentally.

For the conventional shell order, where the valence neutron resides in the $1f_{7/2}$ orbital upon the ^{30}Ne core, an enhanced tail of the density distribution (halo) never develops, being blocked by the high centrifugal barrier. The halo formation of ^{31}Ne is only possible when a strong shell modification occurs, such that the $2p_{3/2}$ orbit lowers below the $1f_{7/2}$ orbit, for instance.

2.3.4.2 Inclusive Coulomb Breakup

We show that inclusive Coulomb breakup can be used to obtain a signal of the existence of a halo structure. In an inclusive breakup experiment for the $1n$ halo nucleus candidate, we measure $1n$ removal cross section on a heavy target. Namely, we measured the counts of ^{30}Ne fragments relative to the counts of ^{31}Ne projectiles which bombarded a Pb target.

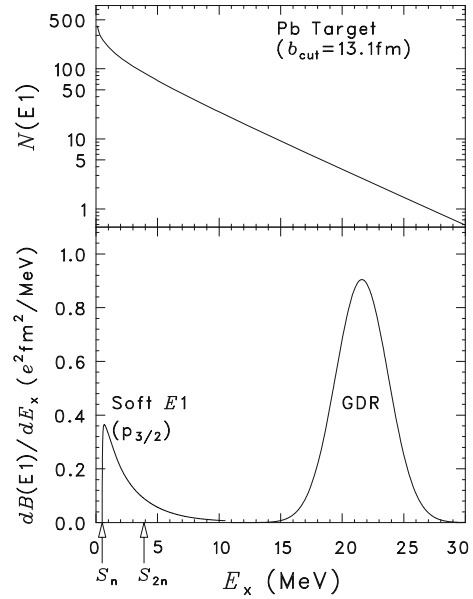
As was mentioned, an exclusive (kinematically complete) measurement requires that of four momentum vectors of all the outgoing particles. In this case we need a coincidence measurement of the neutron, which requires 1-2 order larger yield for the beam. On the other hand, an inclusive measurement is feasible with beam intensity of the order of counts per second or even less, suitable for the earlier stage of the new facility. In the experiment of Ref. [10], typical ^{31}Ne beam intensity was about 5 counts per second and the data was taken only for about 10 hours.

The inclusive Coulomb breakup works in the following way. The inclusive Coulomb breakup cross section can be written as,

$$\sigma(E1) = \int_{S_n}^{\infty} \frac{16\pi^3}{9\hbar c} N_{E1}(E_x) \frac{dB(E1)}{dE_x} dE_x. \quad (2.29)$$

Namely, the product of $N_{E1}(E_x)$ and $dB(E1)/dE_x$ is contained in the cross section. As in Fig. 2.3, and in Fig. 2.12 for this particular case, the photon spectrum falls

Fig. 2.12 *Top:* The $E1$ virtual photon spectrum on Pb target for the projectile at 230 MeV/nucleon at the impact parameter cut of 13.1 fm. *Bottom:* Calculated $B(E1)$ spectrum assuming the soft $E1$ excitation of the ^{31}Ne with the p -wave halo neutron bound by $S_n = 0.5$ MeV (*left*) and the giant dipole resonance (GDR) at $E_x = 21.6$ MeV with the sigma width of 2.13 MeV ($\Gamma = 5$ MeV) and with the full strength of TRK sum rule (*right*)



exponentially with E_x . Thus, $\sigma(E1)$ becomes significant only when the $B(E1)$ is concentrated at low excitation energies (soft $E1$ excitation) as in the case of halo nuclei. The bottom part of Fig. 2.12 shows the comparison of calculations of $B(E1)$ for a halo nucleus (soft $E1$ excitation) and the ordinary nucleus (GDR) for a $A = 31$ nucleus. For the GDR of the ordinary nucleus, we assume that the GDR peak is located at $31.2A^{-1/3} + 20.6A^{-1/6}$ MeV = 21.6 MeV [53] with a width of 5 MeV (Gaussian) exhausting the full TRK sum rule, namely,

$$\int \sigma_\gamma(E1) dE_x = \int \frac{16\pi^3}{9\hbar c} E_x \frac{dB(E1)}{dE_x} dE_x = \frac{60NZ}{A} \text{MeVmb}. \quad (2.30)$$

The TRK sum for the $A = 31$ nucleus is 420 MeVmb. Then the total Coulomb breakup cross section $\sigma(E1)$ for ^{31}Ne on Pb target at 230 MeV amounts to 58 mb.¹

On the other hand, assuming that ^{31}Ne is a halo nucleus and has soft $E1$ strength caused by the valence neutron in $p_{3/2}$ with $S_n = 0.5$ MeV, then the total Coulomb breakup cross section up to $E_x = 10$ MeV is 510 mb, which is about one order of magnitude larger than that due to the GDR. In the measurement, we obtain $1n$ removal Coulomb breakup cross section, whose integration ranges up to $E_x \sim S_{2n}$ instead of infinity. For this range, the GDR strength can yield essentially null cross section, while the soft $E1$ excitation gives rise to the Coulomb breakup cross section in the $1n$ removal channel as 470 mb. With such a distinctive difference, $1n$ -removal Coulomb breakup cross section can be used as a signal showing a halo state.

¹ When we use the $80A^{-1/3}$ formula, we obtain even less cross section.

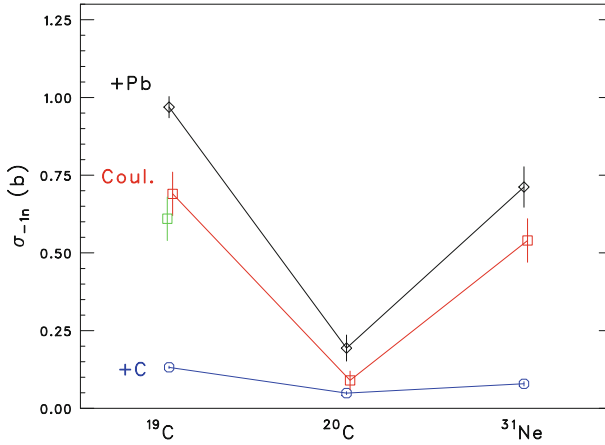


Fig. 2.13 One neutron removal cross sections for ^{19}C , ^{20}C , and ^{31}Ne on Pb (diamonds) and C (circles), and extracted Coulomb breakup cross sections (squares) obtained at about 230 MeV/nucleon. The large Coulomb cross section of ^{31}Ne close to that of ^{19}C (established halo nucleus) indicates the $1n$ halo structure of ^{31}Ne . The Coulomb breakup cross section for ^{19}C estimated from the exclusive one ([41], also see Sect. 3.2 is shown by the square, symbol just left of the current data, which shows consistency. The data for ^{19}C and ^{31}Ne are from Ref. [10]. The data for ^{20}C are preliminary

2.3.4.3 Results of ^{31}Ne Breakup

Figure 2.13 shows the $1n$ removal cross sections of $^{19,20}\text{C}$ and ^{31}Ne on Pb and C targets at 230–240 MeV/nucleon. It is readily seen that the cross sections of ^{19}C and ^{31}Ne are both significantly larger than that of ^{20}C . Secondly, the ratio of the cross section for Pb to that for C is 9.0 ± 1.1 for ^{31}Ne and 7.4 ± 0.4 for ^{19}C , much larger than the ratio for nuclear breakup only, which is estimated to be about 1.7–2.6. This demonstrates that the cross section for a Pb target is dominated by Coulomb breakup for ^{19}C and ^{31}Ne .

The Coulomb breakup component of the $1n$ removal cross section on Pb was deduced by subtracting the nuclear component estimated from $\sigma_{-1n}(\text{C})$. For this purpose, it was assumed that $\sigma_{-1n}(\text{C})$ arises entirely from the nuclear contribution, and that the nuclear component for a Pb target scales with the parameter Γ , as in,

$$\sigma_{-1n}(E1) = \sigma_{-1n}(\text{Pb}) - \Gamma \sigma_{-1n}(\text{C}), \quad (2.31)$$

where Γ was estimated to be ~ 1.7 –2.6. The lower value is the ratio of target+projectile radii, as in Ref. [5], while the upper one is that of radii of the two targets as in the Serber model [113]. The Coulomb breakup cross section for ^{31}Ne was thus obtained to be $\sigma_{-1n}(E1) = 540 \pm 70$ mb, which takes into consideration the ambiguity arising from the choice of these two models. The dominance of the Coulomb breakup for the reaction of ^{31}Ne on Pb and the deduced $\sigma_{-1n}(E1)$ of some 0.5 b, nearly as high as the established halo nucleus ^{19}C , indicates the occurrence of

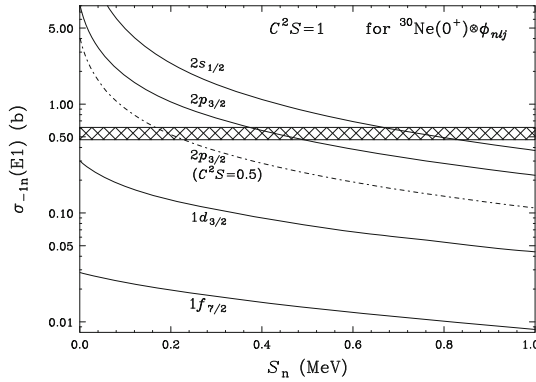


Fig.2.14 The Coulomb breakup cross section for ^{31}Ne on Pb at 234 MeV/nucleon is compared with calculations for configurations of the valence neutron in $2s_{1/2}$, $2p_{3/2}$, $1d_{3/2}$, $1f_{7/2}$ coupled to ^{31}Ne (g.s.) for $C^2S = 1$ as a function of S_n . An example of lower C^2S value ($C^2S = 0.5$) is shown by the dot-dashed curve for the $2p_{3/2}$ configuration

soft $E1$ excitation for ^{31}Ne , thereby providing evidence of $1n$ halo structure of this nucleus.

According to the direct breakup mechanism, the single-particle structure of the ground state of ^{31}Ne can be examined. Figure 2.14 compares the experimentally deduced $\sigma_{-1n}(E1)$ with calculations for possible valence-neutron configurations as a function of S_n . Since there is a large experimental uncertainty in the S_n value of ^{31}Ne , the calculations were shown as a function of S_n .

The figure deals with direct-breakup calculations for a pure single particle configuration $C^2S = 1$ for the valence neutron either in the $2s_{1/2}$, $1d_{3/2}$, $1f_{7/2}$, or $2p_{3/2}$ orbital, being coupled to the ground state of ^{30}Ne . More detailed analysis including possible configurations of the valence neutron coupled to the $^{30}\text{Ne}(2_1^+)$ state is presented in Ref. [10]. The essential point is, however, included in this figure. Namely, the comparison in Fig. 2.14 shows that the data can be reproduced only by the configuration of $|^{30}\text{Ne}(0_1^+) \otimes \nu 2p_{3/2}\rangle$ ($J^\pi = 3/2^-$) or $|^{30}\text{Ne}(0_1^+) \otimes \nu 2s_{1/2}\rangle$ ($J^\pi = 1/2^+$), but not by $|^{30}\text{Ne}(0_1^+) \otimes \nu 1d_{3/2}\rangle$ nor $|^{30}\text{Ne}(0_1^+) \otimes \nu 1f_{7/2}\rangle$. The significant contribution of such low- ℓ valence neutron is again consistent with the $1n$ halo structure in ^{31}Ne . The other important implication of this result is that the conventional shell model configuration of $|^{30}\text{Ne}(0_1^+) \otimes \nu 1f_{7/2}\rangle$ for the $N=21$ nucleus does not represent a primary configuration of the ^{31}Ne ground state. Large-scale Monte-Carlo Shell Model (MCSM) calculations employing the SDPF-M effective interactions [108] support the assignment of $J^\pi = 3/2^-$ having a $|^{30}\text{Ne}(0_1^+) \otimes \nu 2p_{3/2}\rangle$ contribution, which is consistent with the current findings.

The shell model calculations (MCSM) also showed the large configuration mixing, where $|^{30}\text{Ne}(0_1^+) \otimes \nu 2p_{3/2}\rangle$ could be mixed with $|^{30}\text{Ne}(2_1^+) \otimes \nu 2p_{3/2}\rangle$ and $|^{30}\text{Ne}(2_1^+) \otimes \nu 1f_{7/2}\rangle$. Such a large configuration mixing may be better described in terms of deformation. In fact, recently, the current data was interpreted by a deformed mean-field model [114]. There, the 21st neutron ($p_{3/2}$) can be orbiting in a deformed

mean-field potential, namely in the Nilsson levels $[330]1/2^-$ or $[321]3/2^-$, although the possibility of an s -wave valence neutron ($[200]1/2^+$) in a strongly deformed mean field ($\beta > 0.59$) was not fully excluded. More recently, the ground state properties of ^{31}Ne were also discussed using the particle-rotor model, which takes into account the rotational excitation of the ^{30}Ne core [115]. It is interesting to note that halo properties, such as direct breakup dynamics and soft $E1$ excitations, are kept for the wave functions obtained in a deformed mean-field potential.

Recently, there have been debates over the J^π assignment of the ground state of ^{33}Mg [116–119], either with $J^\pi = 3/2^-$ or $J^\pi = 3/2^+$. Note that ^{33}Mg has the same neutron number $N = 21$ as ^{31}Ne . The Coulomb breakup results of ^{31}Ne shown here may provide some hints to understand the structure of ^{33}Mg and other isotones nearby.

We also have a preliminary result of inclusive Coulomb breakup of ^{22}C ($2n$ -halo candidate), where we have obtained evidence for $2n$ halo structure of this nucleus, whose details will be published elsewhere. For this nucleus, the large radius of ^{22}C was recently suggested in the reaction cross section measurement [14], in accordance with the $2n$ halo structure of this nucleus.

As was demonstrated, inclusive measurements are in particular important when the beam intensity is not sufficient. Such a study provides us with a first step to approach the exotic property of extremely neutron rich nuclei. However, for a full understanding of the microscopic structure of ^{31}Ne , exclusive Coulomb breakup experiments would be desired, where C^2S and S_n can be extracted for this $1n$ halo nucleus. At RIBF at RIKEN, such experiments will be realized soon by the completion of the SAMURAI (Superconducting Analyser for MUlti-particles from Radio-Isotope Beam) facility.

2.4 Coulomb Breakup and Soft $E1$ Excitation of $2n$ Halo Nuclei

The phenomena of soft $E1$ excitation for $2n$ halo nuclei have been known since the first inclusive Coulomb breakup experiment for ^{11}Li was performed [5]. However, we still lack a complete understanding of the nature of soft $E1$ excitation for $2n$ halo nuclei due to experimental and theoretical difficulties compared to $1n$ halo cases.

So far, the exclusive Coulomb breakup measurements have been performed for ^6He [120, 121], ^{11}Li [45–50], and ^{14}Be [122]. For ^6He , the two data [120, 121] are not in agreement. Theoretically, there are a number of theoretical publications for ^6He [123–132], although theoretical interpretations of the data [120, 121] are not fully established. For ^{14}Be , the statistics of the experiment in Ref. [118] is apparently not satisfactory to be compared with theories.

The soft $E1$ excitation of ^{11}Li was also controversial, partly due to the inconsistency of three data obtained in the 90's: one measured at MSU at 28 MeV/nucleon [45, 46], one at RIKEN at 43 MeV/nucleon [47], and one at GSI at 280 MeV/nucleon [49] (see Fig. 2.17). More recently, the new data on ^{11}Li was obtained [50] with much higher statistics and with higher sensitivity for two neutron detections. In this section,

we review this data, and discuss the obtained implication of the soft $E1$ excitation and the microscopic structure of the $2n$ halo nucleus ^{11}Li .

2.4.1 Exclusive Coulomb Breakup of ^{11}Li

2.4.1.1 Experimental Setup and Treatment of Neutron Cross Talks

A kinematically complete measurement of the Coulomb breakup of ^{11}Li on Pb at 70 MeV/nucleon was performed at RIKEN [50]. The experimental setup is shown in Fig. 2.15, where the incoming ^{11}Li was excited by absorption of a virtual photon and then broke up into the ^9Li fragment and the two neutrons. The difference from the experiment of $1n$ halo nuclei is that we should take a special care of measurements of the fast two neutrons in coincidence. In order to veto cross talk events which can happen in the two neutron detection, the neutron detectors composed of 54 rods of plastic scintillators ($214(\text{H}) \times 6.1(\text{V}) \times 6.1(\text{D}) \text{ cm}^3$ each) were arranged into two walls (12×2 rods for the front (NEUT-A) and 15×2 rods for the rear (NEUT-B)), separated by 1.09 m.

Since a neutron is scattered easily by the scintillator material, cross-talk events, where one single neutron leaves more than one signal, can occur. Figure 2.16 (left) schematically illustrates how such a cross-talk event occurs. There, one neutron is scattered in a scintillator rod in the first neutron-detector wall (NEUT-A), which reaches another scintillator rod in the second wall (NEUT-B) to be fired again. Such an event arising from a single neutron can be mistaken for two neutrons firing independently these two scintillator rods. When two signals are obtained from the two scintillator rods, each of which belong to a different wall (different-wall event), one can extract the apparent velocity between the two scintillator rods (v_{AB}). One can then utilize the v_{AB} information to reject the cross-talk events by imposing the condition such that the velocity to the first scintillator v_A is smaller than v_{AB} . This condition excludes almost fully the cross-talk events since the neutron has smaller velocity after the scattering. The validity of this method of vetoing the cross-talk events was confirmed by the calibration run using the $^7\text{Li}(p, n)^7\text{Be}$ (g.s.+0.43 MeV) reaction, which emits only one neutron at the forward angles.

We have also events where two neutrons hit two scintillator rods that belong to the same neutron-detector wall. In this case, one cannot distinguish a two-neutron event from a one-neutron event when two hits take place in a close distance. Figure 2.16 (right) shows how the cross-talk events affect the sensitivity at low E_{rel} in $^9\text{Li} + n + n$, where E_{rel} between the two neutrons is also low. There is a dip in the efficiency curve at $E_{\text{rel}} \sim 0$ MeV for the same-wall events due to the insensitivity mentioned, while the different-wall events have a smooth efficiency curve towards $E_{\text{rel}} \sim 0$, which enabled us to measure $B(E1)$ strength down to $E_{\text{rel}} = 0$ MeV. In treating the same-wall events, we confirmed that energy spectrum after the efficiency correction in the same wall events is essentially identical to that for the different wall events.

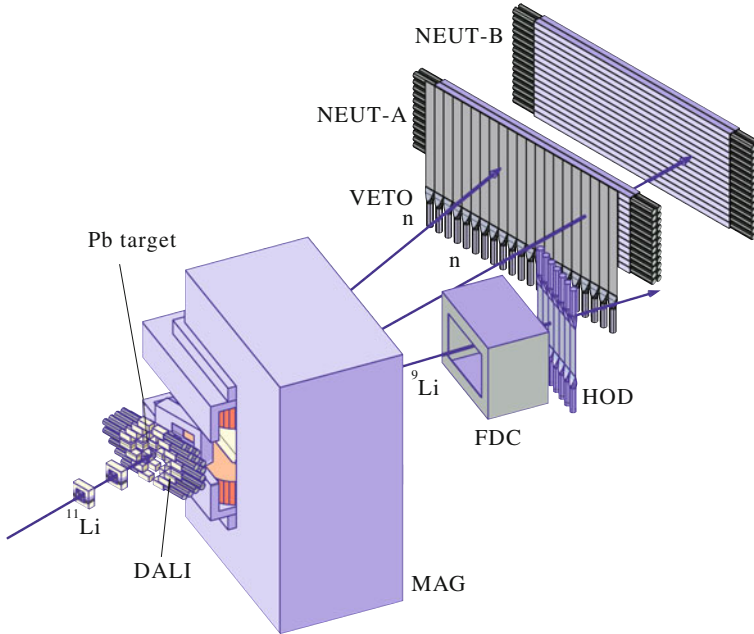


Fig.2.15 The experimental setup for the Coulomb breakup measurement of ^{11}Li on Pb at 70 MeV/nucleon at RIKEN. The setup contains a dipole magnet (MAG), drift chamber (FDC), hodoscope (HOD), and two-walls of neutron detector arrays (NEUT-A,B). (The figure is from T. Nakamura et al. [50])

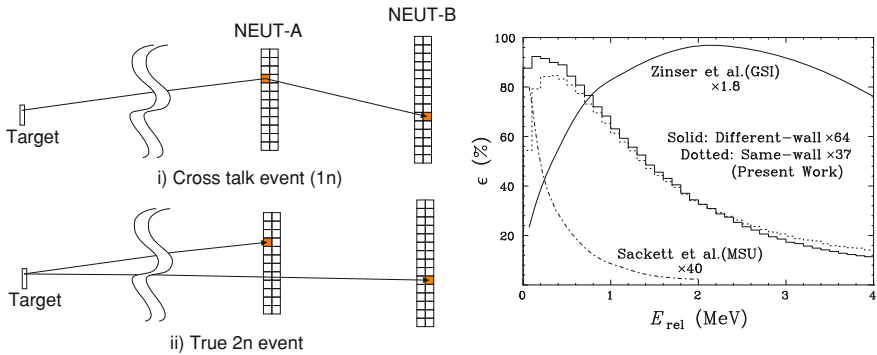


Fig.2.16 Left Schematic explanation of the cross-talk event: (i) Cross-talk event where one neutron fires both NEUT-A and NEUT-B, and (ii) Two neutron event hitting independently NEUT-A and NEUT-B. The cross-talk events shown in (i) can be excluded by imposing the condition $v_A < v_{AB}$, where v_A denotes the neutron velocity between the target and the NEUT-A, and v_{AB} denotes the apparent velocity obtained from the timings at NEUT-A and NEUT-B. Right Estimated efficiencies for the different-wall events and same-wall events. The efficiency is also compared with those from the experiments at MSU [45, 46] and at GSI [49] (The latter figure is from Ref. [50]).

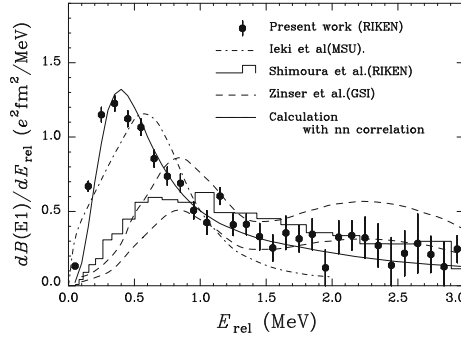


Fig. 2.17 $B(E1)$ spectrum obtained in the Coulomb breakup of ^{11}Li at 70 MeV/nucleon Ref. [50] compared with the previous data obtained at MSU at 28 MeV/nucleon (dot-dashed-line) [45, 46], RIKEN at 45 MeV/nucleon (solid histogram) [47, 48], and at GSI at 280 MeV/nucleon (zone between dashed lines) [49]. The data is also compared with the three-body calculation shown in the solid curve [68, 69]

2.4.1.2 $B(E1)$ Spectrum and Two Neutron Correlation

Figure 2.17 shows the obtained $B(E1)$ distribution, which is compared with the previous three data sets. The result reveals substantial $E1$ strength that peaks at very low E_{rel} around 0.3 MeV. This feature is in contrast to the previous data, which showed much reduced strength towards low relative energies which may be due to the low neutron detection efficiency near $E_{\text{rel}} \sim 0$ MeV in those experiments.

The spectrum amounts to a large energy-integrated $B(E1)$ strength of $1.42 \pm 0.18 \text{ e}^2 \text{fm}^2$ (4.5(6) W.u.), for $E_{\text{rel}} \leq 3$ MeV, which is the largest soft $E1$ strength ever observed. In fact, this $E1$ strengths is about 40% larger than that for the one-neutron halo nucleus ^{11}Be [39, 40].

In extracting this spectrum, the $E1$ virtual photon spectrum assumed $S_{2n} = 0.3$ MeV (2003 Mass Evaluation) [85, 86]. Recently, the mass values with higher precisions have been experimentally obtained at ISOLDE(CERN) [133] and at TRIUMF [134]. The former used the mass spectrometer MISTRAL, which deduced the S_{2n} value to be 0.378(5) MeV, while the latter used the Penning trap technique which enabled an extremely precise mass evaluation of ^{11}Li as $S_{2n} = 0.36915(65)$ MeV. These results provided consistently higher values by about 20% compared to the 2003 mass evaluation, which affects the evaluation of the photon number that is dependent on $E_x = S_{2n} + E_{\text{rel}}$. For the latter S_{2n} value of 0.369 MeV, the $E1$ strength for ^{11}Li re-evaluated is 1.49(19) ($\text{e}^2 \text{fm}^2$) for $E_{\text{rel}} \leq 3$ MeV, or about 5% larger. Such a slight change within the experimental uncertainty does not essentially change the conclusion.

Figure 2.17 also compares the present $B(E1)$ distribution with a calculation using the three-body model proposed by Esbensen and Bertsch [67, 68], which includes the two-neutron correlations both in the initial and final states in the $E1$ excitation. Note that this calculation reproduces the data very well with no adjustment of normal-

ization. Recently, a revised 3-body calculation was made by Esbensen et al. [135], where the recoil effect was taken into account, in addition. Although an overall agreement with the data has been obtained, some deviation occurs around $E_{\text{rel}} \sim 0.5$ MeV as shown in Fig. 2 of Ref. [135]. This may be an indication that the other effects, such as core excitation, may be important. The recent calculation by Myo et al. [31, 32], which incorporated the effect of the core polarization using the tensor optimized shell model, reproduced better the peak region. These overall agreements of both the spectral shape and absolute strength in these calculations indicate the presence of a strong two neutron correlation in ^{11}Li , both in the ground and final states.

2.4.1.3 Non Energy Weighted Cluster Sum Rule for 2n Halo Nuclei and Dineutron Correlation

The spatial two-neutron correlation in the ground state (initial state) of two-neutron halo nuclei can be quantitatively estimated by the non-energy weighted $E1$ cluster sum rule [68, 69]. Such a sum rule was discussed for $1n$ halo nuclei in Sect. 2.3.1.5. For the case of a two-neutron halo nucleus, the $E1$ operator $\mathbf{r}$ is replaced by $\mathbf{r}_1 + \mathbf{r}_2$, where $\mathbf{r}_1$ and $\mathbf{r}_2$ are the position vectors of the two valence neutrons relative to the c.m. of the core. Namely, the sum rule is written as,

$$B(E1) = \frac{3}{4\pi} \left(\frac{Ze}{A} \right)^2 \langle r_1^2 + r_2^2 + 2\mathbf{r}_1 \cdot \mathbf{r}_2 \rangle = \frac{3}{\pi} \left(\frac{Ze}{A} \right)^2 \langle r_{c,2n}^2 \rangle. \quad (2.32)$$

Here, $\mathbf{r}_1 + \mathbf{r}_2$ can be related to $r_{c,2n}$, which is the distance between the c.m. of the core and that of the two halo neutrons. Importantly, the term of $(\mathbf{r}_1 \cdot \mathbf{r}_2)$ involves the opening angle θ_{12} between the two position vectors of the two valence neutrons. The value of $\langle r_{c,2n} \rangle$, and hence $B(E1)$, becomes larger for the smaller spatial separation of the two neutrons, when θ_{12} approaches 0° . The integrated $B(E1)$ thus provides a good measure of the two-neutron spatial correlation.

The integral of the $E1$ -response calculation up to $E_{\text{rel}} = 3$ MeV (solid curve in Fig. 2.17) accounts for about 80% of the total $E1$ cluster sum-rule strength above S_{2n} . Assuming that the $B(E1)$ distribution follows this solid curve, the observed $B(E1)$ strength is then translated into $1.78 \pm 0.22 \text{ e}^2 \text{ fm}^2$ for $E_x \geq S_{2n}$, which corresponds to the value of $\sqrt{\langle r_{c,2n}^2 \rangle} = 5.01 \pm 0.32$ fm. Adopting the sum rule value, $1.07 \text{ e}^2 \text{ fm}^2$, for two non-correlated neutrons calculated in Ref. [68], the value $1.78 \pm 0.22 \text{ e}^2 \text{ fm}^2$ corresponds to $\langle \theta_{12} \rangle = 48_{-18}^{+14}^\circ$. This angle is significantly smaller than the mean opening angle of 90° expected for the two non-correlated neutrons. Hence, an appreciable two-neutron spatial correlation is suggested for the two halo neutrons. Reference [135] estimated $\sqrt{\langle r_{c,2n}^2 \rangle} = 5.22$ fm, while Ref. [31] calculated $\sqrt{\langle r_{c,2n}^2 \rangle}$ to be 5.69 fm. These predicted values are close to the experimental estimation.

The important point for the soft $E1$ excitation of $2n$ halo nucleus is that the larger polarization of the charge due to the stronger dineutron-like correlation enhances the

soft $E1$ excitation. The charge radius measurement of ^{11}Li also extracted the distance $\sqrt{\langle r_{c,2n}^2 \rangle} = 5.97$ (22) [135–137], which is higher than the value from the Coulomb breakup. This discrepancy could be related to the possible core polarization effect [135].

It can be shown that spatial nn correlation is related to a mixture of different parity states in the valence neutrons of ^{11}Li . In a simple shell model picture where the inert ^9Li core is assumed, the ^{11}Li could be described as,

$$\Psi(^{11}\text{Li}(\text{g.s.})) = \alpha |^9\text{Li}(\text{g.s.}) \otimes v(2s_{1/2})^2\rangle + \beta |^9\text{Li}(\text{g.s.}) \otimes v(1p_{1/2})^2\rangle. \quad (2.33)$$

Here, we are interested in the mean opening angle between $\mathbf{r}_1$ and $\mathbf{r}_2$. The expectation value of $\cos \theta_{12}$ can be written as,

$$\begin{aligned} \langle \cos \theta_{12} \rangle &= \alpha^2 \langle (2s)^2 | \cos \theta_{12} | (2s)^2 \rangle + \beta^2 \langle (1p)^2 | \cos \theta_{12} | (1p)^2 \rangle \\ &\quad + 2\alpha\beta \langle (1p)^2 | \cos \theta_{12} | (2s)^2 \rangle \end{aligned} \quad (2.34)$$

$$= 2\alpha\beta \langle (1p)^2 | \cos \theta_{12} | (2s)^2 \rangle \quad (2.35)$$

The terms for α^2 and β^2 are null since these are odd functions of $\cos \theta_{12}$. Hence, a non-zero expectation value implies a mixture of these different parity configurations. Namely, no mixture of different parity states (either $\alpha^2 = 0$ or $\beta^2 = 0$) gives rise to $\langle \theta_{12} \rangle = 90^\circ$ and no $2n$ correlation, while the mixture leads to the $2n$ spatial correlation.

Other than shown above, there are extensive theoretical studies on the three-body nature and the breakup dynamics of ^{11}Li [23, 68, 131, 135, 138–146]. Our Coulomb breakup result, in combination with these theoretical studies, should provide fruitful information on the crucial properties of this intriguing Borromean system.

To summarize the soft $E1$ excitation of $2n$ halo nuclei, as in the case of $1n$ halo, the strong low-energy $E1$ transitions certainly occurs for $2n$ halo nuclei. For ^{11}Li , the integrated soft $E1$ strength is about 40% larger than for ^{11}Be . Such an enhancement is also related to the nn spatial correlation (dineutron-like correlation), which can be understood by the $\mathbf{r}_1 \cdot \mathbf{r}_2$ term in the non-energy weighted cluster sum rule. Experimentally, it is of great importance to detect two neutrons in coincidence unambiguously. A novel detection scheme, in combination with an analysis procedure using the kinematical condition for excluding cross-talk events, was introduced in Ref. [50]. Such a method would be evolved further for multi-neutron detections for a breakup of $4n$ halo nuclei in the near future.

2.5 Spectroscopy of Unbound States via the Nuclear Breakup

We now focus on the breakup with a light-mass target, where nuclear breakup dominates over the Coulomb breakup. The nuclear breakup accompanied by $1n$ or $2n$ emissions, which we treat here, are categorized into two mechanisms:

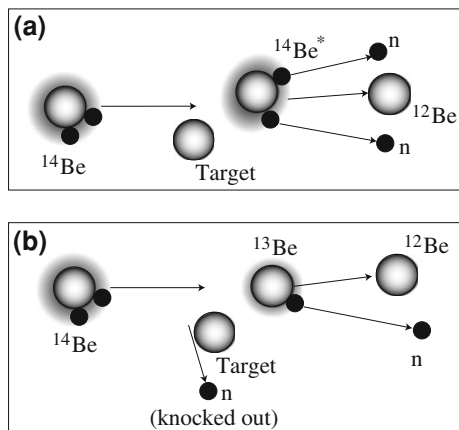


Fig. 2.18 Schematic drawings of the neutron removal processes. *Upper figure (a)* shows diffractive dissociation (or inelastic scattering/elastic breakup) for the case of ^{14}Be . For instance, unbound resonances such as the first 2^+ state can be excited. In the forward detectors, the ^{12}Be fragment and the two neutrons are detected. The *bottom figure (b)* shows the $1n$ knockout process. In this case, the remaining ^{13}Be is produced as an intermediate unbound state followed by the decay into ^{12}Be and n . In the forward detectors, the ^{12}Be fragment and the neutron are detected

1. Diffractive dissociation (or Elastic breakup/Inelastic scattering): This process is inelastic scattering into the resonant state or non-resonant continuum as shown in (Fig. 2.18a). The term elastic breakup is used since this process corresponds to an elastic scattering of the neutron off the target. In this process, the neutron(s) are basically going in the forward directions which can be covered by the neutron detectors in the standard setup of invariant-mass spectroscopy of neutron-rich nuclei.
2. Knockout reaction (or Stripping/Inelastic breakup): The knockout reaction may be viewed as a quasi-free inelastic scattering of the neutron off the target (Fig. 2.18b). In this process, the neutron is scattered to a large angle due to a relatively large momentum transfer or even be absorbed by the target. As a consequence, the neutron will not appear in the forward direction. This process is sometimes referred to as absorption.

Experiments using the neutron removal reactions of radioactive nuclei with light targets have been extensively studied [147], as a powerful spectroscopic tool as in Coulomb breakup. Inelastic breakup can be used to excite directly unbound resonances. In Sect. 2.3.1.2, the case for $^{11}\text{Be} + \text{C}$ was briefly mentioned, where two resonances of ^{11}Be above the $1n$ -decay threshold were observed (see Fig. 2.5b). In this section, we show the excitation of ^{14}Be using the inelastic scattering with carbon and proton targets.

In the knockout reaction, the momentum distribution of the core fragment, and the cross section can be used to determine the orbital angular momentum (ℓ) of the removed neutron. At RI-beam facilities using high/intermediate-energy fragmenta-

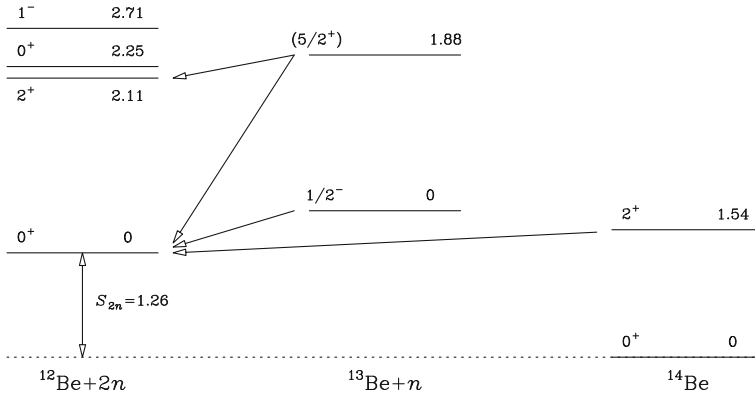


Fig. 2.19 Energy levels of low-lying states of ^{12}Be , ^{13}Be , and ^{14}Be , where the excitation energies are shown in MeV. The energy and the spin-parity of the first excited state of ^{14}Be were obtained from the elastic breakup of ^{14}Be on a carbon target [148], which was later confirmed by the breakup on a proton target. The level scheme of ^{13}Be was obtained from the $1n$ removal reaction of ^{14}Be on the proton target. The S_n value of the ^{13}Be ground state was found $-0.51(1)$ MeV (see text). The arrows from the ^{13}Be to ^{12}Be correspond to the decays observed in this experiment. The direct decay from the 2_1^+ state of ^{14}Be into the ground state of ^{12}Be was also observed, which follows the phase-space decay (see Fig. 2.22)

tion, there have been extensive experimental studies on neutron removal reactions using a variety of radioactive beams on light targets [147]. At MSU, a method of measuring γ rays in coincidence with the core fragment has been developed, which can determine the final bound excited state of the core fragment. Here, we show the case of determining the “unbound” final states of ^{13}Be , following the one-neutron removal of ^{14}Be . This requires extra cares, compared to the bound excited state, as described below.

In what follows, we review experimental studies using the ^{14}Be beam at about 70 MeV/nucleon on carbon and proton targets [51, 148]. The unbound low-lying states of ^{14}Be and ^{13}Be were studied, whose level schemes, including the ones obtained in these experiments are summarized in Fig. 2.19.

2.5.1 Inelastic Scattering of ^{14}Be

2.5.1.1 Issues with ^{14}Be

^{14}Be is the most neutron-rich bound beryllium isotope with the two-neutron separation energy $S_{2n} = 1.26(13)$ MeV [86, 87] (see Figs. 2.1 and 2.19). This nucleus is a Borromean nucleus since ^{13}Be and the two neutrons are unbound, and is known to have two-neutron halo structure due to the weak binding of the two valence neutrons. The structure of ^{14}Be has been investigated theoretically as a $^{12}\text{Be} + n + n$

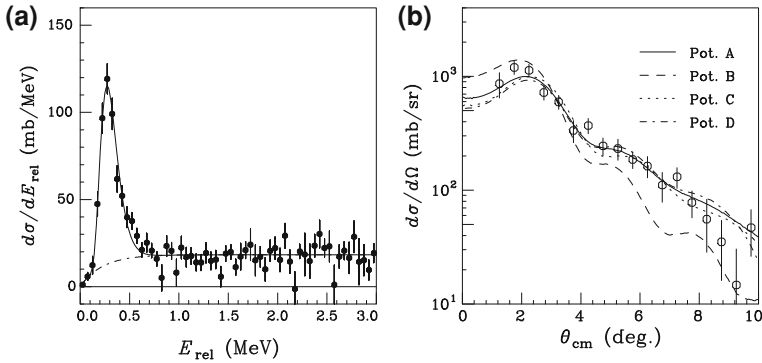


Fig. 2.20 **a** Relative energy spectrum of $^{12}\text{Be} + n + n$ in the inelastic scattering of ^{14}Be on a carbon target at 68 MeV/nucleon. **b** Differential cross sections for the inelastic scattering of ^{14}Be . Curves show the DWBA calculations using optical potential parameter sets. The figures are from Ref. [148]

three-body system [149–153]. This nucleus is also discussed in terms of $\alpha - \alpha$ clustering structure as a common property of the neutron-rich beryllium isotopes [154].

The energies of the first 2^+ states (2_1^+) are important benchmarks to investigate the shell gaps, and their associated nuclear magicity. The 2_1^+ states of most nuclei are bound, and thus can be studied by in-beam γ ray spectroscopy as in the case of ^{12}Be [155]. For ^{12}Be , notably large deformation length was obtained by the (p, p') reaction, despite the fact that ^{12}Be has $N = 8$. Meanwhile, the 2_1^+ state of ^{14}Be has long been controversial, which is lying above the $2n$ decay threshold. A candidate of the 2_1^+ state was reported at around $E_x = 1.6$ MeV [156, 157]. However, subsequent experiments did not show evidence of the state at around 1.6 MeV [19, 122]. In addition, no spin-parity assignment was done in these experiments. This nucleus was thus investigated by the kinematically complete measurement of ^{14}Be breakup on a carbon target with higher statistics at RIKEN [148].

2.5.1.2 Relative Energy Spectrum and Angular Distribution

Figure 2.20a shows the relative energy spectrum of the $^{12}\text{Be} + n + n$ system measured in the breakup of ^{14}Be on a carbon target at 68 MeV/nucleon [148]. The detector setup used is identical to the one in Fig. 2.15. The two neutrons in coincidence with ^{12}Be at forward detectors were measured, which corresponds to the measurement of the elastic breakup (inelastic scattering/diffractive).

A clear resonance peak has been observed at $E_{\text{rel}} = 0.28(1)$ MeV, which was assigned to the first excited state at $E_x = 1.54(13)$ MeV. It should be noted that the uncertainty of E_x is mainly from that of S_{2n} of ^{14}Be . The spin and parity of the state were determined from the analysis of the angular distribution of the inelastically scattered $^{14}\text{Be}^*$ ($^{12}\text{Be} + n + n$). This angular distribution was obtained using the same procedure as in the Coulomb breakup experiments of ^{11}Be , $^{15,19}\text{C}$, and ^{11}Li

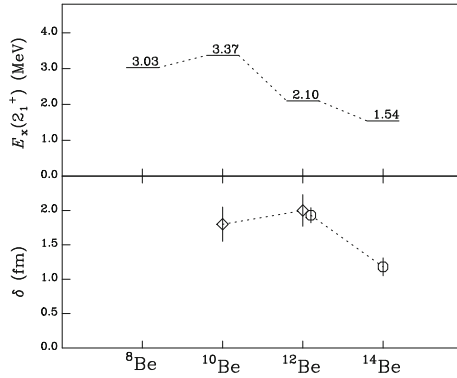


Fig. 2.21 Systematics of the 2_1^+ excitation energies $E_x(2_1^+)$ (top) and quadrupole deformation lengths δ for beryllium isotopes (bottom) are plotted, including the ^{14}Be results [148]. In the bottom figure, the open diamonds represent the result from the inelastic scattering with a ^{12}C target, while the open circles are those with a proton target. The systematics shows the melting of the $N = 8$ shell gap at ^{12}Be . ^{14}Be has the least excitation energy and the least deformation length among the Be isotopes. The figure is from Ref.[148]

described in the previous sections. Figure 2.20b shows the differential cross sections for populating the 1.54-MeV state as a function of the scattering angle. Based on the angular distribution, which is well fitted with curves of the DWBA calculations for the $\Delta L = 2$ transition, the observed resonance was assigned as a $J^\pi = 2^+$ state. The quadrupole deformation length was extracted from the DWBA analysis to be 1.18(13) fm. It is interesting to note that the observed $E_x(2_1^+)$ value of ^{14}Be is smaller than that of ^{12}Be as compared in Fig. 2.21. Contrary to the naive picture that the lower $E_x(2_1^+)$ indicates a larger collectivity for ^{14}Be , the deformation length was observed to be significantly smaller than that of ^{12}Be . Such small collectivity in ^{14}Be may be related to the quenching of effective charges due to the high isospin value as in neutron-rich B isotopes [158, 159]. It was also found that the shell model calculations with effective interactions more appropriate to neutron-rich nuclei in the p -shell (SFO) [160] reproduced the properties of the first 2_1^+ states better both for ^{12}Be and ^{14}Be , rather than the conventional ones (PSDMK) [161].

2.5.2 Breakup of ^{14}Be with a Proton Target and Spectroscopy of ^{13}Be

^{14}Be was also studied by the reaction $^1\text{H} (^{14}\text{Be}, ^{12}\text{Be} + 2n)$ at 69 MeV/nucleon using a liquid hydrogen target provided by the cryogenic target system CRYPTA [162]. Since the reaction yield per energy loss for liquid hydrogen is larger than any other target with a larger mass number, the use of such a target is advantageous for RI beam experiments. The γ ray detectors (DALI NaI(Tl) array) were also installed,

surrounding the target. The experimental setup was essentially similar to the one used for the Coulomb breakup of ^{11}Li (see Fig. 2.15), except for the liquid hydrogen target.

In the Eikonal terminology, the breakup with a proton target at the energy of about 70 MeV is treated as an elastic breakup, irrespective of the amplitude of the neutron momentum transfer, since the proton remains in the ground state through the reaction in any cases. However, here, we distinguish the case where the two neutrons and the core fragment (^{12}Be) are captured in the range of the forward detectors, from the one where one neutron is deflected with a large momentum transfer and thus only the ^{12}Be and the neutron are in the range of the forward detectors. The former corresponds to the case shown in Fig. 2.18a, while the latter corresponds to the case shown in Fig. 2.18b. In the former case, we find that the major contribution is the excitation to the 2_1^+ state of ^{14}Be , and the latter case corresponds to the production of ^{13}Be in the intermediate state. Both channels can be studied in the same experimental setup. As later described, some events from the $2n + ^{12}\text{Be}$ channel can be mixed with the $1n + ^{12}\text{Be}$ channel due to finite efficiency of the neutron detection. Hence, a careful subtraction was made for $1n + ^{12}\text{Be}$ spectrum.

2.5.2.1 Elastic Breakup and Study of the Three-Body Decay

The analysis of the $2n + ^{12}\text{Be}$ channel showed a similar energy spectrum as Fig. 2.20, and confirmed the existence of 2_1^+ state at about $E_x = 1.5$ MeV, whose detailed analysis on the spectrum is published elsewhere. It should be noted that there was no coincidence with γ rays associated with the 2_1^+ state of ^{12}Be which supports that the 2_1^+ state decays into the ground state of ^{12}Be .

We also investigated the property of the three-body decay from this state. Figure 2.22 shows the two dimensional plots of the two-body relative energies, so called Dalitz plot, for the decay of the 2_1^+ state. The experimental distribution is well described by the phase-space decay simulation with no signal of any correlation, and hence no evidence for the sequential decay through a ^{13}Be state was provided. This implies that there are no resonance states of ^{13}Be up to about 0.28 MeV ($=E_{\text{rel}}(2_1^+)$) above the $^{12}\text{Be} + n$ decay threshold. In the subsequent subsections, we show that excitation to the 2_1^+ state in ^{14}Be can affect the spectrum of ^{13}Be , which will be properly subtracted.

2.5.2.2 One-Neutron Removal Reaction of ^{13}Be -Introduction

The $1n$ removal reaction of ^{14}Be on a proton target at 69 MeV/nucleon was used to study ^{13}Be [50], whose production process is schematically shown in Fig. 2.18b. Here, we describe how one could extract the spectrum of the intermediate unbound states of ^{13}Be by the nuclear breakup at intermediate energies.

The energy levels of the unbound nucleus ^{13}Be were controversial because several experimental studies [163–171] were not consistent. In particular, there had

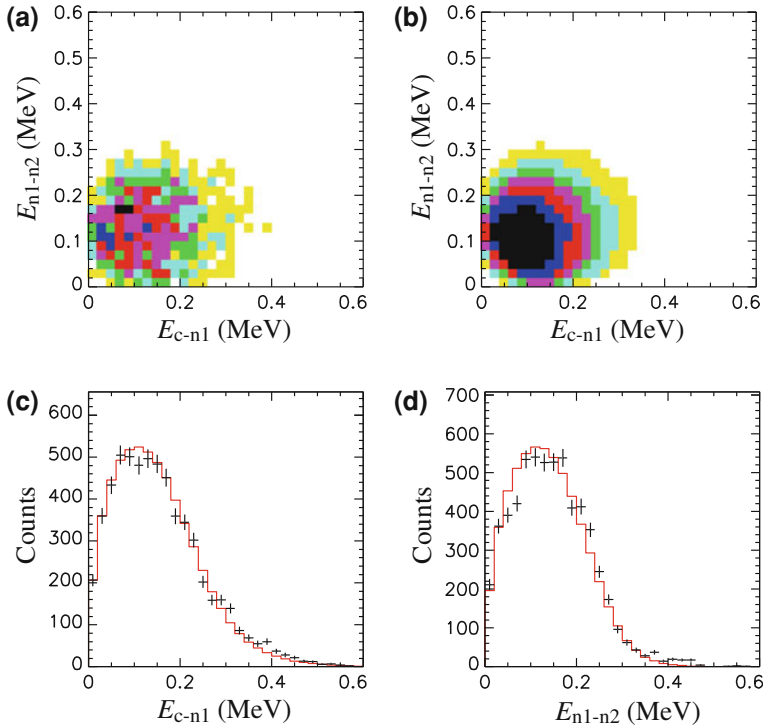


Fig. 2.22 **a:** Experimental Dalitz plot for the decay of the 2^+ state of ^{14}Be . E_{c-n1} and E_{n1-n2} represent two-body relative energies of $^{13}\text{Be}-n$ and the two neutrons, respectively. **b:** Simulation results of the same Dalitz plot by assuming the decay according to the three-body phase space. **c** and **d:** Projected histograms of **a** on E_{c-n1} and E_{n1-n2} , respectively. Simulations shown by *histograms* reproduce the experimental distributions very well.

been large ambiguities in spin-parity assignments. The resonances of the two-body constituent, ^{13}Be , of the three-body system ^{14}Be is a key to understand its Borromean structure. In addition, theoretically, there is an interesting question as to whether at $N = 9$ the parity inversion as in ^{11}Be occurs [172] or not. The experiment of Ref. [51] was thus performed to disentangle the situation and to clarify the low-lying unbound levels of the ^{13}Be nucleus by determining both the energy and J^π .

Similar spectroscopic studies to the case of ^{13}Be were performed for the two-body unbound resonance states in Borromean nuclei, such as ^5He [120, 173, 174], ^7He [173–175], ^{10}Li [49, 171, 176], by the breakup of nuclei ^6He , ^8He , and ^{11}Li , respectively. The proton knockout reactions, which may have different selection rules for the production, have been applied for the study of ^{16}B [177] and ^{18}B [178]. Some of the earlier breakup extracted the momentum distribution of ^5He [179], ^{10}Li [180] and ^{16}B [177], to provide spectroscopic information such as the amplitude and ℓ of the removed neutron (proton). However, the distribution obtained was only

inclusive. Namely, the momentum distributions in those experiments were obtained without selecting the state in the energy (mass) spectrum.

The work on ^{13}Be measured E_{rel} and the momentum distribution, simultaneously. The high statistics of the experiment in Ref. [51] enabled to subtract the effect of the $2n + ^{12}\text{Be}$ channel, as described later. The γ -ray coincidence also allowed to distinguish the decay into the daughter fragment ^{12}Be in the excited states. Such a kinematically complete measurement and analysis was realized in this experiment for the first time.

2.5.2.3 Momentum Distribution of the Bound and Unbound State Following the Neutron Removal

The inclusive momentum distribution of the fragment following the neutron removal reaction has been used as a spectroscopic tool to probe the extension of the radial wave function, in particular for halo nuclei since the early work on ^9Li fragment from ^{11}Li [2, 3].

At MSU, the method of combining γ -ray detection following the neutron removal has been successfully developed to identify the final state of the core fragment as in Ref. [59] and references in Ref. [147]. For $1n$ removal, the momentum distribution for a specific core state was used to determine the orbital angular momentum (ℓ) of the removed neutron, leading to the spin-parity assignment of the relevant state. In addition, the partial cross sections to individual final states provide the spectroscopic factors by applying reaction theory such as the Eikonal model. The Eikonal models to analyze such experimental observables are reviewed in detail in Ref. [181].

At RIKEN, the one-neutron removal reactions of ^{18}C and ^{19}C on a proton target were studied [182] to probe the single particle states of these nuclei and their daughter nuclei. Figure 2.23 shows the momentum distribution of ^{17}C following the $1n$ removal of ^{18}C at 81 MeV/nucleon on a proton target with identifying the final state of outgoing ^{17}C by detecting de-excitation γ rays [182]. In this work, the experimental momentum distributions were compared with the theoretical ones calculated by the Continuum-Discretized Coupled-Channels (CDCC) method [183], instead of the Eikonal method. The Eikonal calculation always treat the $1n$ removal on the proton target as elastic breakup, and thus it is difficult to distinguish an excitation to a state of the projectile, and the breakup associated with the large momentum transfer to the neutron. The CDCC calculations can treat such processes on equal footing.

In this measurement, the momentum distribution for populating the first excited state of ^{17}C tagged by the 0.21-MeV γ rays (Fig. 2.23a) is well described by the calculation of the neutron removal from the $\nu 2s_{1/2}$ orbital, while the other one (Fig. 2.23b) for the second excited state is well described by the calculation for the neutron removal from the $\nu 1d_{5/2}$ orbital. These results led to the confirmation of the spin-parity assignments of $J^\pi = 1/2^+$ and $J^\pi = 5/2^+$ for the first and second excited states of ^{17}C , as proposed in Ref. [184].

When the final state of the core is an unbound resonance as in ^{13}Be from ^{14}Be , one cannot determine the energy of the state by measuring the γ ray but the decaying

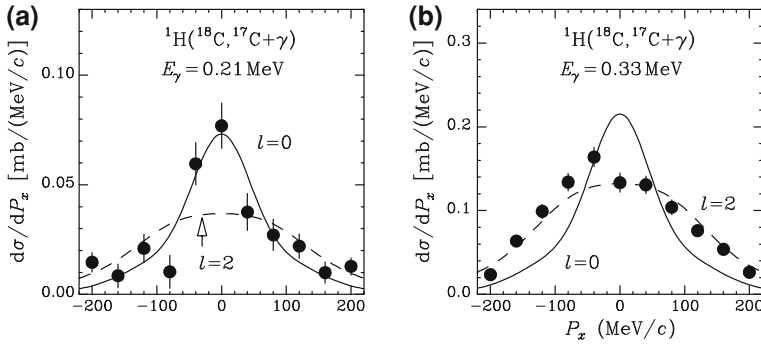


Fig. 2.23 Transverse momentum distributions of ^{17}C in coincidence with de-excitation γ rays following the $1n$ removal from ^{18}C with a proton target at 81 MeV/nucleon [182]. The solid and dashed curves correspond to the CDCC calculations for the assumption of removal of s -wave and d -wave neutron, respectively. The figures are from Ref. [182]

particles. Hence, the invariant-mass spectroscopy is suitable for such a case instead of in-beam γ -ray spectroscopy. For the measurement of the unbound nucleus ^{13}Be in Ref. [51], invariant mass spectroscopy was combined with the measurement of the momentum distribution measurement.

2.5.2.4 Extraction of ^{13}Be states: Selection of $1n + ^{12}\text{Be}$ Events

In the $1n$ removal process (Fig. 2.18b), one neutron is emitted in the forward direction after the decay of ^{13}Be , while the neutron removed first is deflected in a large angle. As such, the first neutron is out of range of the neutron detectors. Therefore, the $M_n = 1$ events, where M_n represents the neutron multiplicity, were selected for this process.

However, we should note that the $M_n = 1$ events also contain contributions from the inelastic process (Fig. 2.18a), since the efficiency of the neutron detection is not 100% but finite (22%). In the inelastic process, two neutrons are emitted in the forward direction, but could be recorded as an $M_n = 1$ event when only one neutron is detected due to this finite efficiency of the neutron detectors. Here, the amount of mixture of two-neutron events was extracted by analyzing the $M_n = 2$ events since we have such events as in Fig. 2.22.

Figure 2.24 (left) shows the total $1n + ^{12}\text{Be}$ spectrum (solid curve), as well as the estimation of the two-neutron events mixed in the $M_n = 1$ events (dashed curve). The latter was obtained by reconstructing the $n - ^{12}\text{Be}$ energy for the $2n + ^{12}\text{Be}$ events and by normalizing the spectrum properly by using the efficiency values. It was found that the lowest peak corresponds to the decay of the 2_1^+ state of ^{14}Be . The contaminant from the inelastic process in the $M_n = 1$ events, which is mainly from the excitation to the 2_1^+ state of ^{14}Be , is thus subtracted in the analysis.

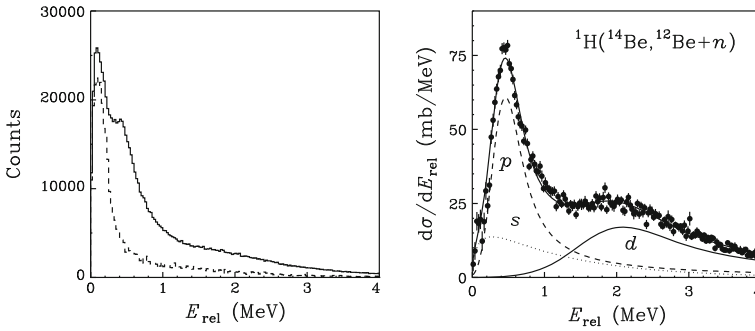


Fig. 2.24 (Left) Relative energy spectrum for the $M_n = 1$ events. The *dashed histogram* shows the contribution from the inelastic scattering of ^{14}Be , estimated from the $M_n = 2$ events. The lowest peak thus corresponds primarily to the decay from the 2_1^+ state of ^{14}Be . This figure is adopted from Ref. [51]. (Right) Relative energy spectrum for ^{13}Be after subtracting the contribution from $2n + ^{12}\text{Be}$ events which are dominated by the excitation of 2_1^+ . The peak at 0.5 MeV and the shoulder around 2 MeV are observed

It should be noted that earlier work on ^{13}Be using the inclusive breakup reaction may be affected by the contribution from the 2_1^+ state of ^{14}Be . In this sense, it is important to perform a kinematically complete measurement. Note also that the effect of inelastic excitation to resonances (diffractive dissociation) is expected to be larger for lower incident energies. The eikonal calculations by Hencken et al. [185] predicted that the contributions from diffractive dissociation and stripping (knockout) reaction are comparable below around 80 MeV/nucleon, while above 200 MeV/nucleon the stripping (knockout) reaction is dominant over the diffractive dissociation. This may be suggestive when one uses inclusive nuclear breakup reactions.

2.5.2.5 Relative Energy Spectra and Momentum Distributions

Figure 2.24 (right) shows the relative energy spectrum of $^{12}\text{Be} + n$ after subtracting the inelastic component shown in Fig. 2.24 (left). Two peaks at around 0.5 and 2 MeV are observed. The γ -ray coincident events were also analyzed to verify whether the final state of ^{12}Be in the decay is the ground state. Figure 2.25 shows the E_{rel} spectra obtained in coincidence with the 2.1-MeV (filled circles) and 2.7-MeV (open triangles) γ rays, corresponding to the decays to $^{12}\text{Be}(2_1^+) + n$ and $^{12}\text{Be}(1_1^-) + n$ (see also Fig. 2.19). A peak at $E_{\text{rel}} \sim 0$ for the 2.1-MeV γ coincidence events is likely to correspond to the resonance at around 2 MeV in Fig. 2.24 (right). The cross sections up to $E_{\text{rel}} = 4$ MeV were 16(2) mb and 9(1) mb for the 2.1-MeV and 2.7-MeV γ -ray coincidence events, respectively, which are small compared with 103(7) mb for the inclusive spectrum in Fig. 2.24 (right). Hence, in the discussion hereafter, we neglect the contribution of the γ -ray related events.

The contribution of the decay to the isomeric state $^{12}\text{Be}(0_2^+)$ was not taken into consideration in the analysis, which could not be extracted experimentally due to its

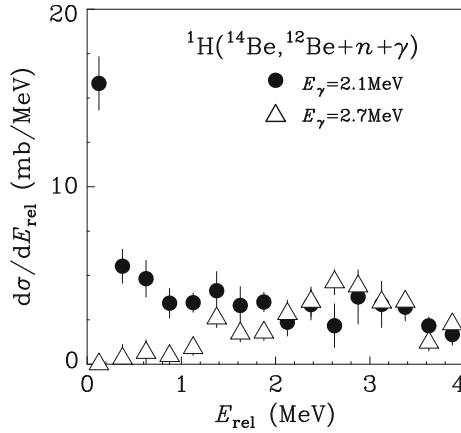


Fig. 2.25 Relative energy spectra of ^{13}Be in coincidence with 2.1-MeV and 2.7-MeV γ ray decay in ^{12}Be in the breakup of ^{14}Be on the proton target [51]. For the coincidence with the 2.1-MeV γ in ^{12}Be , the peak at $E_{\text{rel}} \sim 0$ MeV corresponds to the excitation energy of the d -wave peak of ^{13}Be in Fig. 2.24 (right). See also Fig. 2.19

long mean life time, 331(12) ns, of this state [184]. However, the 0.5-MeV peak is likely to be relevant to the decay to the ground state but not to the isomeric state, from the consideration of penetration factor [51].

The transverse momentum distributions of ^{13}Be were extracted as shown in Fig. 2.26, depending on the energy region. The difference of widths corresponds to the different orbital angular momentum of the removed neutron. A simultaneous fitting of the relative energy spectrum and the momentum distributions determines the dominant angular momentum of $\ell = 1$ for the 0.5-MeV peak. The extracted resonance energy and width were 0.51(1) MeV and 0.45(3) MeV, respectively. This width is consistent with the single-particle width of 0.55 MeV for the $\ell = 1$ decay. These results led to the spin-parity assignment of $1/2^-$, which is different from the assignment of the earlier experiments. However, we notice that the spectrum of GSI experiment [171] is rather similar to the current result (although their primary assignment was s -wave). Our result is also consistent with the recent theory [172], which predicted the existence of this low-lying p -wave state.

The 2 MeV peak was assigned as the d -wave component in agreement with most of the previous work, although we note that the width is much wider than the single-particle estimate. This could imply that this peak is composed of a few states rather than a single resonance.

The s -wave component is also found to exist in the spectrum, for the analysis of which we assumed this to be a virtual state [187]. The scattering length was thus extracted to be $a_s = -3.4(6)$ fm, which is very small and thus implies a weak correlation between ^{12}Be and the s -wave neutron. This is consistent with the fact that in the three-body decay of the 2_1^+ state of ^{14}Be , no signal of the resonance state (nor strong virtual state) of ^{13}Be below $E_{\text{rel}} = 0.28$ MeV was observed. In this

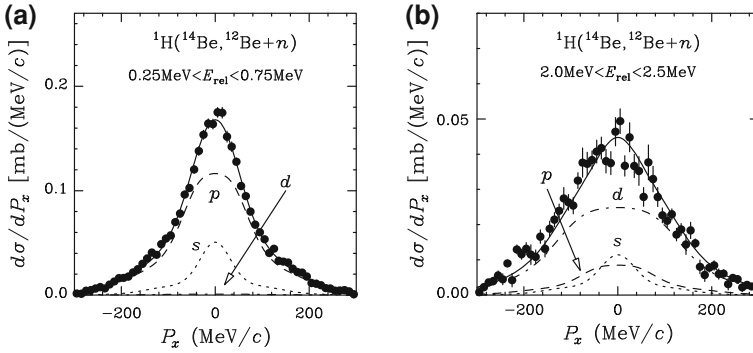


Fig. 2.26 Transverse momentum distributions of ^{13}Be for (a) $0.25\text{ MeV} < E_{\text{rel}} < 0.75\text{ MeV}$, and (b) $2.0\text{ MeV} < E_{\text{rel}} < 2.5\text{ MeV}$, in the one-neutron knockout reaction of ^{14}Be . The curves show the result of the simultaneous fitting, assuming that the energy spectrum is composed of s -, p -, and d -wave components. The figures are from Ref. [51]

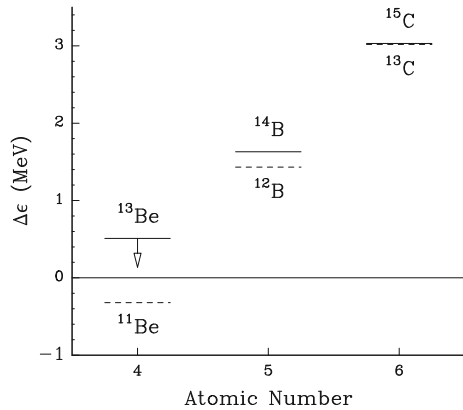
sense, it is not appropriate to refer the s -wave level as a resonance or virtual state. Instead, it is likely that the weak s -wave continuum is distributed at low-energy range ($E_{\text{rel}} \sim 0 - 2\text{ MeV}$), and its level energy is not definite. The level and decay scheme for the structures of ^{13}Be and ^{14}Be , including the three-body decay and the γ -decay branches, are summarized in Fig. 2.19.

2.5.2.6 Disappearance of $N = 8$ Shell Gap

The notable finding in the result of Ref. [51] was the existence of a p -wave resonance as the ground state of ^{13}Be . Taking consideration of the low-lying s -wave strengths, it may be more appropriate to conclude that the p -wave ground state is almost degenerate in energy with the s -wave contribution. We now show the systematics of energy difference ($\Delta\epsilon$) between the $1/2^+$ and $1/2^-$ states for the $N = 7$ and $N = 9$ nuclei as shown in Fig. 2.27. Since the position of the $1/2^+$ state of the unbound nucleus ^{13}Be cannot be defined, only the upper limit is shown for ^{13}Be . The slope of $\Delta\epsilon$ with respect to the atomic number for the $N = 9$ nuclei is nearly identical to the one for $N = 7$. The latter was originally plotted by I. Talmi and I. Una for the difference of the single particle $p_{1/2}$ and $s_{1/2}$ states [28], and was summarized in Ref. [187] with other $N = 9$ nuclei. This results suggest the melting of the $N = 8$ shell gap in ^{13}Be .

Such a shell evolution could be interpreted by modern shell models. One explanation was given by inclusion of the spin-flip p - n monopole interaction [160, 191], which could explain the structure of neutron rich p -shell nuclei. In the stable nuclei ^{13}C and ^{15}C , the $\pi p_{3/2}$ orbital is fully occupied, resulting in the $N = 8$ shell gap due to the strong interaction with the $\nu p_{1/2}$ orbital. Since the interaction becomes weak at ^{11}Be and ^{13}Be by decreasing the occupation number of the $\pi p_{3/2}$, the $\nu p_{1/2}$ goes up and the gap between the neutron sd -shells weakens. The shell model calculation

Fig. 2.27 Energy difference of $1/2^+$ and $1/2^-$ states for $N = 7$ (dashed) and 9 (solid) nuclei as shown in Fig. 8 of Ref. [184], as a function of atomic number. A similar plot for the single particle states was presented for $N = 7$ in Ref. [28]. The upper-limit value is shown for ^{13}Be [51]. The energy values except for ^{13}Be are taken from Refs. [188–190]



including this effect by introducing the enhanced spin-flip p - n monopole interaction [160] provides the intruder $1/2^-$ ground state. This agreement may indicate the importance of this effect in the neutron-rich $N = 8$ region. As was mentioned, this shell model calculation reproduced the overall level schemes of the low-lying states of $^{12-14}\text{Be}$.

However, we also should note that the shell model may not explain the effect of strong deformation expected in the neutron-rich Be isotopes. In fact, strong deformation in ^{12}Be was observed [155]. For neutron-rich weakly-bound nuclei and unbound nuclei, we also should note that the use of harmonic oscillator wave functions may not be appropriate. Recently, the properties of the neighboring nuclei $^{11,12}\text{Be}$ were investigated in terms of single-particle motion in deformed potential [192], where the two Nilsson levels $[101]_{\frac{1}{2}}^-$ and $[220]_{\frac{1}{2}}^+$ become almost degenerate at large prolate deformation. This can also be true for the 9th neutron of ^{13}Be . As such, the $1/2^-$ state may become the ground state. Note that, in this case, the single particle orbital at the spherical limit has still a significant gap between $\nu 1p_{1/2}$ and $\nu 2s_{1/2}$. It is interesting to note that prolate deformation can be strongly induced in the neutron-rich region even near the magic number due to the nuclear Jahn-Teller effect (or a spontaneous breaking of symmetry). Low- ℓ orbitals as a function of the potential depth has smoother function than the higher- ℓ orbitals, which tend to cause the degeneracy in the unbound region between the different ℓ orbitals, resulting in the Jahn-Teller effect [193]. Hence, the deformation can play major roles in the structure of neutron-rich weakly-bound and unbound nuclei.

It is interesting to investigate how these theoretical approach, such as shell models and deformed potential models, can be understood in a universal way. In this respect, spectroscopic studies of neutron-rich weakly-bound and unbound nuclei are of great importance.

2.6 Concluding Remarks

This lecture note has reviewed breakup reactions of halo nuclei, and their related topics, primarily from the experimental point of view. Halo nuclei are interesting many-body quantum states, where one or two neutrons extend outside of the range of nuclear mean field potential. A neutron halo nucleus breaks up easily with a high cross section in response to Coulomb/nuclear interactions with a target nucleus. Hence, the breakup can be a probe of microscopic structure of halo nuclei.

In Sect. 2.2, we described the method of the Coulomb breakup of halo nuclei at intermediate/high energies. We emphasized that the Coulomb breakup is a suitable tool when we apply this method to radioactive nuclei. This is partly because Coulomb breakup at intermediate/high energies gains yield due to a large photon number, availability of a thick target, and to kinematic focusing. We also note that the relatively good energy resolution can be obtained in the invariant mass method when it is applied to breakup experiments, which is advantageous compared to missing-mass spectroscopy.

In the following sections (Sect. 2.3 and Sect. 2.4), recent Coulomb breakup experiments of several halo nuclei, mainly using the data from our group, were reviewed. We clarified that the main mechanism of the soft $E1$ excitation is attributed to direct breakup, and as such the final state is not a resonance but rather structure-less continuum. The phenomena and spectroscopic significance appear in a different manner between $1n$ - and $2n$ halo nuclei. For $1n$ halo nuclei, the final state represents simply a relative motion between the neutron and the core. As such, the spectrum can be described by the matrix element shown in Eq. (2.14). Since the Coulomb breakup is highly sensitive to the tail of the radial wave function. The spectroscopic amplitude and ℓ of the halo configuration, as well as the S_n of the nucleus, can be extracted by a kinematically complete measurement (exclusive measurement). Examples shown were the cases of ^{11}Be and $^{15,19}\text{C}$. The Coulomb breakup of ^{11}Be provided the basis of the experimental and analysis methods of intermediate-energy Coulomb breakup. The latter experiments were the cases to demonstrate how the Coulomb breakup of $1n$ -weakly bound nuclei can be a useful spectroscopic tool. For ^{19}C , we could also extract the S_n value by a novel method using the angular distribution in the Coulomb breakup.

We have also demonstrated the usefulness of inclusive Coulomb breakup, by showing the case of ^{31}Ne , whose experimental work was long scarce due to the small yield of this nucleus. Inclusive measurement is more feasible for very exotic nuclei with the beam yield of the order of particle per second. Here, evidence is shown for the first time for a heavy halo nucleus, ^{31}Ne , much beyond the known halo nuclei.

It should be noted, however, that the exclusive measurement would provide more structure information, as illustrated in the Coulomb breakup experiments of ^{11}Be and $^{15,19}\text{C}$. In 2012 at RIBF, we plan a commissioning experiment of the SAMURAI facility, which is equipped with the superconducting magnet with the 80 cm gap and the maximum magnetic field of about 3 T, and with the large-area neutron detectors,

NEBULA (NEutron-detection system for Breakup of Unstable Nuclei with Large Acceptance). We plan to perform an exclusive Coulomb breakup experiment of ^{31}Ne in the near future. Such an experiment would clarify the microscopic structure (ℓ , shell configurations, and S_n) of this nucleus.

For Coulomb breakup of $2n$ halo nuclei, the initial and final states are much more complicated. However, we have demonstrated that spatial dineutron correlation may play significant roles in the enhancement of the strong $E1$ strength observed in ^{11}Li . We have also shown the importance of unambiguous $2n$ detection, which has been accomplished by the novel method, using a kinematical condition of velocities associated with the two neutrons. With such high-statistical data combined with the high sensitivity down to $E_{\text{rel}} = 0$ MeV, reliable comparisons with theories have become possible for the first time. We showed some of such comparisons. We should note, however, that the theoretical interpretation is still not fully settled, partly due to effects of the core excitation. Inclusion of such effects was attempted theoretically by Myo et al. [31, 32].

Recently, evidence for the two-neutron halo structure in ^{22}C has been provided by the reaction cross section measurement [14]. We have also preliminary results on the Coulomb breakup of this nucleus. Study of such a heavy $2n$ halo nucleus having a different shell configuration is very important to clarify the nature of dineutron correlation. Understanding of dineutron correlations in halo nuclei is essential to investigate such correlations in neutron-skin nuclei in heavier mass regions. In addition, studies of halo nuclei with $4n$ or multiple halo neutrons become more important for the future. Such studies would shed light on the physics of neutron stars, as well.

In the final part of this lecture note, we showed examples of ^{14}Be breakup on the light targets, which undergo the diffractive dissociation to the excitation to the 1st excited state of ^{14}Be , and the $1n$ removal process to produce the ^{13}Be unbound states. We have shown that such a kinematically complete measurement is powerful to determine the spin-parities and the energies of the levels of the $-1n$ unbound system. As such, this method provided the basis of studying the $1n$ removal channel.

Through this lecture note, we showed typical experimental tools for halo nuclei and neighboring states including unbound nuclei. With the advent of new-generation facilities, where RIKEN has already launched such a facility, RIBF, and FAIR, FRIB, KoRIA, and SPIRAL2 will be commissioned in a few to several years, these experimental tools will play more significant roles when we explore closer to the bound limit in heavier mass regions.

Acknowledgments This work has been supported in part by a Grant-in-Aid for Scientific Research (B) (22340053) from the Ministry of Education, Science and Culture (MEXT). We thank the support by the GCOE program “Nanoscience and Quantum Physics”. We are grateful to J.A. Tostevin and H. Esbensen for fruitful theoretical discussions.

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Clusters in Nuclei, Vol.2

Beck, C. (Ed.)

2012, XV, 353 p. 167 illus., Softcover

ISBN: 978-3-642-24706-4