Particle Physics with Cold Neutrons

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Abstract. Cold and ultracold neutrons are used in a larger number of experiments to explore current problems from the fields of particle physics and cosmology. An overview is given on the physics questions addressed with these neutron experiments.

INTRODUCTION

Today most of particle physics is being done at high energies at the GeV up to the TeV range. But interesting questions of particle physics and cosmology can also be pursued at the other extremes of the energy scale, using cold neutron beams with energies from the milli- down to the nano-eV range.

Useful work can be done at these low energies because of the incredibly high sensitivities reached in the experiments. To give some examples: With cold neutrons, interaction energies down to $10^{-23}$ eV can be resolved. This corresponds to Bohr frequencies of a few cycles per year, which, for instance, is the sensitivity of the present experiment on the electric dipole moment of the neutron, while a search for neutron-antineutron oscillations was sensitive to oscillation periods of several years. Changes in neutron momentum can be measured to $10^{-11}$ precision. This corresponds to a 1 Ångstrom lateral deviation on 10 m length of neutron beam, which determines the detection limit of an experiment on the neutron charge. Finally, changes in neutron polarization down to $10^{-8}$ are measurable in experiments on parity P and time reversal T violating properties of matter.

The neutrons used in these experiments are produced in reactor neutron sources such as ILL at Grenoble or the new FRM2 at Munich, or in spallation neutron sources like ISIS near Oxford, LANSCE at Los Alamos, or the future SNS at Oak Ridge or the KEK/JAERI joint project in Japan. Thermal neutrons are moderated to room temperature in heavy water, while cold neutrons are moderated to about 40 K in liquid deuterium. The neutrons from these moderators then are channeled through long neutron guides (typical cross section 100 cm²) to experiments up to 100 m away. Neutron flux densities are $10^9$ to $10^{10}$ cm⁻²s⁻¹. Ultracold neutrons (UCN) have an effective temperature of 1 mK, kinetic energies of order 100 neV, and velocities below 10 m s⁻¹. Their energy is low enough that they can be stored in vessels for times approaching the lifetime of the free neutron.

Today particle physics and astrophysics are closely linked to each other. The early history of the universe is a sequence of phase transitions right after the Planck time:

$t = 10^{-43}$ s: Planck time

Inflation

Grand Unification

$t = 10^{-12}$ s: electroweak transition

chiral ~ probably coinciding with:

quark-gluon nucleon freeze-out

$t = 10^2$ s: nuclear freeze-out

$t = 10^{14}$ s: atomic freeze-out

Galactic freeze-out

$t = 10^{18}$ s: Now

This paper is organized such that, while going down this list, we shall discuss the contributions of neutron particle physics to the various stages of the evolving universe. Of course, only a limited number of topics can be touched here, while other intriguing topics related to neutron-particle physics must be left
out. For a general survey see the conference proceedings [1]. Only references that are not listed in the Particle Data Group’s compilation of neutron properties [2] shall be quoted here.

THE GRAND UNIFICATION ERA

We start with the Grand Unification era, where several basic questions can be addressed by slow neutron physics.

Are Lepton and Baryon Numbers Conserved?

There exists no law of Baryon or Lepton number conservation. No symmetry is known that would require such a conservation law. To the contrary, in all Grand Unification schemes, leptons and quarks are members of a common multiplet that can transform into each other, so their respective numbers cannot be conserved individually. B- and L-number violation signals the presence of a higher symmetry, and not the violation of a symmetry.

Experiments both on lepton-number violating neutrino oscillations and on baryon-number violating neutron oscillation were done at nuclear reactors. Neutrino oscillation searches were numerous and will not be listed here. The experimental limit on the neutron-antineutron-oscillation time is $0.86 \times 10^8$ s at 90% c.l., which means that the corresponding transition matrix element is below some $10^{-23}$ eV. This limit probes the $10^{5}$-GeV range (depending on the model used), an energy scale not accessible to the present day’s accelerators. The experiment took place in the early nineties at ILL.

Are There Extra Dimensions of Space-Time?

A more recent development is the experimental study of pico-eV neutron quantum states bound in the gravitational potential of the earth [3]. The experiment places upper limits on deviations from Newton’s law on the $\mu$m length scale. Such deviations could arise due to the compactification of extra dimensions in theories of the Klein-Kaluza type [4]. Such experiments are important in the context of exotic dark matter and dark energy, which make up for 96% of the total mass-energy content of the universe.

Why is Charge Quantized?

Charge conservation is a direct consequence of the gauge principle on which the Standard Model is based and would be painful to lose. Charge quantization, on the other hand, is not required by the three-generation Standard Model [5]. On the other hand, Grand-Unified Theories do require charge quantization. Only a massive Dirac neutrino could generate an extra charge proportional to $B - L$. Hydrogen with $B = L = 1$ could not have such an excess charge, but the neutron with $B = 1, L = 0$ could.

The experimental limit on the neutron charge is extremely severe: $q < 2 \times 10^{-21}$ e (90% c.l.). Very likely, the extraordinary smallness of this number is not purely by chance, but points beyond the Standard Model, favoring grand unified models with Majorana neutrinos only.

Why Has So Much Matter Survived the Big Bang?

The hot Big Bang model predicts that, right after the start of the universe, baryons and antibaryons should almost quantitatively have annihilated each other. Baryons and antibaryons should occur in equal numbers, and both should be only a $10^{-18}$ fraction of photon number. However, in reality antibaryon density is negligible, while baryon density is as large as $10^{-9}$ of photon density. This ‘baryon asymmetry’ can have been generated in the early universe only far-off thermal equilibrium, and only if both baryon number $B$- and CP-symmetry are violated.

During the many phase transitions in the early universe (including inflation) there are many situations far-off equilibrium favorable for the generation of baryon asymmetry. B-violation also poses no principal problem, as stated above. CP-violation is more difficult. From the Kaon system CP symmetry is known to be violated. This violation is being taken care of within the Standard Model by applying (in flavor space) a small complex rotation to the CKM quark-mixing matrix. However, this CP-violation is far too small to explain the observed baryon asymmetry of the universe.

If, in Grand Unified Theories, CP-violation is made strong enough to explain baryon asymmetry, then this should lead to an electric dipole moment (EDM) of the neutron of order $d_n \sim 10^{-27}$ e cm. If, on the other hand, CP-violation comes in only via the CKM matrix of the Standard Model, then this leads, as a second
order effect, to an unobservably small neutron EDM $d_n \sim 10^{-21}$ cm. A neutron EDM is being searched for for decades; progress in sensitivity is one order of magnitude every seven years. The EDM limit from the ongoing experiment at the Institut Laue-Langevin dates from 1999 and is $6.3 \times 10^{-26}$ cm at 90% c.l. At present this error is being diminished at a rate of $1.8 \times 10^{-25}$ cm per day, and the 1σ statistical error reached is $1.5 \times 10^{-26}$ cm, though a new neutron EDM limit has not been released yet.

For further information on EDM projects see the papers in this conference by W. M. Snow and S. K. Lamoreaux [6,7].

Is the Left-Handedness of Nature an ‘Emergent Property’?

The electroweak interaction of the Standard Model violates left-right symmetry to 100%. This parity or P-violation is built into the Standard Model ‘by hand,’ and the question is whether the universe really was completely asymmetric right from the beginning.

Indeed, most modern theories beyond the Standard Model start out with a left-right symmetric universe. In these models, the left-handedness of the universe is an ‘emergent property,’ i.e., arises as an order parameter generated by spontaneous symmetry breaking during one of the phase transitions of the early vacuum. In the process the right-handed W-boson develops a mass that is much larger than the well-known mass of the left-handed W-boson, which the latter mediates the weak interaction of the Standard Model. This mass splitting diminishes the range of the right-handed part of the weak interaction and generates a left-right asymmetry that, however, should be below 100%.

Such right-handed amplitudes change the characteristics of neutron decay angular distributions. Therefore, from measurements of neutron decay angular correlations one is able to derive a good limit for the mass of such a right-handed W-boson, which at present is at 280 GeV (90% c.l.). A very stringent upper limit is also derived for the relative phase between the left- and the right-handed amplitudes.

THE ELECTROWEAK ERA

We now enter the realm of the electroweak transition, which is very accurately described by the Standard Model. Also in this realm a number of very interesting questions can be pursued with the help of slow neutron experiments.

How Strong is the Weak Interaction?

Today all semileptonic weak interaction processes involving leptons and nucleons at low energies must be calculated from neutron decay parameters, because their cross-sections are too small to be measured directly with great precision. Table 1 gives examples of processes having the same Feynman diagram as neutron decay (W-production is added for completeness).

<table>
<thead>
<tr>
<th>Process</th>
<th>Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primordial element formation</td>
<td>$n + e^- \rightarrow p + \nu_e$</td>
</tr>
<tr>
<td>Solar cycle</td>
<td>$p + p \rightarrow ^4H + e^- + \nu_e$</td>
</tr>
<tr>
<td>Neutron star formation</td>
<td>$n + e^- \rightarrow p + \nu_e$</td>
</tr>
<tr>
<td>Neutino detectors</td>
<td>$\nu_e + p \rightarrow n + e^-$</td>
</tr>
<tr>
<td>Neutino forward scattering</td>
<td>$\nu_e + n \rightarrow p + e^-$</td>
</tr>
<tr>
<td>W and Z - production</td>
<td>$u + d \rightarrow W_n \rightarrow e^- + \nu_e$ etc.</td>
</tr>
</tbody>
</table>

Free neutrons decay weakly with a lifetime of $(885.7 \pm 0.7)$ s. Observables in neutron decay are, besides the lifetime $\tau$, various correlation coefficients involving neutron spin and momenta of the emitted particles, such as the beta asymmetry $\lambda$, the neutrino asymmetry $B$, the electron-neutrino correlation coefficient $a$, and the time reversal T-violating triple correlation coefficient $D$. In recent experiments, also correlations involving the spins of the emitted particles are being looked for.

In the Standard Model three parameters are needed to describe neutron decay, which enter via the neutron-to-proton weak interaction matrix element

$$\langle p | j_{\mu} | n \rangle = V_{ud} \left[ \gamma_{\mu} (1 + \lambda \gamma_5) + i(\mu_p - \mu_n)/2 m_p \sigma_{\mu \nu} g_\nu \right] n.$$

Parameters are the element $V_{ud}$ of the CKM quark mixing matrix, and the amplitude $|g_A/g_V|$ and (T-violating) phase $\varphi$ of the ratio $\lambda = |g_A/g_V| e^{i\varphi}$ of axial-vector to vector coupling constants. In principle, $\lambda$ could be calculated from QCD, though with very limited precision. The experimental values are derived from free neutron decay parameters to $|V_{ud}| = 0.9717(13), |g_A/g_V| = 1.2739(19)$, and $\varphi = 180.05^\circ \pm 0.08^\circ$. (The weak magnetism amplitude on the
right-hand side is given by the well-known difference of the proton and neutron magnetic moments $\mu_p - \mu_n$.) If CVC, i.e., the Conservation of the weak Vector Current, is assumed to hold then also $V_{ud}$ as obtained from nuclear superallowed 0$^+$– 0$^+$ transitions can be used as input.

Hence, the number of observables $\tau, a, A, B, D$, etc., accessible in free neutron decay is larger than the number of Standard Model parameters. The problem is strongly over-determined, and precise checks on the physics beyond the Standard Model are possible. The search for a right-handed component of the electroweak interaction, as discussed in the preceding section, is one example.

### How Strong is the Electromagnetic Interaction?

At first sight one does not expect a precision measurement of the strength of the electromagnetic interaction to take place at a neutron source. Still, a very precise value of the fine structure constant $\alpha = e^2/\hbar c$ comes from a neutron experiment. From simultaneous measurements of the neutron de Broglie wavelength and the neutron velocity, one obtains the quantity $\hbar/m$, where $h$ is Planck’s constant and $m$ is the neutron mass. If one combines this number with the Rydberg constant multiplied with the mass ratios $m_e/m_p$ and $m_p/m_n$, each known with high accuracy, one obtains $\alpha$ largely independent of assumptions on quantum electrodynamics or on solid-state physics as

$$\alpha^{-1} = 137.036 \pm 0.0113(52).$$

### Is Quark Mixing Unitary?

A topic of current interest is the question of the unitarity of the CKM matrix. As is well known, the eigenstates $d', s', b'$ of the quarks under the electroweak interaction are not identical to their mass eigenstates $d, s, b$. In the Standard Model this state mixing is described by a small rotation in flavor space of the weak quark states, described by the unitary CKM-matrix $V_{\text{eff}}$.

So far, only the first line of this matrix can be tested for unitarity with some precision:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 .$$

$|V_{ud}|$ is determined by measuring both the lifetime $\tau$ and the beta decay asymmetry $A$ of the neutron and using

$$\tau^{-1} = (G_F^2 m_e^2 / (2\pi^2)) |V_{ud}|^2 (1 + 3|\lambda|^2) / (1 + \Delta_R),$$

$$A = -2 (|\lambda|^2 + \text{Re}(\lambda)) / (1 + 3|\lambda|^2) .$$

$G_F$ is known to high precision from muon decay, and the phase space factor $f = 1.71335(15)$ and the correction $\Delta_R = 0.0240(8)$ are calculated quantities. Using the values $|V_{us}| = 0.2196(23)$, and $|V_{ub}| = 0.0036(9)$, we arrive at

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 - \Delta = 0.9442 + 0.0482 + 0.0000 = 0.9924(28),$$

a 2.7$\sigma$ deviation from unitarity:

$$\Delta = -0.0076 \pm 0.0028 .$$

In the evaluation we do not use those earlier experiments that required large systematic corrections. Unitarity of the CKM matrix is re-established by either shifting $|\lambda|$ by 3$\sigma$, or the lifetime $\tau$ by 10$\sigma$, the matrix element $V_{us}$ by 8$\sigma$, or the theoretical radiative corrections $\Delta_R$ by 10$\sigma$. So the next move should be to improve the accuracy of the measured beta asymmetry $A$ (or, alternatively, of the electron-neutrino correlation coefficient $a$). At present in Heidelberg we are constructing a new neutron decay instrument of the PERKEO type, in which the four leading errors in $\beta$-asymmetry measurements (neutron polarization, background radiation, detector edge, and magnetic mirror effects) will be simultaneously suppressed to a high degree.

Similar deviations from CKM unitarity are observed in superallowed $\beta$-decay from nuclei, as described in the paper by J. Hardy [8]. For recent compilations see also [9].

### THE NUCLEAR FREEZE-OUT

Nuclear freeze-out takes place during the ‘first three minutes.’ Also here neutron decay data play an important role.

The hot Big Bang model is well confirmed by high-precision measurements. The strongest support for the Big Bang model still comes from the measured abundances of the light primordial elements, in particular of $^4$He, $^2$H, $^6$Li relative to hydrogen H.
calculated abundances depend on some very well-known nuclear data, and on three further input parameters: the number of particle families \( N \), the density of baryonic matter \( \rho \), and the neutron lifetime \( \tau \). Hence, from the observed abundances one can derive both \( N \) and \( \rho \), once \( \tau \) is known with sufficient accuracy. The evaluation gives \( N = 2.5 \pm 0.6 \) and \( \rho / \rho_c = (3.3 \pm 0.7)\% \), with the critical density \( \rho_c \) of our flat universe.

The lifetime \( \tau \) enters these calculations twice. First \( \tau \) is needed to calculate the neutrino cross sections that determine at what time and temperature neutrons and protons (up to then kept in thermal Boltzmann equilibrium by the reactions displayed in Table 1) decouple such that their relative number freezes to a fixed value, namely to 1/7 at about 1 s after the Big Bang. \( \tau \) enters a second time because it takes several minutes until the light nuclei are formed from the protons and the freely decaying neutrons. The dependence on the neutron lifetime turns out to be rather strong. For instance for the \(^4\)He yield the derived values for \( N \) and \( \rho \) vary strongly with the neutron lifetime \( \Delta N = 13 \Delta \tau / \tau \) and \( \Delta \rho / \rho = 20 \Delta \tau / \tau \), respectively, so larger shifts in \( \tau \) will have an effect on the internal constancy of primordial abundance studies.

Meanwhile, \( N \) and \( \rho \) have been obtained also from other sources, \( N \) from the \( Z_0 \)-width, and \( \rho \) from microwave background measurements. Therefore, the primordial abundances can nowadays be calculated with no free parameter, once the neutron and nuclear data are known well enough, and these abundances provide one of the pillars of the hot Big Bang model. For a recent discussion of the role of the neutron lifetime for this Big Bang consistency check see [10].

**REFERENCES**


**SUMMARY AND ACKNOWLEDGMENTS**

In past years, only a small number of researchers worked in the field of particle physics with low-energy neutrons, in any case small as compared to the number of researchers in any one of the high-energy particle physics collaborations. Today this is changing, and we see powerful young groups entering the field on each side of the Atlantic and the Pacific. Both the United States and Japan will soon have impressive new pulsed-neutron sources delivering the highest peak fluxes in the world, while Europe will have the strongest continuous neutron sources. I hope that the neutron communities will take this complementarity as an incentive to exchange projects and people both ways. Finally, I want to thank the organizers of ND2004 for letting me give this presentation.