1 Introduction

1.1 General remarks

This subvolume contains the second part of the compilation of resonance parameters in nuclear reactions induced by charged particles from protons up to α-particles (called for simplicity PRF - Proton Resonance parameters File). Data on light nuclei ($Z < 20$) are given in the first subvolume.

We have collected also data on proton resonances in heavy nuclei ($A > 60$) which are the positions of gross-structure resonances corresponding to the excitations of the analog state (values $E^*_{\rm analog}$ in Tables). In Table 1 the numbers of resonances in this part of PRF are given. Simultaneously with proton resonances we have collected branching ratios (see Table 2) and reaction amplitudes of unbound compound levels seen as proton and α-particle resonances. These data are included in PRF in separate two-dimensional tables.

Parameters given in the PRF tables are the results of fitting measured cross-sections, γ-ray yield, or other effects, by means of several kinds of resonance formulas discussed in the introduction to the first subvolume of PRF.

For each resonance of a certain isotope all available data were collected and the values of resonance parameters selected out of them are forming a single data-line. Each data-line starts with the energy of the resonance $E_\circ$ in the laboratory frame and ends with the energy of the compound state E^* followed by the reference-codes to show where the data given were taken from. The direct referencing on the original papers at the end of each data-line could be used by the interested reader for his own judgement. Additional references given at the end of the tables and in comments could serve for a better orientation in the material. In all cases the first three columns are reserved to $E_\circ$, spin J and parity of the compound nucleus state (resulting from the interaction with the incoming proton or α-particle), and with isotopic spin T given in the third column. As in many other compilations we give values $2J^\pi$ and $2T$ for all A-odd nuclei ($2J^\pi = 1^+$ instead of $J^\pi = 1/2^+$, etc.). The double spin notation 1^-3^- or 3^+5^+ usually corresponds to $\ell = 1$ or $\ell = 2$ in the case of even-even target (A-odd compound nucleus). Notations "odd" and "even" as well as "not 2" or N (or N^+) on the second place correspond to the J-values (with N – Normal sequence $J = 0^+, 1^-, 2^+, 3^-$, etc. and N^+ – positive-parity part of this sequence $J = 0^+, 2^+$, etc.).

A special column is devoted to the value of the resonance energy in the center-of-mass frame ($E_{\rm cm}$) calculated in most cases by the simplified expressions $E^* = S_{\rm p} + E_{\rm cm}$ and $E^* = Q_\alpha + E_{\rm cm}$ for proton resonances and resonances in reactions induced by α-particles, respectively:

$$E^*_{\rm p} = S_{\rm p} + \frac{m_t}{m_t + m_{\rm p}} E_\circ, \qquad E^*_\alpha = Q_\alpha + \frac{m_t}{m_t + m_\alpha} E_\circ, \tag{1}$$

where masses m_t and $m_{\rm p}$ (or m_α) are masses of target nucleus and incident particle, respectively.

Data-lines for resonances for each isotope and for the given reaction (induced by proton or α-particle) are ordered by increasing $E_\circ$ and form one isotope-table which ends by reference-codes where an additional information can be found and by short comments. Each isotope-table is labelled by the atomic number (Z) and the atomic weight (A) of the compound nucleus.

The whole set of isotope-tables for a given element (Z) is ordered by increasing atomic weights (A) of the compound nucleus and forms the unit of the total file mentioned in the list of contents. Ordered by Z these files for all the elements make up the total file PRF with references presented at the end of the book.

Proton separation energies ($S_{\rm p}$) or α-particle Q-values are the division lines between the energies of bound and unbound excited states (E^*) of the compound nucleus. Separation energies are calculated from nuclear binding energies (taken from the Atomic Mass Evaluation [95Au04]) and are given in the headings of each PRF table besides A and Z of the compound nucleus and the type of reaction (with protons or with α-particle).

Table 1. Contents of the volume I/19A2, compound nuclei with $Z \geq 19$:
^{A}Z – compound nucleus,
$N_{\rm p}$ and N_α – number of data-lines for p and α projectiles, respectively.

^{A}Z	$N_{\rm p}$	N_α	^{A}Z	$N_{\rm p}$	N_α	^{A}Z	$N_{\rm p}$	^{A}Z	$N_{\rm p}$	^{A}Z	$N_{\rm p}$	^{A}Z	$N_{\rm p}$
^{37}K	78		^{56}Fe	92		^{77}Br	8	^{101}Tc	4	^{117}Sb	5	^{145}Pm	4
^{39}K	99		^{55}Co	321		^{79}Br	8	^{97}Rh	2	^{118}Sb	10	^{147}Pm	4
^{41}K	256		^{57}Co	587		^{81}Br	7	^{99}Rh	4	^{119}Sb	7	^{149}Pm	1
^{40}Ca	364	18	^{58}Co	135		^{83}Br	15	^{101}Rh	5	^{120}Sb	10	^{151}Pm	2
^{42}Ca	356	59	^{59}Co	194		^{85}Rb	2	^{102}Rh	1	^{121}Sb	13	^{145}Eu	19
^{41}Sc	182		^{58}Ni		4	^{87}Rb	14	^{103}Rh	3	^{123}Sb	8	^{149}Eu	2
^{42}Sc	112		^{60}Ni	22		^{88}Sr	9	^{105}Rh	4	^{125}Sb	9	^{151}Eu	2
^{43}Sc	315		^{59}Cu	359		^{85}Y	15	^{103}Ag	2	^{124}Te	3	^{159}Tb	2
^{44}Sc	4		^{61}Cu	592		^{87}Y	11	^{105}Ag	19	^{123}I	14	^{167}Tm	1
^{45}Sc	1110		^{63}Cu	369		^{88}Y	8	^{107}Ag	11	^{125}I	18	^{169}Tm	1
^{47}Sc	294		^{65}Cu	88		^{89}Y	30	^{109}Ag	4	^{126}I	1	^{171}Lu	7
^{49}Sc	107		^{62}Zn		2	^{90}Zr	23	^{111}Ag	7	^{127}I	23	^{173}Lu	6
^{44}Ti		66	^{64}Zn	2		^{91}Nb	30	^{108}Cd	11	^{129}I	11	^{175}Lu	13
^{46}Ti	166		^{66}Zn	22		^{92}Nb	5	^{110}Cd	8	^{131}I	27	^{177}Lu	10
^{47}V	282		^{65}Ga	220		^{93}Nb	10	^{107}In	3	^{137}Cs	14	^{179}Ta	2
^{48}V	105		^{67}Ga	156		^{95}Nb	18	^{109}In	3	^{131}La	5	^{205}Tl	10
^{49}V	1213		^{69}Ga	23		^{97}Nb	4	^{111}In	33	^{133}La	5	^{204}Pb	1
^{50}V	98		^{71}Ga	15		^{94}Mo	23	^{112}In	2	^{135}La	8	^{206}Pb	1
^{51}V	322		^{71}As	52		^{93}Tc	240	^{113}In	30	^{137}La	8	^{205}Bi	1
^{52}Cr	32		^{73}As	36		^{95}Tc	9	^{114}In	2	^{139}La	16	^{207}Bi	4
^{51}Mn	406		^{75}As	23		^{96}Tc	12	^{115}In	25	^{140}Ce	14	^{208}Bi	44
^{53}Mn	973		^{77}As	10		^{97}Tc	12	^{117}In	4	^{141}Pr	18	^{209}Bi	8
^{54}Mn	281		^{76}Se	17		^{98}Tc	12	^{113}Sb	3	^{143}Pr	8		
^{55}Mn	374		^{75}Br	11		^{99}Tc	6	^{115}Sb	4	^{143}Pm	8		

Table 2. Radiative decay data in the volume I/19A2, compound nuclei with $Z \geq 19$:
$N_{\rm p}$, N_α – number of proton or α-particle resonances, respectively
N_γ – number of γ–transitions to low-lying levels.

^{A}Z	$N_{\rm p}/N_\gamma$	^{A}Z	$N_{\rm p}/N_\gamma$	N_α/N_γ	^{A}Z	$N_{\rm p}/N_\gamma$	^{A}Z	$N_{\rm p}/N_\gamma$
^{37}K	12/6	^{45}Sc	6/22		^{54}Mn	42/26	^{61}Cu	45/22
^{39}K	39/23	^{44}Ti		6/19	^{55}Mn	68/24	^{65}Cu	9/18
^{41}K	36/23	^{46}Ti	4/22		^{56}Fe	21/26	^{64}Zn	2/22
^{40}Ca	50/22	^{47}V	42/21		^{55}Co	101/35	^{65}Ga	6/12
^{42}Ca	17/28	^{49}V	61/25		^{57}Co	32/23	^{67}Ga	1/9
^{41}Sc	21/9	^{51}V	7/24		^{58}Co	10/27	^{69}Ga	4/11
^{42}Sc	4/25	^{52}Cr	12/15		^{59}Co	16/12	^{71}As	2/13
^{43}Sc	16/21	^{51}Mn	109/25		^{60}Ni	10/22	^{75}As	1/12
^{44}Sc	4/23	^{53}Mn	126/23		^{59}Cu	60/24		

For compound nuclei ^{48}V, ^{50}V, ^{63}Cu and ^{66}Zn only branching ratios for transitions between low-lying levels are known.

Table 3. List of principal notations in PRF.

No.	Symbol	Its meaning	REFERENCE Explanation
			PROPERTIES OF TARGET NUCLEUS
	Z	Atomic number	Integer number Z
	A	Atomic weight	Integer number A
	$I^{\pi}_{\circ}$	Spin	π indicates parity
	Abundance	Abundance	Percentage of isotope abundance [00TuZZ]
	$T_{1/2}$	Half-life	Half-life of disintegration [00TuZZ, 98Ho0A]
	$S_{\rm p}$	Separation energy	Proton separation energy in nucleus $A+1$ [95Au04]
	$Q_{\rm d}, Q_{\rm t}$	Q-value	Q-values of reactions with hydrogen ions
	Q_{τ}, Q_{α}	Q-value	Q-values of reactions with ^{3}He- and ^{4}He-ions
1			RESONANCE PARAMETERS
	$E_{\circ}$	Resonance energy	Energy of a resonance in the laboratory frame
	$E_{\rm cm}$	Resonance energy	Energy of a resonance in center-of-mass frame
	E^*	Total energy	Total energy of a state in the compound nucleus
	$E^*_{\rm analog}$	Energy of the analog state	Excitation energy of the state with analogous quantum numbers J^{π}, T in the neighbor nucleus
	J^{π}	Spin	Total spin of compound state, π indicates parity
	T	Isotopic spin	
	l	Orbital moment	Orbital moment of incoming particle
	Γ	$\Gamma = \sum \Gamma_i$	Total width
	$\Gamma_{\rm cm}$	$M/(M+m)\Gamma$	Total width in the center-of-mass frame
	$t_{1/2}$	Half-life	Half-life of the disintegration [02Nu0A]
	S_{ij}	$(2J+1)\Gamma_i\Gamma_j/\Gamma$	Resonance strength of (i,j) reaction ($i = {\rm p}, \alpha$, etc.)
	$\omega\gamma_{i,j}$	$g\Gamma_i\Gamma_j/\Gamma$	Resonance strength of (i,j) reaction ($i = {\rm p}, \alpha$, etc.)
	$\omega\gamma$	$g\Gamma_{\rm p}\Gamma_{\gamma}/\Gamma$, $g\Gamma_{\alpha}\Gamma_{\gamma}/\Gamma$	Radiative capture resonance strengths $\omega\gamma_{\rm p\gamma}$, $\omega\gamma_{\alpha\gamma}$
	$\omega\gamma_{\rm cm}$	$M/(M+m)\omega\gamma_{i,j}$	$\omega\gamma$, $\omega\gamma_{\rm p\gamma}$, $\omega\gamma_{\alpha\gamma}$ in the center-of-mass frame
2			INGOING AND OUTGOING PROTONS
	$\Gamma_{\rm p}$, $\Gamma_{\rm p_o}$	$\Gamma_{\rm p_o} = \Gamma_{\rm p}$	Proton elastic scattering widths
	$\Gamma_{\rm pcm}$	$M/(M+m)\Gamma_{\rm p}$	Proton width in the center-of-mass frame
	$\gamma^2_{\rm p}$	$\Gamma_{\rm p}/P$	Reduced proton elastic scattering width
	$\gamma^2_{\rm p'}, \gamma^2_{\rm p_1}, \gamma^2_{\rm p^*}$	$\Gamma_{\rm p'}/P, \Gamma_{\rm p_1}/P, ...$	Reduced proton inelastic scattering width
	$\Gamma_{\rm p'}$	$\Gamma_{\rm p'} = \Gamma_{\rm p_1}, \Gamma_{\rm p_2}, ...$	Proton inelastic scattering widths
	$\theta^2_{\rm p}$	$\gamma^2_{\rm p}/\gamma^2_{\rm W}$	Normalized reduced proton width
	$(2J+1)\theta^2_{\rm p}$	$(2J+1)\gamma^2_{\rm p}/\gamma^2_{\rm W}$	Normalized reduced proton width
	$\theta^2_{\rm p_1}, \theta^2_{\rm p_2}$	$\gamma^2_{\rm p_1}/\gamma^2_{\rm W}, \gamma^2_{\rm p_2}/\gamma^2_{\rm W}$	Normalized reduced width of inelastic scattering
	$(2J+1)\theta^2_{\rm p_i}$		Normalized partial reduced proton width
	$S_{\rm pp'}$	$(2J+1)\Gamma_{\rm p}\Gamma_{\rm p'}/\Gamma$	Resonance strength of (p,p′) scattering
	$S_{\rm pp_1}, S_{\rm pp_2}, ...$	$S_{\rm p_1}, S_{\rm p_2}, ...$	$(2J+1)\Gamma_{\rm p}\Gamma_{\rm p_1}/\Gamma, (2J+1)\Gamma_{\rm p}\Gamma_{\rm p_2}/\Gamma, ...$
	$S_{\rm p\alpha}$	$(2J+1)\Gamma_{\rm p}\Gamma_{\alpha}/\Gamma$	Resonance strength of (p,α) reaction
	$S_{\rm p\alpha_0}, S_{\rm p\alpha_1}$		$(2J+1)\Gamma_{\rm p}\Gamma_{\alpha_0}/\Gamma, (2J+1)\Gamma_{\rm p}\Gamma_{\alpha_1}/\Gamma$
	$\omega\gamma_{\rm p\alpha}$	$g\Gamma_{\rm p}\Gamma_{\alpha}/\Gamma$	Resonance strength of (p,α) reaction
	$\omega\gamma_{\rm p\alpha cm}$	$A/(A+1)\omega\gamma_{\rm p\alpha}$	Strength of (p,α) reaction in the c.m. frame
	s	Spin of the channel	Spin and moment of inelastic scattering channel s
	γ^2_{sl}	$\gamma^2_{s13}, \gamma^2_{s15}$, etc.	Reduced width (inelastic scattering amplitude)^2
	$\gamma_{sl}\gamma_{sl}$	$\gamma_{s13}\gamma_{s15}$, etc.	Product of amplitudes in different channels s
	γ^2_{sl}, $\gamma_{sl}\gamma_{sl}$	$\gamma^2_{20}, \gamma_{20}\gamma_{22}$, etc.	Reduced width and product of amplitudes

Table 3 (continued).

No.	Symbol	Its meaning	REFERENCE Explanation
3			OUTGOING γ-RAYS
	Γ_γ		Total radiative width
	$\Gamma_{\gamma_\circ}$		Partial width of γ-transition to the ground state
	Γ_{γ_i}	Γ_{γ_i}=Γ_{γ_1}, Γ_{γ_2} ...	Partial radiative width
	Γ_{γ_E}		Width for γ-transition to the level at E^*
	$S_{\mathrm{p}\gamma}$	$(2J{+}1)\Gamma_\mathrm{p}\Gamma_\gamma/\Gamma$	Resonance strength of (p,γ) reaction
	$S_{\mathrm{p}\gamma_\circ}$	$(2J{+}1)\Gamma_\mathrm{p}\Gamma_{\gamma_\circ}/\Gamma$	Strength of resonance in (p,$\gamma_\circ$) reaction
	E_γ		Energy of γ-transition
	E^*_f		Energy of the final state in transition
	Br	Branching	Branching ratio in percents
	$\Gamma_{\gamma_\circ}$, Γ_{γ_1} ...		Radiative width of individual transition
	Mult.	E1, M1 ...	Multipolarity of the γ-transition
4			OUTGOING NEUTRONS
	Γ_n		Total neutron width
	S_pn		Neutron emission in reaction with proton
	$S_{\mathrm{pn}_\circ}$		The same with residual nucleus at the ground state
	γ^2_n, $\gamma^2_{\mathrm{n}^*}$, γ^2_pn		Reduced widths of neutron emission
	θ^2_n	$\gamma^2_n/\gamma^2_\mathrm{W}$	Normalized reduced neutron width, γ^2_W–Wigner unit
5			INGOING AND OUTGOING α-PARTICLES
	Γ_α		Total α-particle width
	$\Gamma_{\alpha\mathrm{cm}}$	$\mathrm{A}/(\mathrm{A}{+}4)\Gamma_\alpha$	Total α-particle width in center-of-mass frame
	γ^2_α	Γ_α/P	Reduced α-particle width
	θ^2_α	$\gamma^2_\alpha/\gamma^2_{\alpha\mathrm{W}}$	Normalized reduced α-particle width
	$\Gamma_{\alpha_\circ}$		Partial α-particle elastic scattering width
	Γ_{α_1} ...		Partial α-particle inelastic scattering width
	$S_{\alpha\gamma}$	$(2J{+}1)\Gamma_\alpha\Gamma_\gamma/\Gamma$	
	$S_{\alpha\gamma_\circ}$, $S_{\alpha\gamma_i}$	$S_{\alpha\gamma_1}$, $S_{\alpha\gamma_2}$ ...	Strength of α-induced γ-transitions
	$S_{\alpha\alpha_1}$, $S_{\alpha_\circ\alpha_1}$	$(2J{+}1)\Gamma_{\alpha_\circ}\Gamma_i/\Gamma$	Resonance strength of inelastic α scattering measured by γ-rays from the residual nucleus
	$S_{\alpha\mathrm{p}_\circ}$	$(2J{+}1)\Gamma_\alpha\Gamma_{\mathrm{p}_\circ}/\Gamma$	Resonance strength of (α,p) reaction with residual nucleus staying at the ground state
	$S_{\alpha\mathrm{p}_1}$	$(2J{+}1)\Gamma_\alpha\Gamma_{\mathrm{p}_1}/\Gamma$	Resonance strength of (α,p) reaction with residual nucleus staying at the excited state
	$S_{\alpha\mathrm{p}}$, $\omega\gamma_{\alpha\mathrm{p}}$	$g\Gamma_\alpha\Gamma_\mathrm{p}/\Gamma$	Parameters of α-induced proton emission
	$S_{\alpha\mathrm{n}}$, $\omega\gamma_{\alpha\mathrm{n}}$	$g\Gamma_\alpha\Gamma_\mathrm{n}/\Gamma$	Parameters of α-induced neutron emission
	$S_{\mathrm{p}\alpha}$	$(2J{+}1)\Gamma_\mathrm{p}\Gamma_\alpha/\Gamma$	Resonance strength of (p,α) reaction
	$S_{\mathrm{p}\alpha_\circ}$, $S_{\mathrm{p}\alpha_1}$		$(2J{+}1)\Gamma_\mathrm{p}\Gamma_{\alpha_\circ}/\Gamma$, $(2J{+}1)\Gamma_\mathrm{p}\Gamma_{\alpha_1}/\Gamma$
	$\omega\gamma_{\mathrm{p}\alpha}$	$g\Gamma_\mathrm{p}\Gamma_\alpha/\Gamma$	Resonance strength of (p,α) reaction
	$\omega\gamma_{\mathrm{p}\alpha\mathrm{cm}}$	$\mathrm{A}/(\mathrm{A}{+}1)\omega\gamma_{\mathrm{p}\alpha}$	Strength of (p,α) reaction in the c.m. frame
6			ADDITIONAL PARAMETERS
	S_pp S_dp	Spectroscopic	Spectroscopic factors from (p,p) and (d,p)-reactions
	C^2S	factors	Spectr. factors including Clebsch-Gordon factor
	Γ_d	Γ_d, $\Gamma_{\mathrm{d}_\circ}$ ...	Partial width of deuteron emission
	Part. out	p_i,d,t,α_i,^{3}He,^{8}Be	Outgoing particles in different reactions

1.2 List of notations

The notations of the parameters for resonances with energies situated between the resonance energy $E_\circ$ at the beginning of the line and the above mentioned energies $E_{\rm cm} - E^*$ at the end are listed in Table 3. They are the same as used in most of the original works, review papers and compilations. Total width and common parameters S_{ij} and $\omega\gamma$ are given in the upper part of Table 3, other parameters are given separately for protons, γ-rays, neutrons and α-particles, respectively.

The scattering parameters are in most cases the result of a multi-level analysis of the cross-sections. To distinguish $\Gamma_{\rm p}$ (width of the entrance channel) from the inelastic proton width $\Gamma_{\rm p'}$ special notations are used corresponding to the proton transition to the ground state (elastic scattering) and to a certain excited state of the residual compound nucleus (inelastic scattering). The reduced width in the proton channels is given by $\gamma_{\rm p}^2 = \Gamma_{\rm p}/2P_{\rm p}$, with $P_{\rm p}$ the proton penetrability in the respective (entrance or exit) channel. The penetrability factor for a specified orbital angular momentum of the proton or other projectiles depends on the nuclear potential form used in the calculations. Therefore the same $\Gamma_{\rm p}$ in different papers could be given with somewhat different reduced widths. For obtaining dimensionless values, reduced widths could be expressed in Wigner single particle units $\gamma_{\rm sp}^2 = \hbar^2/\mu R^2$ [58La0A, 92Wi13], where μ is the reduced mass in the decay channel and R is the channel radius estimated as $R = 1.4\ A^{1/3}$fm (A – atomic mass number).

The proton width $\Gamma_{\rm p}$ and the α-widths Γ_α together with the respective reduced widths (spectroscopic factors) are situated, as a rule, in the first columns of the PRF isotope-tables.

If in any reaction the residual nucleus is staying at the ground state or with certain excitation, say, at the first excited state, indexes $\circ$ or $i = 1$ ... are added as subscripts: $\alpha_\circ$ or α_1, $\gamma_\circ$ or γ_1, $p_\circ$ or p_1 means the emission of a particle when the nucleus is left at the ground state or at the first excited state, respectively.

Γ_γ is the radiative width. Several specifications for this value and its combinations with other parameters are used in the literature and are preserved here. γ_E means the observation of γ-rays with energy E or with energy larger than that. The value $\Gamma_{\gamma'}$ corresponds to all transitions except the ground state transition. Parameters of the type $\Gamma_{\gamma_\circ}$(M1) $\Gamma_{\gamma_\circ}$(E2) correspond to specific gamma transitions and their meaning should be examined by the original papers. For example, the notations Γ_{12} or Γ_{376} for $E^* = 12$ and 376 keV are used for the description of the experimental results in which direct γ-transitions to these excited states are measured (after charged particle capture on the given resonance). The abbreviation Br is used for the branching ratios (in %). Some other quantitative measures of resonance reaction are explained in the comments just after the corresponding Table of PRF or in the right part of Table 2. The mark "include" in all tables means that the value given in the line situated above the marked one belongs to two resonances.

1.3 Acknowledgments

This project has much benefitted from the input of several sets of unpublished data measured in TUNL and sent to us by G.E. Mitchell. We thank C. Angulo and P. Descouvemont for the useful discussions, and we appreciate communications of data and references by C. Angulo, E. Arai, K. Ideno, J. Keinonen, A. Coc, F. Gunsing, S. Abramovich, A. Vodin, K. Vierinen, F. Herrmann, A. Ventura, C. Rossi-Alvarez, G. Vingiani.

We are extremely grateful to the PNPI scientific library staff.

Programs for the data handling and text preparation were developed by D. Sukhoruchkin.

The work was facilitated by the existence of the international computer Nuclear Science References file maintained in NNDC (Brookhaven National Laboratory, USA).