Science, Belgrade, Yugoslavia.
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[1]A. Bohr and B. R. Mottelson, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. 27, No. 16 (1953).
[2]I. Talmi and I. Unna, Nucl. Phys. 19, 225 (1960).
[3]T. Yamazaki, H. Ikegami, and M. Sakai, Nucl. Phys. 30, 68 (1962).
[4]B. Van Nooijen, W. Lourens, H. Van Krugten, and A. H. Wapstra, Nucl. Phys. 63, 241 (1965).
[5]A. C. Rester, Ph. D. thesis, Vanderbilt University, 1969 (unpublished).
[6]Q. L. Baird, J. C. Nall, S. K. Haynes, and J. H. Hamilton, Nucl. Instr. Methods 16, 275 (1962).
[7]R. H. Pratt, R. D. Lever, R. L. Pexton, and W. Aron, Phys. Rev. 134, A898 (1964).
[8]R. S. Hager and E. C. Seltzer, Nucl. Data A4, 1 (1968).
[9]C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes* (John Wiley & Sons, Inc., New York, 1967), 6th ed.
[10]A. V. Ramayya, J. H. Hamilton, J. A. Deye, R. L. Robinson, and J. L. C. Ford, private communication.
[11]*Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences – National Research Council, Washington, D. C.).
[12]R. G. Arns, D. V. Martin, W. G. Monahan, and S. W. Sprague, to be published.
[13]A. V. Ramayya, J. H. Hamilton, J. A. Deye, R. L. Robinson, and J. J. Pinajian, Nucl. Phys. A127, 60 (1969).

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Lifetimes of Excited Levels and Electromagnetic Transition Rates in ^{51}V, ^{75}As, ^{90}Y, and ^{123}Sb

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The lifetimes of the excited states in ^{51}V, ^{75}As, ^{90}Y, and ^{123}Sb have been measured by the delayed-coincidence technique using a time-to-amplitude converter. The results are $T_{1/2}$(319.5 keV, ^{51}V) = 0.190 ± 0.030 nsec, $T_{1/2}$(927.5 keV, ^{51}V) = 0.070 ± 0.025 nsec, $T_{1/2}$(198.0 keV, ^{75}As) = 0.75 ± 0.15 nsec, $T_{1/2}$(202.7 keV, ^{90}Y) = 0.180 ± 0.030 nsec, $T_{1/2}$(160.2 keV, ^{123}Sb) = 0.60 ± 0.08 nsec. The energies and relative intensities of the γ rays in these nuclei have been determined with the help of a Ge(Li) detector. On the basis of these measurements and the values of multipole mixing ratios, the reduced $B(M1)$ and $B(E2)$ transition probabilities have been deduced for various transitions in these nuclei. The hindrance and enhancement factors are determined with respect to the Weisskopf single-particle estimates for $M1$ and $E2$ transitions, respectively.

INTRODUCTION

In the present investigation we have measured the lifetimes of the excited states in ^{51}V, ^{75}As, ^{90}Y, and ^{123}Sb using the delayed-coincidence technique. The measurements of the half-lives of the 927.5- and the 202.7-keV levels in ^{51}V and ^{90}Y, respectively, are being reported for the first time. In the case of the 198.0-keV level in ^{75}As, only one report is available,[1] giving a half-life of 0.9 nsec using the pulsed-beam technique. The measurements of the half-lives in the case of the 319.5-keV level in ^{51}V and 160.2-keV level in ^{123}Sb have been repeated in the present work as check experiments.

Also we have measured the energies, intensities, and branching ratios of the γ rays in these nuclei with a Ge(Li) detector. This new information together with the earlier known electron intensities, total conversion coefficients, and multipole mixing ratios, has made it possible to deduce reduced $B(M1)$ and $B(E2)$ transition probabilites from our measured lifetimes.

EXPERIMENTAL PROCEDURE

The lifetimes were measured with the help of a fast-slow coincidence set up using a time-to-amplitude converter (ORTEC model No. 263) and a 512-channel analyzer (ND 120). For the detection of β and γ rays, detectors consisting of 2.5-cm-diam × 3-mm-thick NE810 and 2.5-cm-diam × 2.5-cm-long NE102A plastic scintillators, respectively, optically coupled to RCA 7850 photomultipliers, were used. The time resolution [full width at half maximum (FWHM)] of the whole system was 0.6 nsec, and the slope (= instrumental half-life) was 0.14 nsec as measured with a ^{60}Co source. Details of the electronic system and time calibration have been given previously.[2]

A ^{60}Co source was used to obtain the prompt-time distribution in the case of ^{90}Y. In the ^{51}V, ^{75}As, and ^{123}Sb cases, ^{24}Na sources were used. The ^{24}Na source was produced through the reaction $^{27}Al(n, \alpha)^{24}Na$, by irradiating spectroscopically pure aluminum foil with 14-MeV neutrons for 8–10 h.

The delayed and prompt data in all cases were recorded by successive accumulation in alternate short runs of 10–20-min duration. Several runs were performed in each measurement, usually for 10–16-h periods. Repeated measurements were made in each case by changing the time scale and the energy settings to avoid any systematic error. The data were analyzed for the lifetimes and their statistical errors by computing moments of various orders for the delayed and prompt curves.

MEASUREMENTS AND RESULTS

1. Lifetimes of Excited Levels

927.5- and 319.5-keV Levels in ^{51}V

The lifetimes of the levels in ^{51}V were determined by recording the delays between the β rays from the 5.8-min ^{51}Ti feeding levels in ^{51}V and the following γ rays. Spectroscopically pure vanadium metal powder was irradiated with 14-MeV neutrons to produce ^{51}Ti through the (n, p) reaction. Fresh vanadium targets were used after every five runs to avoid the pileup of the 1.8-day ^{48}Sc activity.

In measuring the lifetime of the 927.5-keV level, the channels for energy selection were set to select 0.4- to 1.2-MeV β energy and the Compton hump due to the 927.5-keV γ ray. The delayed and

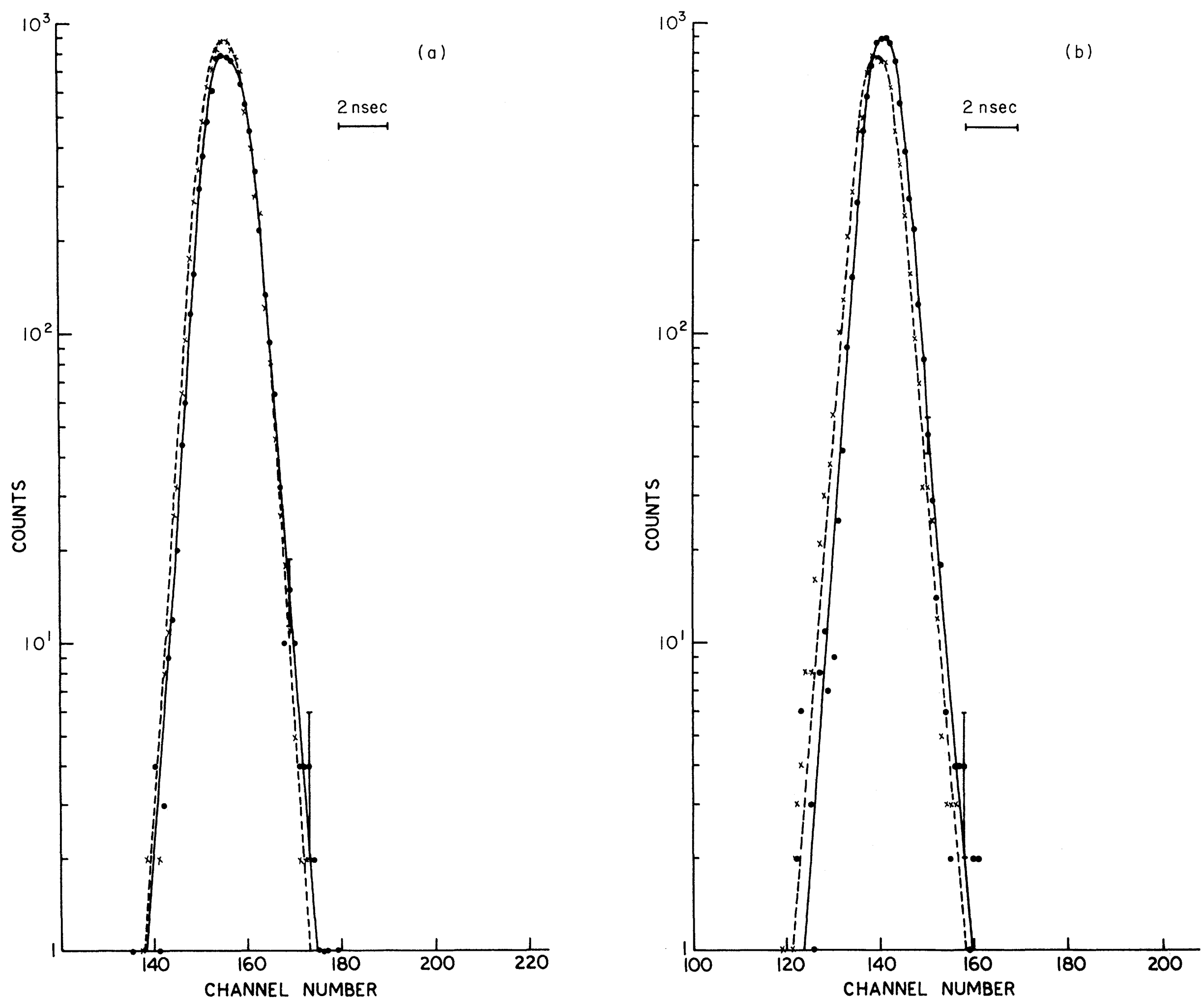

FIG. 1. The delayed and prompt time spectra recorded in the measurement of the lifetimes of (a) the 927.5- and (b) the 319.5-keV levels in ^{51}V. The delayed and prompt data are shown by dots and crosses, respectively.

the prompt data obtained in a measurement are shown in Fig. 1(a). Five independent measurements were made. The mean value for the half-life is

$$T_{1/2}(927.5\text{-keV level}) = 70 \pm 25 \text{ psec.}$$

For the measurement of the lifetime of the 319.5-keV level of ^{51}V, the β and γ rays were selected in the energy intervals 0.4 to 0.6 and 0.17 to 0.23 MeV, respectively. Typical delayed- and prompt-time distributions obtained are shown in Fig. 1(b). The mean value deduced from six independent measurements for the half-life of this level is

$$T_{1/2}(319.5\text{-keV level}) = 0.19 \pm 0.03 \text{ nsec.}$$

This value differs markedly from the results of Schopper[3] and Nainan[4] but agrees closely with the other reported values.[1,5-7]

202.7-keV Level in ^{90}Y

The first excited level at 202.7-keV energy in ^{90}Y can be reached in the 3.1-h isomeric decay of ^{90m}Y. The lifetime of this level was determined by recording the time delay between the 479.2- and the 202.7-keV γ rays populating and depopulating the level. The 3.1-h ^{90m}Y was produced by the reaction $^{93}Nb(n, \alpha)^{90m}Y$ using 14-MeV neutrons and spectroscopically pure niobium target (^{93}Nb). The period of irradiation was typically 5 h. In addition to ^{90m}Y, a small amount of the 10.2-day ^{92}Nb was also produced as a result of $(n, 2n)$ reaction on ^{93}Nb. Since lifetime of ^{92}Nb is long compared with the period of irradiation, the amount of ^{92}Nb produced is very small and, further, its decay to the higher excited levels in ^{92}Zr occurs via weak electron-capture branches so that the transitions in ^{92}Zr in coincidence with each other are weak, and hence they have essentially no effect upon our measurements. In order to avoid the pileup of the 10.2-day activity a fresh niobium target was taken for each irradiation. The channels for the selection of γ-ray energies were set to select energies in the intervals 300–390 and 150–200 keV. The delayed and prompt data were recorded alternately in intervals of 20 min each, and they were successively accumulated for a total period of 6 h. After this, a fresh niobium target was irradiated with neutrons and the above procedure repeated. About five such irradiations

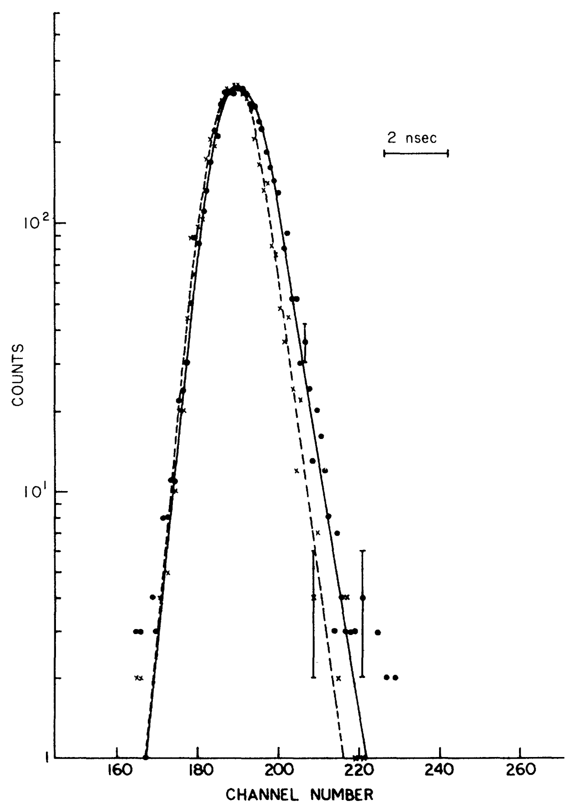

FIG. 2. The delayed (dots) and prompt (crosses) time distributions observed in the measurement of the lifetime of the 202.7-keV level in ^{90}Y. The prompt data were recorded with a ^{60}Co source.

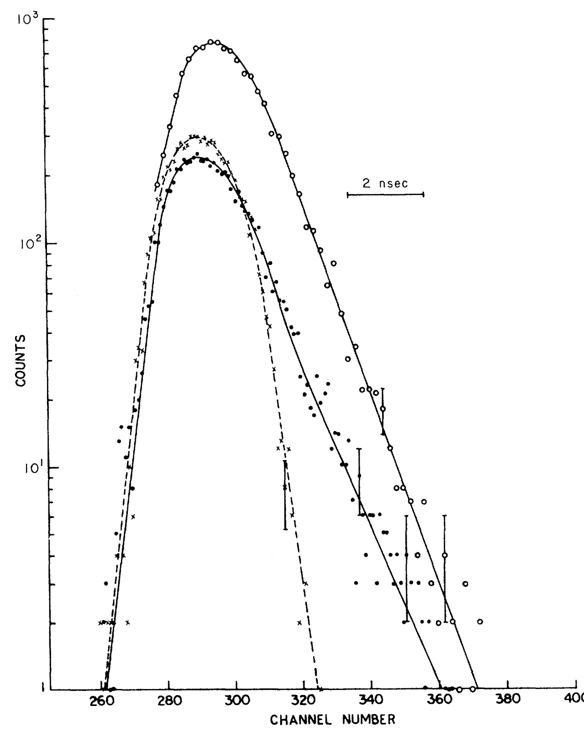

FIG. 3. The lifetimes of the 198.0- and 263.7-keV levels in ^{75}As and 160.2-keV level in ^{123}Sb. The delayed data, taken with a ^{75}Ge source, observed in the case of ^{75}As (dots) indicate a mixture of two lifetimes. The corresponding prompt curve recorded with a ^{24}Na source is shown by crosses. The delayed curve, recorded with a ^{123}Sn source, shown by open circles gives the lifetime of the 160.2-keV level in ^{123}Sb.

were required to obtain data with sufficient statistical accuracy. The typical delayed and prompt curves obtained in a measurement are shown by continuous and dotted lines, respectively, in Fig. 2.

The value of the half-life, obtained by taking the mean of three independent measurements is found to be

$$T_{1/2}(202.7\text{-keV level}) = 180 \pm 30 \text{ psec.}$$

263.7- and 198.0-keV Levels in ^{75}As and 160.2-keV Level in ^{123}Sb

The ^{75}Ge (83-min) and ^{123}Sn (40-min) sources were produced with 14-MeV neutron irradiation through the reactions ^{76}Ge$(n, 2n)^{75}$Ge and ^{124}Sn$(n, 2n)$-^{123}Sn. Enriched targets were used.

In measuring the lifetimes of the levels in ^{75}As, the β rays in the energy interval 0.45 to 0.75 MeV were selected in the start channel. The stop channel selecting the γ rays was set to select 45% of the Compton continuum due to the 198.0- and 263.7-keV γ rays. Therefore, the time distributions due to both the levels were recorded simultaneously (Fig. 3). In order to determine the lifetimes from the composite delayed curve, the first, second, and third moments of the delayed and prompt data were determined and compared with those computed for various assumed values of the lifetimes in the mixture and their relative intensities. The experimental values from six independent measurements were taken. The results are

$$T_{1/2}(198.0\text{-keV level}) = 0.75 \pm 0.15 \text{ nsec,}$$

$$T_{1/2}(263.7\text{-keV level}) < 0.08 \text{ nsec,}$$

percentage of the longer half-life component in the mixture = 15.

The observed percentage of the longer lifetime component in the mixture is in fair agreement with the relative intensities of the β groups feeding the 198.0- and 263.7-keV levels and the corresponding γ rays and their branching ratios.[8]

The 160.2-keV level in ^{123}Sb is strongly fed by a 1.26-MeV β group (100%) in the decay of the 40-min ^{123}Sn. The lifetime of this level was determined from the delayed-coincidence curves measured between the feeding β continuum and the deexciting γ transition. Three independent measurements give the following value for the half-life of this level:

$$T_{1/2}(160.2\text{-keV level}) = 0.60 \pm 0.08 \text{ nsec.}$$

This value agrees within experimental error with those reported earlier.[9,10] Typical delayed curves recorded with ^{75}Ge and ^{123}Sn sources are shown in Fig. 3, and the results of the measurements of the half-lives are summarized in Table I.

TABLE I. Results of lifetime measurements.

Nucleus	Level (keV)	$T_{1/2}$ (nsec) Present	Previous
^{51}V	927.5	0.070 ± 0.025	...
^{75}As	198.0	0.75 ± 0.15	0.9 [a]
^{90}Y	202.7	0.180 ± 0.030	...

[a]See Ref. 1.

2. Energies and Relative Intensities of γ Rays

The energies and relative intensities of γ rays in ^{51}V, ^{75}As, and ^{90}Y have been determined from the γ-ray spectra of ^{51}Ti, ^{75}Ge, and ^{90m}Y recorded with the help of a 2.00-cc Ge(Li) detector. The detector system had a resolution of 3 keV (FWHM) at 661 keV. The γ-ray energies and relative intensities are included in Table II along with the previously known values with Ge(Li) detector.

TRANSITION PROBABILITIES AND DISCUSSION

The results of the measurements of the lifetimes and the relative intensities of the γ rays in the present work are combined with the values of conversion coefficients and the multipole mixing ratios from literature to calculate the partial γ-ray transition probabilities for the competing multipole orders. The experimental values of the transition rates have been compared with those due to the Weisskopf single-particle estimate as shown in Table III.

The 319.5- and 608.3-keV $M1$ transitions in ^{51}V are hindered by factors of 318 and 5450, respec-

TABLE II. The energies and relative intensities of γ rays measured in the present work and the previously known values with Ge(Li) detector.

Source	γ-ray energy (keV) Present	Previous	Relative intensity of γ rays Present	Previous
^{51}Ti (5.8 min)	319.5	319.7 [a]	100	...
	608.3	609.4 [a]	1.34	...
	927.5	929.1 [a]	9.0	...
^{75}Ge (83 min)	65.7	...	2.61	...
	198.0	...	11.02	...
	263.7	...	100	...
^{90m}Y (3.1 h)	202.7	...	100	...
	479.2	...	98.5	...

[a]See T. Hayashi *et al.*, J. Phys. Soc. Japan 27, 1375 (1969).

TABLE III. Partial γ-ray transition probabilties (λ_γ), reduced $B(M1)\downarrow$ and $B(E2)\downarrow$ transition probabilties, hindrance factors (F_W), and enhancement factors ($1/F_W$) for transitions in ^{51}V, ^{75}As, ^{90}Y, and ^{123}Sb.

Nucleus	Transition energy (keV)	$\delta^2 = \left[\frac{I(E2)}{I(M1)}\right]$	Total conversion coefficient	Multi-polarity	$10^9\lambda_{\gamma\text{exp}}$	$10^9\lambda_{\gamma\text{s.p.}}$	$B(M1)\downarrow \times \left(\frac{e\hbar}{2Mc}\right)^2$	$B(E2)\downarrow$ ($e^2\times10^{-48}$ cm^4)	F_W $\left(=\frac{\lambda_{\gamma\text{s.p.}}}{\lambda_{\gamma\text{ exp}}}\right)$ (for $M1$)	$1/F_W$ (for $E2$)
^{51}V	319.5	0.1416 [a]	1.63×10^{-3}	$M1$	3.1898	1013.2	0.005 59		317.64	
			a	$E2$	0.4517	4.64×10^{-2}		0.0112		9.72
	608.3	0 [b]		$M1$	1.2829	6992.6	0.003 25		5450.3	
	927.5			$E2$	8.6170	9.5795		0.0010		0.9
^{75}As	198.0	0.2968 [c]	0.024 [d]	$M1$	0.6958	2.4115×10^{2}	0.005 12		346.6	
				$E2$	0.2065	8.943×10^{-3}		0.0559		23.1
^{90}Y	202.7	0.1529 [e]	0.03 [f]	$M1$	3.242	258.7	0.0222		79.8	
				$E2$	0.4957	1.02×10^{-2}		0.1192		48.7
^{123}Sb	160.2	···	0.17 [g]	$M1$	0.9872	127.7	0.0137		129.4	

[a] See O. Dragoun *et al.*, Nucl. Phys. A124, 337 (1969).
[b] Assumption.
[c] Calculated from experimental [see Nucl. Data B1, (No. 6), 92 (1966)] and theoretical K-shell conversion coefficients [see L. A. Sliv and I. M. Band, in *Alpha-, Beta-, Gamma-Ray Spectroscopy*, edited by K. Seigbahn (North-Holland Publishing Company, Amsterdam, The Netherlands, 1965)].
[d] See Nucl. Data B1, (No. 6), 92 (1966).
[e] Calculated from experimental [see R. L. Heath *et al.*, Phys. Rev. 123, 903 (1961)] and theoretical (see Sliv and Band, Ref. c above) K-shell conversion coefficients.
[f] See Heath *et al.*, Ref. e above.
[g] See Sliv and Band, Ref. c above.

tively. The ^{51}V nucleus has three protons outside the closed shells of 20 protons and 28 neutrons. According to the jj coupling theory $M1$ transitions between pure states of $(f_{7/2})^3$ configuration are forbidden. Thus, a large retardation in $M1$ transition rates, as obtained here, supports this type of description for the 319.5- and 927.5-keV levels of ^{51}V. If, instead, the states result from the coupling of the single particle to the first core state, the $M1$ transition probability should only be a factor of 2 smaller than the single-particle prediction.[11]

The 160.2-keV proton transition in ^{123}Sb, most probably $d_{5/2}\to g_{7/2}$, is an l-forbidden $M1$ transition. The large value for the hindrance factor observed in this case supports the forbidden nature of the $M1$ transition.

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[1] E. N. Shipley, F. J. Lynch, and R. E. Holland, Bull. Am. Phys. Soc. 4, 404 (1959); E. N. Shipley, R. E. Holland, and F. J. Lynch, Phys. Rev. 182, 1165 (1969).
[2] B. Sethi and S. K. Mukherjee, Phys. Rev. 166, 1227 (1968).
[3] V. H. Schopper, Z. Physik 144, 476 (1956).
[4] T. D. Nainan, Phys. Rev. 123, 1751 (1961).
[5] R. S. Weaver *et al.*, Can. J. Phys. 40, 660 (1962).
[6] A. W. Sunyar, in *Proceedings of the Second United Nations International Conference on Peaceful Uses of Atomic Energy, Geneva, 1958* (United Nations, Geneva, Switzerland, 1958), Vol. 14, p. 347.
[7] N. N. Delyagin and M. Preisa, Zh. Eksperim. i Teor. Fiz. 36, 1586 (1959) [transl.: Soviet Phys. – JETP 9, 1127 (1959)].
[8] C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes* (John Wiley & Sons, Inc., New York, 1967).
[9] R. E. Holland, F. J. Lynch, and E. N. Shipley, Bull. Am. Phys. Soc. 5, 424 (1960); E. N. Shipley, R. E. Holland, and F. J. Lynch, Phys. Rev. 182, 1165 (1969).
[10] M. Schmorak, A. C. Li, and A. Schwarzschild, Phys. Rev. 130, 727 (1963).
[11] A. de Shalit, Phys. Rev. 122, 1530 (1961).