Decay of Eu^{145}†

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The decay scheme of Eu^{145} was studied by means of the techniques of beta and gamma spectroscopy. The half-life was measured to be 5.93 ± 0.1 days. Thirty-three gamma transitions were identified by means of NaI and germanium gamma detectors and 180° magnetic spectrometers. Gamma-gamma coincidences were performed using both NaI and germanium detectors. Most of the transitions were incorporated into the decay scheme in a consistent manner. The multipolarity of several gamma transitions was determined from measurement of conversion coefficients, and a positron spectrum containing two branches was observed. The level scheme of Sm^{145} contains a first excited state at 0.895 MeV and a second excited state at 1.437 MeV. Above 1.5 MeV, the level density greatly increases. Levels with both even and odd parities were observed, and the energy between the ground states of Eu^{145} and Sm^{145} was determined to be about 2.75 MeV. Systematics for the first excited states of nuclei with even proton number and a neutron number near 82 are presented.

I. INTRODUCTION

THE decay of Eu^{145} to the excited states of Sm^{145} has been studied by several investigators[1–3] since its discovery by Rasmussen *et al.*[4] The first decay scheme was proposed by Antoneva *et al.*[5] Since then three other decay schemes have been proposed.[6–8] These decay schemes disagree in regard to half-life, number of transitions, and arrangement of levels, and were constructed from gamma spectra measured by means of NaI detectors. This work was undertaken to construct a more realistic decay scheme with the aid of data obtained from high-resolution lithium-drifted germanium gamma detectors. The conversion electron and positron spectra were observed with the aid of a 180° magnetic spectrometer, and gamma-gamma coincidences were studied.

Another objective of the study of the decay of Eu^{145} was to gain more information concerning nuclear systematics for nuclei near the closed shell of 82 neutrons. The energies of the first excited states of many nuclei in this region are compared. The first-excited-state energy of Sm^{145} is consistent with that of other nuclei with 83 neutrons and an even number of protons, but the nature of the excitation remains obscure.

II. SOURCE PREPARATION

Samples of samarium oxide enriched to 94.5% in Sm^{144} were bombarded by 9.5-MeV deuterons accelerated in the Purdue cyclotron. Typical bombardments lasted for 30 h at an average beam current of 140 μA. The Eu^{145} was produced by the reaction $Sm^{144}(d,n)Eu^{145}$. After bombardment, the rare earths were purified as a group using the procedure of Stevenson and Nervik.[9] Europium was then separated from the other rare earths by elution from an ion-exchange column, containing Dowex 50 cation resin. The elutant used was 1M lactic acid adjusted to a pH of 3.6 as suggested by Stevenson and Nervik.[9] The yield of europium was 85%, and the separation took about 8 h.

In order to produce sources suitable for conversion-electron studies carrier-free material was prepared. The europium from the rare-earth separation was adjusted to a pH of 1.5 with HCl, and the mixture was passed through a polyethylene ion-exchange column 8-mm i.d. and 5 cm long containing Dowex 50 (−400 mesh) resin. The column was washed with 50 column volumes of H_2O to remove lactic acid and 20 column volumes of 1M HCl to remove calcium and magnesium. The activity was eluted with 6M HCl into a polyethylene beaker, and evaporated to a volume of a few drops under a heat lamp. The above procedure was repeated using a polyethylene column 2-mm i.d. and 2 cm long containing the same type of ion-exchange resin. The carrier-free europium was eluted in a few drops of 6M HCl. All containers used in the final stages of purification were made of polyethylene.

For measurements using the 180° magnetic spectrometer the europium was deposited directly onto a strip of polystyrene foil measuring $0.0013\times0.1\times1$ cm

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[1] G. M. Gorodinskii, A. N. Murin, V. N. Pokrovskii, B. K. Preobrazhenskii and N. E. Titov, Dokl. Akad. Nauk SSSR **3**, 405 (1957) [English transl.: Soviet Phys.—Doklady **2**, 39 (1957)].
[2] J. R. Grover, Phys. Rev. **116**, 406 (1959).
[3] A. A. Bashilov, O. V. Larionov, M. K. Nikitin, and V. B. Smirnov, Izv. Akad. Nauk SSSR, Ser. Fiz. **24**, 788 (1960) [English transl.: Bull. Acad. Sci. USSR **24**, 791 (1960)].
[4] R. W. Hoff, J. O. Rasmussen, and S. G. Thompson, Phys. Rev. **83**, 1068 (1951).
[5] N. M. Antoneva, A. A. Bashilov, B. S. Dzhelepov, K. G. Kaun, A. F. A. Meyer, and V. B. Smirnov, Zh. Eksperim. i Teor, Fiz. **40**, 23 (1961) [English transl.: Soviet Phys.—JETP **13**, 15 (1961)].
[6] Y. A. Alexsandrov and M. K. Nikitin, Izv. Akad. Nauk SSSR, Ser. Fiz. **25**, 1176 (1961) [English transl.: Bull. Acad. Sci. USSR **25**, 1181 (1961)].
[7] I. Demeter, F. Molnar, E. Nadzhakov, and A. F. Novgorodov, Joint Inst. for Nuclear Research, Dubna (USSR) Lab. of Nuclear Problems, 1965 (unpublished) [U. S. Atomic Energy Commission Report No. JINR–P–2052 (unpublished)].
[8] Zh. Zhelev and G. Muziol, Joint Inst. for Nuclear Research, Dubna (USSR) Lab. of Nuclear Problems, 1965 (unpublished) [U. S. Atomic Energy Commission Report No. JINR–P–2314 (unpublished)].
[9] P. C. Stevenson and W. E. Nervik, U. S. At. Energy Comm. Report No. NAS–NS–3020 (1961).

that had been previously sulfonated by the method of Bjornholm and Lederer.[10] Sulfonation produced ion-exchange groups on the surface of the backing that distributed the Eu^{3+} ions in a uniform manner over a well-defined area.

For measurements, using the 180° permanent-magnet spectrographs, the carrier-free europium in HCl was evaporated to dryness and dissolved in isopropyl alcohol. The europium was deposited as the chloride onto a 10-mil platinum wire by the method of molecular plating suggested by Parker.[11] A potential of 400 V was used. After plating the chloride was burned to the oxide, and the source was mounted for counting.

III. HALF-LIFE DETERMINATION

The half-life of Eu^{145} was measured by following the decay of all gamma radiations with energy greater than 0.75 MeV using a 3×3-in. NaI(Tl) scintillation spectrometer shielded with 2 in. of lead. The intensity of the source was recorded each day for 80 days, and the well known gamma lines from Cs^{137} and Mn^{54} were used as calibration points. The decay curve contained a weak long-lived contribution from Eu^{148} ($\tau_{1/2}=54$ days).[12] After subtraction of the Eu^{148} and a χ^2 analysis of the decay curve the half-life of Eu^{145} was found to be 5.93±0.1 days.

IV. THE GAMMA-RAY SPECTRUM

Gamma-ray energies were measured with a Li-drifted germanium detector having an area of 2.7 cm^2 and a depletion depth of 2 mm. The detector was operated at liquid-nitrogen temperatures under a reverse bias of 150 V. The linewidth measured at the 400-channel pulse-height analyzer was 7.5 keV for the 0.662-MeV gamma ray from Cs^{137}. For purposes of comparison a gamma-ray spectrum was obtained using a 3×3-in. NaI(Tl) crystal surrounded by 2 in. of lead. The source was mounted 20 cm above the detector, and a 1 cm thick polystyrene disk was placed directly above the detector to absorb incoming electrons and positrons.

The gamma spectra were calibrated using 4 prominent lines in Eu^{145} whose energies were measured precisely using permanent-magnet spectrographs described below. The energies of these lines were measured to be 0.1109, 0.1915, 0.654, and 0.895 MeV. Well-known lines in Co^{60}, Na^{24}, and ThB were used as calibration standards in the region above 1.0 MeV.

Gamma-ray spectra obtained from both the germanium detector and the NaI detector are compared in Figs. 1 and 2. No gamma transitions were observed with energy greater than 2.51 MeV, and no peaks due to accidental summing of coincident gamma rays were seen. The energies and errors of the gamma transitions observed are listed in Table I. Errors quoted represent probable errors estimated from the reproducibility of all measurements. A source was observed for a period of several half-lives and impurities from Eu^{147}, Eu^{148}, and Eu^{149} were noted after a period of about three weeks.

Relative gamma intensities were measured by determining the number of counts in each photoelectric peak observed in the spectrum from the germanium detector. The relation of efficiency to energy was not available for this detector so relative intensities were obtained by dividing the photopeak counts by the photoelectric cross section for germanium given by Storm.[13] A further correction was made to account for contributions to the full energy peak from Compton and pair-production processes. In order to determine this correction the NaI singles spectrum was unfolded using the efficiency

TABLE I. Gamma-ray and conversion-electron energies, and relative intensities.

Energy (MeV)	Relative gamma intensity	Correction to Ge detector intensity	Relative K conversion-electron intensity
0.1109±0.0006[a]	2.6 ±0.5[b]	3.32±0.7	927 ±300
0.1915±0.0007[a]	1.5 ±0.6[c]		71 ± 20
0.258 ±0.003[d]			1.40± 0.4
0.293 ±0.004[d]			0.80± 0.3
0.317 ±0.003[d]			1.44± 0.4
0.340 ±0.004[c]			1.29± 0.5
0.353 ±0.005[d]			1.13± 0.6
0.374 ±0.005[d]			1.54± 0.6
0.434 ±0.004[d]			0.66± 0.3
0.454 ±0.004[d]			0.50± 0.3
0.473 ±0.005[d]			0.89± 0.4
0.511 ±0.004[c]	7.4 ±2[c]		
0.542 ±0.004[c]	8.6 ±2[c]		8.5 ± 2.5
0.654 ±0.002[a]	24.6 ±3[b]	1.34±0.2	15.3 ±2
0.766 ±0.005[c]	2.8 ±1[c]		5.5 ±1
0.895 ±0.002[a]	100.0[f]	1.00	100.0[f]
1.083 ±0.006[c]	1.1 ±0.5[c]		0.95± 0.2
1.240 ±0.025[g]			
1.430 ±0.012[d]			0.40± 0.15
1.534 ±0.012[d]			0.26± 0.1
1.659 ±0.005[c]	28.1 ±3[b]	1.12±0.2	8.3 ± 1.5
1.801 ±0.006[c]	1.8 ±0.6[c]		
1.856 ±0.010[c]	0.5 ±0.2[c]		
1.874 ±0.006[c]	2.3 ±0.8[c]		
1.994 ±0.005[c]	13.9 ±1.5[b]	1.22±0.2	
2.130 ±0.008[c]	0.31 ±0.1[c]		
2.152 ±0.010[c]	0.11 ±0.06[c]		
2.271 ±0.008[c]	0.22 ±0.08[c]		
2.326 ±0.008[c]	0.45 ±0.1[c]		
2.344 ±0.008[c]	0.39 ±0.1[c]		
2.381 ±0.008[c]	0.038±0.02[c]		
2.420 ±0.008[c]	0.31 ±0.1[c]		
2.477 ±0.008[c]	0.34 ±0.1[c]		
2.503 ±0.008[c]	0.38 ±0.1[c]		

[a] From conversion-electron spectrum using permanent-magnet spectrographs.
[b] From unfolding of NaI gamma spectrum.
[c] From Ge spectrum using correction from NaI analysis.
[d] From conversion-electron spectrum using 180° magnetic spectrometer.
[e] From gamma spectrum using Ge detector.
[f] Intensities normalized to 100 for transition at 0.895 MeV.
[g] From gamma-gamma coincidence studies.

[10] S. Bjornholm and C. M. Lederer, Nucl. Instr. Methods **15**, 233 (1962).
[11] W. Parker, H. Bildstein, N. Getoff, H. Fischer-Colbrie, and H. Regal, Nucl. Instr. Methods **26**, 61 (1964).
[12] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington 25, D. C.) NRC 61-4-61.
[13] E. L. Storm, E. Gilbert, and H. Israel, U. S. Atomic Energy Commission Research and Development Report No. LA-2237, 1958 (unpublished).

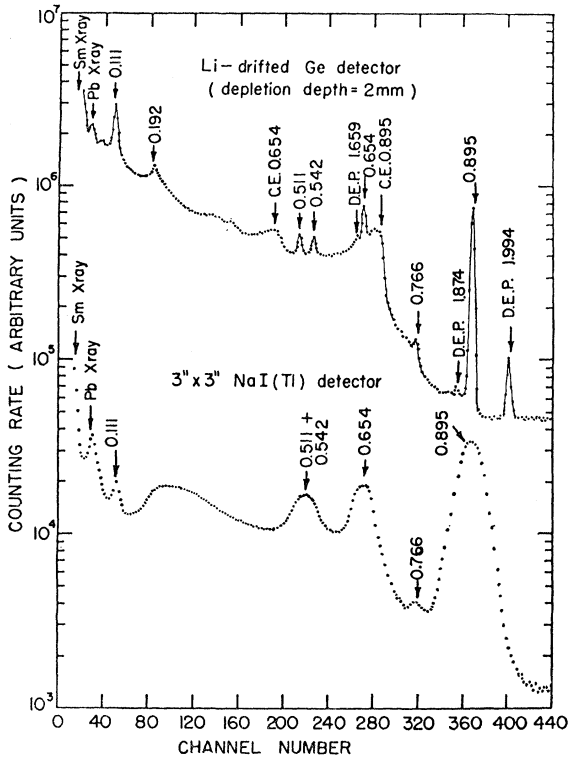

FIG. 1. Spectrum of gamma radiation with energies from 0 to 1.0 MeV accompanying the decay of Eu^{145}. D.E.P. denotes double escape peak resulting from gamma ray whose energy is given. C.E. denotes Compton edge resulting from gamma ray whose energy is given. All energies are in MeV.

values and techniques given by Heath.[14] Spectrum shape as a function of energy was determined using a number of monoenergetic gamma emitters.

The intensities of the gamma rays at 0.111, 0.654, 0.895, 1.659, and 1.994 MeV in the NaI spectrum were used to determine the correction to the germanium-detector data. The true relative intensity and the correction to the germanium photopeak intensity are shown in Table I. It is evident that the correction factor varies slowly with energy except in the region below 0.6 MeV. Errors given for the relative intensities reflect uncertainty in photopeak area, germanium photoelectric cross section, and correction factor.

TABLE II. Results of gamma-gamma coincidence measurements.

Gate (MeV)	Gamma rays in coincidence (MeV)
0.111	0.542, 0.895
0.192	0.542, 0.895
0.511+0.542	0.111, 0.192, 0.895
0.654	0.895
0.895	0.111, 0.192, 0.511+0.542, 0.654 0.766, 1.083, 1.240, 1.430, 1.534
1.659	0.340
1.994	0.370 (complex)

[14] R. L. Heath, U. S. Atomic Energy Commission Research and Development Report No. IDO-16408, 1957 (unpublished).

V. GAMMA-GAMMA COINCIDENCE MEASUREMENTS

Gamma-gamma coincidence studies were made with two 3×3-in. NaI(Tl) crystals oriented at 90°. A lead shield was placed between the two detectors to minimize scattering. Similar studies were made by replacing one of the NaI detectors with the germanium detector

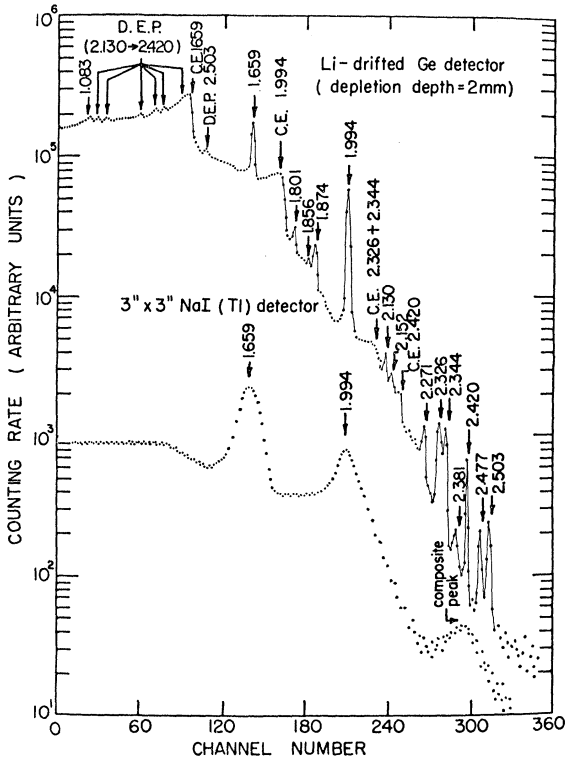

FIG. 2. Spectrum of gamma radiation with energies from 1.0 to 2.6 MeV accompanying decay of Eu^{145}. Symbols have same meaning as in Fig. 1.

described above. In both cases a gating pulse was obtained from the NaI detector, and the coincident spectrum was recorded on a 400-channel pulse-height analyzer. In both cases the resolving time was about 60 nsec, and a 0.5-μsec delay was introduced to estimate the contribution from random coincidences. All spectra shown are corrected for chance coincidences. The coincidence relations between the various gamma transitions are given in Table II.

Spectra observed in coincidence with the 0.895-MeV gamma ray are shown in Fig. 3. No true coincidences were observed above 1.6 MeV, and the Compton contribution under the 0.895-MeV photopeak was negligible except for a small peak at 0.895 MeV. Strong coincidences were observed at 0.111, 0.542, 0.654, and 0.766 MeV. Weaker but definitely observable coincidences were observed at 0.192, 0.511, and 1.083 MeV. Weak peaks at 1.24 and 1.48 MeV were also seen. After subtraction of chance coincidences it was evident that

the peak at 1.24 MeV contained a single gamma ray and that the peak at 1.48 MeV was complex. These peaks were not observed in the germanium-detector spectrum because of poor statistics. The energy of the single peak was measured to be 1.240 ± 0.25 MeV. The composite peak was associated with two transitions that were observed in the conversion-electron spectrum at 1.430 and 1.534 MeV. A reconstruction of the composite peak using photopeaks of the above energy indicated that the above method gave consistent results.

The NaI spectra in coincidence with the 0.111- and 0.192-MeV gamma transitions are shown in Fig. 4. The transition at 0.111 MeV is seen to be in coincidence with gamma rays at 0.542 and 0.895 MeV. Compton contributions were too small to account for these peaks. The gamma transitions at 0.192 MeV was found to be in coincidence with gamma peaks at 0.542 and 0.895

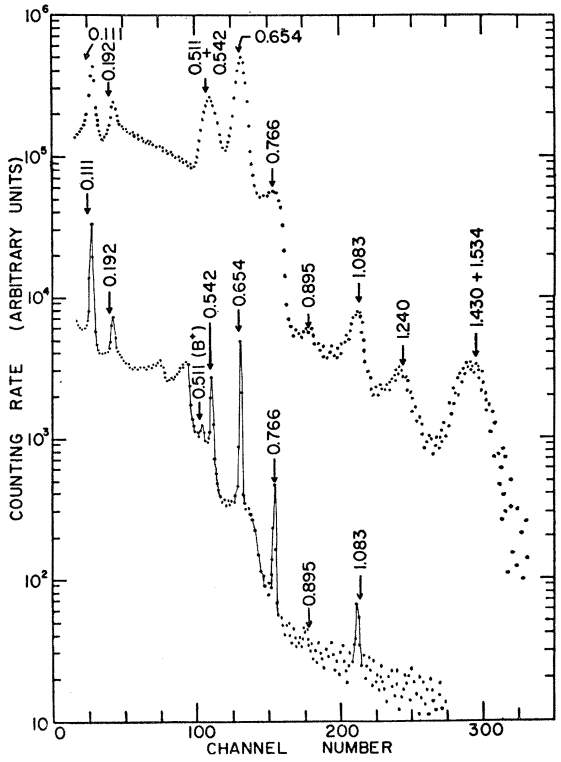

FIG. 3. Gamma spectrum in coincidence with the 0.895-MeV gamma ray using NaI detector (upper curve) and Ge detector (lower curve). Analyzer gated by pulse from NaI detector.

MeV. To rule out coincidences due to Compton contributions from higher energy gamma rays the analyzer was gated on the Compton distribution just above the peak at 0.192 MeV. Comparing this spectrum with the coincidence spectrum from the 0.192-MeV peak it is seen that only the peaks at 0.542 and 0.895 MeV increase relative to the peak at 0.192 MeV.

The spectra in coincidence with the 0.654-MeV gamma ray are shown in Fig. 5. A strong coincidence was seen only at 0.895 MeV. The spectra in coincidence with the peaks at 0.542 and 0.511 MeV are also shown in Fig. 5. A definite coincidence was observed with gamma rays at 0.111, 0.192, and 0.895 MeV. The germanium-detector spectrum in coincidence with the 0.654-MeV gamma ray was observed over a period of 15 days to determine if a coincidence existed between the gamma rays at 0.654 and 0.542 MeV. Subtraction of chance and Compton contributions from spectra observed two days after bombardment indicated the major contribution to the 0.542-MeV gamma peak to be from Compton electrons from the 0.895-MeV gamma ray. Two weeks later a large peak from coincidences between the 0.631- and 0.551-MeV gamma rays of Eu^{148} was observed. The germanium-detector spectrum in coincidence with the 0.542-MeV gamma ray was analyzed in a similar manner. This analysis indicated that no coincidences existed between the 0.654- and 0.542-MeV gamma rays in Eu^{145}. The growth of contributions from Eu^{148} is illustrated in Fig. 5.

Spectra in coincidence with the gamma rays at 1.659 and 1.994 MeV were measured with 2 NaI detectors. Similar measurements with a germanium detector were unsuccessful because of very low coincidence counting rates. A gamma ray at 0.340 MeV was the only coincidence observed with the 1.659-MeV gamma. A complex peak at about 0.370 MeV was observed in coincidence

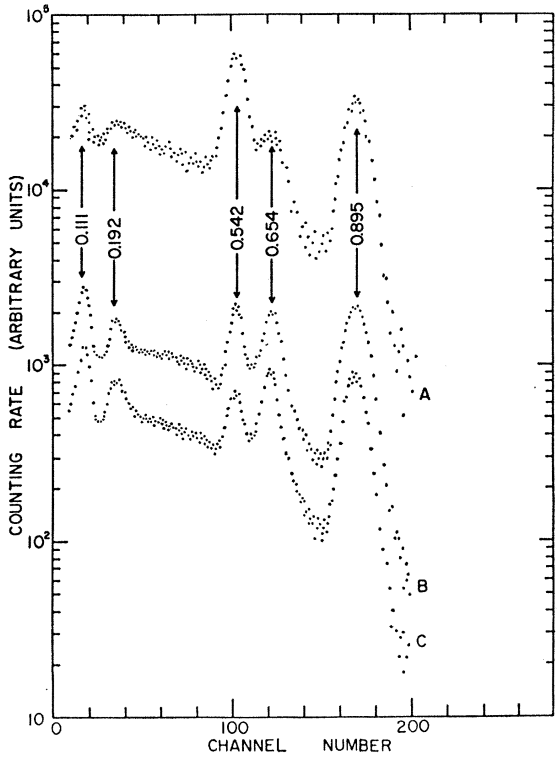

FIG. 4. Gamma spectrum in coincidence with A: 0.111-MeV gamma ray, B: 0.192-MeV gamma ray, and C: region at 0.3 MeV used to estimate Compton contributions to the 0.192-MeV gamma ray. Analyzer gated by pulse from NaI detector.

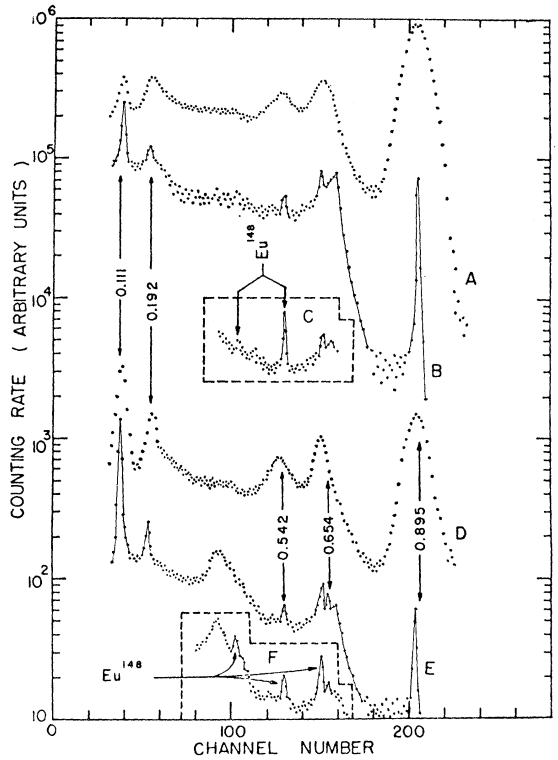

FIG. 5. Gamma spectrum in coincidence with A: 0.654-MeV gamma ray using NaI detector, B: 0.654-MeV gamma ray using Ge detector, C: 0.654-MeV gamma ray as in B but 10 days later, D: 0.511 and 0.542-MeV gamma rays using NaI detector, E: 0.511 and 0.542-MeV gamma rays using Ge detector, F: 0.511 and 0.542-MeV gamma rays as in E but 10 days later. Analyzer gated by pulse from NaI detector.

with the gamma ray at 1.994 MeV, but no conclusions concerning its exact nature could be drawn.

VI. INTERNAL-CONVERSION-ELECTRON SPECTRUM

Conversion electrons were observed using two permanent-magnet spectrographs covering the energy ranges 0.01 to 0.3 and 0.1 to 2.5 MeV, respectively. The photographically recorded spectra were calibrated using well-known conversion lines in I^{131}, Cs^{137}, and ThB. The conversion-electron energies were calculated, and from them the corresponding gamma-ray energies were determined using atomic binding energies tabulated by Hagstrom.[15] Because of difficulty in making strong thin sources for the spectrographs the energies of only four lines were measured. These energies are given in Table I. Conversion lines from Eu^{147} were also noted on the plates.

Conversion-electron spectra were also obtained using a 180° shaped field magnetic spectrometer of the Indiana type[16] with a 10-cm radius of curvature. The electrons were detected by a silicon-surface-barrier detector under a reverse bias of 150 V. Both source and detector were in the shape of rectangles 1 mm×1 cm, and the resolution of the spectrometer was about 1.2%. Conversion lines measured by the permanent-magnet spectrographs were used as calibration points. The K conversion line from the 1.659-MeV transition in Eu^{145} was used as a high-energy calibration point.

The region from 0.03 to 1.7 MeV was scanned several times to determine the origin of various lines. The conversion-electron spectrum from 0.03 to 0.55 MeV is shown in Fig. 6 and the spectrum from 0.50 to 1.7 MeV is shown in Fig. 7. Lines due to Eu^{147}, Eu^{148}, Eu^{149}, and

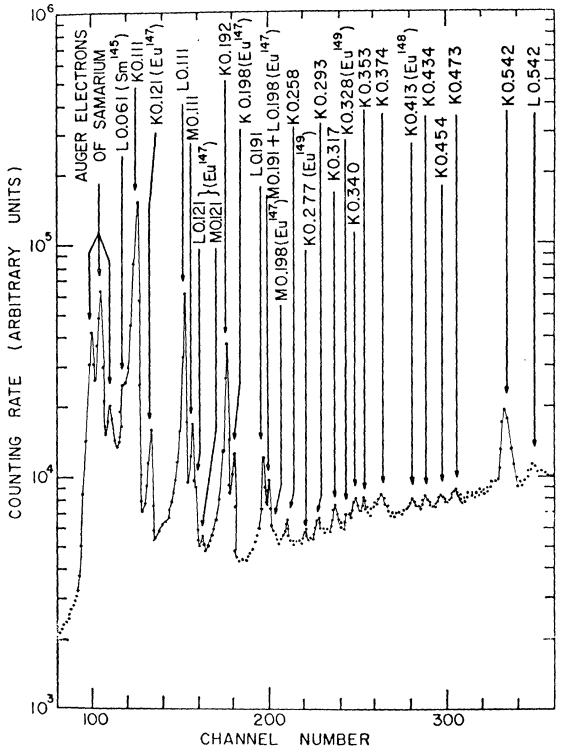

FIG. 6. Spectrum of conversion electrons with energies from 0.03 to 0.55 MeV accompanying decay of Eu^{145}.

Sm^{145} were also observed. Energies and errors measured for the various transitions in Eu^{145} are given in Table I. Errors were estimated from the reproducibility of all measurements.

Several transitions not seen in the germanium-detector spectra because of large Compton background appeared in the conversion-electron spectra. Nine weak K conversion lines were observed representing transitions with energies between 0.25 and 0.48 MeV. The half-life of these lines was approximately the same as that of Eu^{145}, but it was possible to incorporate only one of the lines into the decay scheme because of low intensities and lack of coincidence data on the high-energy transitions.

[15] S. Hagstrom, C. Nordling, and K. Siegbahn, in *Alpha-, Beta-, and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1964), Appendix 2.

[16] L. M. Langer and C. S. Cook, Rev. Sci. Instr. **19**, 257 (1948).

TABLE III. Multipolarity assignments to several transitions.

Transition energy (MeV)	Measured quantity	Experimental[a]	Theoretical[a] $E1$	$E2$	$M1$	Assignment
0.111	α_K	9.1±4.8(−1)	1.4(−1)	6.8(−1)	8.8(−1)	$M1+E2$
	K/L	5.4±1.0(0)	7.4(0)	1.6(0)	7.9(0)	
0.192	α_K	1.2±0.8(−1)	4.3(−2)	1.8(−1)	2.3(−1)	$E1$ or
	K/L	8.1±2.0(0)	7.5(0)	3.2(0)	8.0(0)	$M1+E2$
0.542	α_K	2.6±1.5(−3)	2.9(−3)	8.6(−3)	1.4(−2)	$E1$
	α_{LM}	4.9±3.5(−4)	5.1(−4)[b]	1.9(−3)[b]	2.7(−3)[b]	
0.654	α_K	1.6±0.5(−3)	2.0(−3)	5.5(−3)	8.8(−3)	$E1$
	α_{LM}	2.2±1.2(−4)	3.5(−4)[b]	1.1(−3)[b]	1.7(−3)[b]	
0.766	α_K	5.2±2.8(−3)	1.5(−3)	3.7(−3)	6.0(−3)	$M1+E2$
	α_{LM}	1.3±1.0(−3)	2.4(−4)[b]	7.0(−4)[b]	1.1(−3)[b]	
0.895	α_K	2.5±0.4(−3)	1.1(−3)	2.6(−3)	4.3(−3)	$M1+E2$
	α_{LM}	4.7±1.0(−4)	1.7(−4)[b]	4.4(−4)[b]	7.0(−4)[b]	
1.083	α_K	2.2±1.3(−3)	7.7(−4)	1.8(−3)	2.7(−3)	$M1+E2$
1.659	α_K	7.8±2.5(−4)	3.6(−4)	7.7(−4)	1.0(−3)	$M1+E2$

[a] The numbers within the parentheses give the power of 10 by which the preceding number should be multiplied.
[b] The M coefficient of Rose [M. E. Rose, *Internal Conversion Coefficients* (North-Holland Publishing Company, Amsterdam, 1958)] reduced by a factor of 2 to roughly correct for screening [Y. Y. Chu and M. L. Perlman, Phys. Rev. **135**, B319 (1964)] was used. Error in theoretical LM coefficients is about 10%.

These lines probably represent transitions between weakly populated levels from 1.4 to 2.5 MeV.

Because of high background from Compton and scattered electrons the intensity of the conversion-electron peaks was determined by measuring the area under each peak and subtracting out the visually estimated background. The peak area was divided by $B\rho$ at the peak to give the correct relative intensity. A correction of the intensity of conversion lines below 0.52 MeV was necessary because of the loss of small pulses due to discrimination against noise from the surface-barrier detector. In order to determine an approximate intensity correction beta spectra of P^{32} and Ca^{45} were measured, and the correction factor needed to linearize their Kurie-Fermi plots was determined.

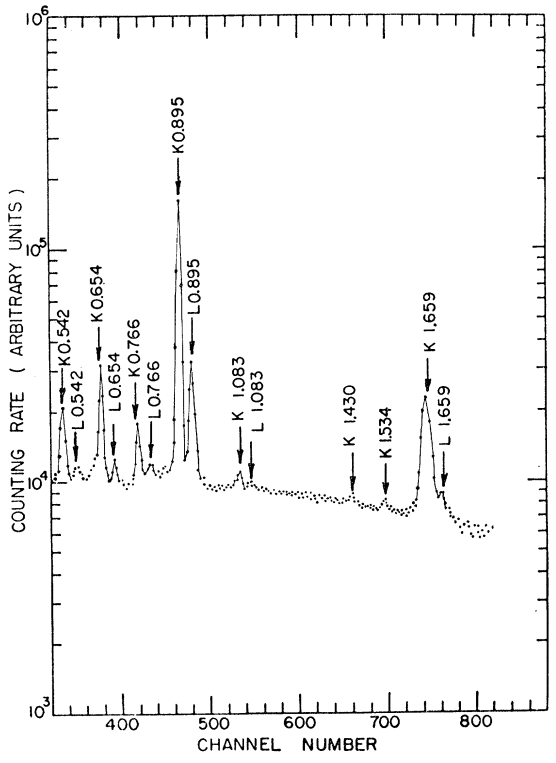

FIG. 7. Spectrum of conversion electrons with energies from 0.5 to 1.7 MeV accompanying decay of Eu^{145}.

The relative intensities of the K conversion-electron lines are given in Table I. The errors reflect the uncertainty in the determination of detector efficiency and background. An additional uncertainty arises in the determination of the intensity of the 0.542-MeV transition due to a contribution from the strong Eu^{148} transition at 0.551 MeV.

VII. INTERNAL-CONVERSION COEFFICIENTS AND TRANSITION MULTIPOLARITIES

The K conversion coefficient for the 0.895-MeV transition was measured directly using the well-known K conversion coefficient of the 0.899-MeV gamma ray of Y^{88} as a standard. The gamma and conversion-electron spectra of both isotopes were measured. Since identical counting geometry was used for each isotope the efficiency factors were almost the same and cancelled in the expression for the conversion coefficient. The 0.899-MeV transition in Y^{88} is known to be $E1$ in character,[17] therefore, the theoretical conversion coeffi-

[17] Ernest D. Klema, Phys. Rev. **102**, 449 (1956).

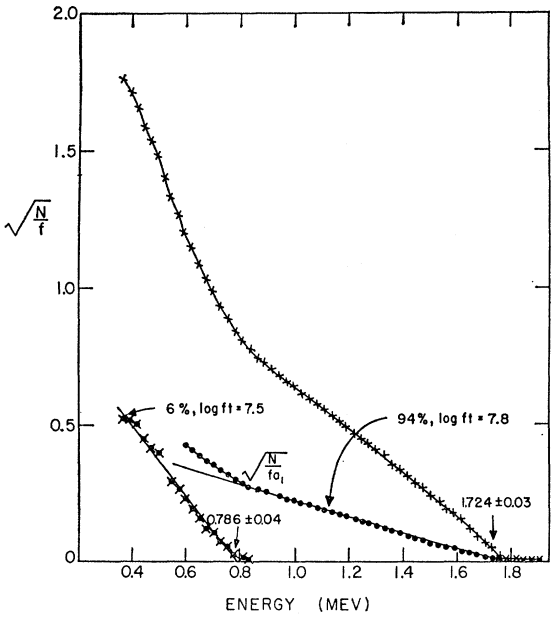

FIG. 8. Fermi analysis of the positron spectra accompanying decay of Eu^{145}. The first-forbidden unique correction has been applied to the high-energy group.

cient given by Sliv and Band[18] was used. The conversion coefficient for the 0.895-MeV transition in Eu^{145} was measured to be $(2.5\pm0.4)\times10^{-3}$ indicating the radiation to be $E2$ in character. A small $M1$ admixture could not be ruled out because of the large error.

The conversion coefficients for seven other transitions in Eu^{145} were determined using the value of the 0.895-MeV transition coefficient as a standard. The errors arose primarily from the errors in the gamma-ray and conversion-electron intensities. The experimentally determined K/L ratios and conversion coefficients and the multipolarities associated with them are shown in Table III. The theoretical coefficients given were interpolated from the tables of Sliv and Band.[18]

Both Antoneva *et al.*[5] and Zhelev and Muziol[8] proposed the 0.895-MeV transition to be pure $E2$ and the 0.111-MeV transition to be a $M1$-$E2$ mixture. Zhelev and Muziol also proposed the 0.192-MeV transition to be an $E1$-$M2$ mixture. These proposals are consistent with but more definite than the proposals of this experiment.

VIII. POSITRON SPECTRUM

The positron spectrum of Eu^{145} was measured using the 180° magnetic spectrometer. The spectrometer was calibrated by using conversion lines of known energy in Eu^{145} gamma rays. Interference from positron groups in other europium isotopes was negligible.

The resulting spectrum was analyzed as shown in Fig. 8. Two positron groups with end-point energies of 1.724 ± 0.030 and 0.786 ± 0.040 MeV and relative intensities of about 94% and 6%, respectively, were observed. Zhelev and Muziol[8] observed relative intensities of 74% and 26%, respectively, for the high- and low-energy positron groups, in disagreement with the results given here. They determined the logft value for the high-energy group to be 8.9. The Fermi plot of the high-energy group was definitely nonlinear. Application of the appropriate shape factor showed the group to be probably unique first-forbidden in character. The measured logf_1t value of 7.8 is compatible with logf_1t values for other unique first-forbidden transitions from nuclei in the rare-earth region.[12]

IX. DECAY SCHEME AND DISCUSSION

The gamma and conversion-electron transition energies and intensities and their coincidence relationships have been interpreted on the basis of the decay scheme shown in Fig. 9. The ground state of Eu^{145} was determined to be 2.75 ± 0.04 MeV above the ground state of Sm^{145}. This result is consistent with the prediction of Yamada.[19] The first-excited state of Sm^{145} was proposed at 0.895 MeV. This choice is consistent with the high intensity of the 0.895-MeV gamma ray, the large

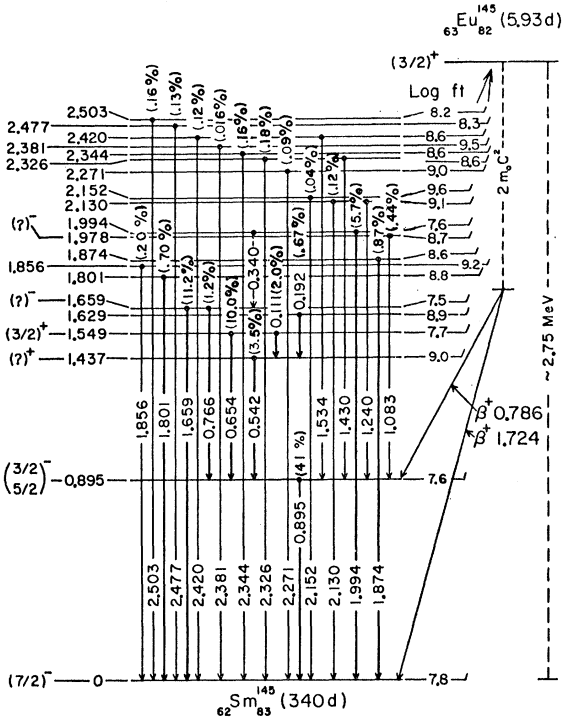

FIG. 9. Proposed decay scheme of Eu^{145}. The 0.340-MeV transition is dashed to express the uncertainty in the existence of this line.

[18] L. A. Sliv and I. M. Band, in *Alpha-, Beta-, and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1964), Appendix 5.

[19] M. Yamada and Z. Matumoto, J. Phys. Soc. Japan **16**, 1497 (1961).

TABLE IV. Absolute beta-decay branch intensities and logft values.

Level energy (MeV)	Electron captures per 100 decays	Positrons per 100 decays	Logft this work	Logft Ref. 8
0	31[a]	7.9[a]	7.8[c]	8.9
0.895	25[a]	0.5[a]	7.6	7.5 or 8.0
1.437	0.80[b]		9.0[b]	8.3
1.549	12.0		7.7	7.5
1.629	0.65		8.9[d]	8.5
1.659	12.5		7.5	7.4
1.801	0.70		8.8[d]	
1.856	0.20		9.2[d]	
1.874	0.87		8.6[d]	8.0
1.978	0.43		8.7[d]	
1.994	5.7		7.6	7.3
2.130	0.12		9.1[d]	
2.152	0.04		9.6[d]	
2.271	0.09		9.0[d]	
2.326	0.18		8.6[d]	
2.344	0.16		8.6[d]	
2.381	0.016		9.5[d]	7.5
2.420	0.12		8.6[d]	
2.477	0.13		8.3[d]	
2.503	0.16		8.2[d]	

[a] Theoretical capture-to-positron ratios were used.
[b] The feeding to this level could be zero within experimental error.
[c] Logft was calculated using first-forbidden corrections given in Ref. 22.
[d] These logft values could be changed considerably by the unplaced gamma transitions with energies between 0.25 and 0.48 MeV. The intensity of these transitions is of the same order of magnitude as that of the transitions above 2.0 MeV.

number of gamma rays in coincidence with the 0.895-MeV gamma ray, and the difference in end-point energy of the two positron groups. The conditions given above demand that all transitions of energy greater than 1.85 MeV proceed directly to the ground state.

The transitions with energies of 0.766, 1.240, 1.430, and 1.534 MeV are in coincidence with only the 0.895-MeV transition. Cross-over transitions were observed in each case establishing levels at 1.659, 2.130, 2.326, and 2.420 MeV, respectively. The relatively intense 1.659-MeV transition is not in coincidence with any transition and thus proceeds directly to the ground state. The 0.654- and 1.083-MeV transitions are also in coincidence only with the 0.895-MeV transition establishing levels at 1.549 and 1.978 MeV, respectively. No transition was observed from the levels at 1.549 and 1.978 MeV to the ground state.

The transitions at 0.111 and 0.542 MeV are in coincidence with each other but not with the 0.654-MeV transition. All three are in coincidence with the 0.895-MeV transition indicating that the 0.654-MeV transition crosses over the 0.111- and 0.542-MeV transitions to the 0.895-MeV level. The 0.542-MeV transition is more intense than the 0.111-MeV transition establishing a level at 1.437 MeV. The 0.192-MeV transition is in coincidence with the 0.895- and 0.542-MeV transitions but not with the 0.654- and 0.111-MeV transitions. The 0.192-MeV transition thus originates from a level at 1.629 MeV.

The transitions at 1.801 and 1.856 MeV proceed directly to the ground state, since the 0.895-MeV transition is not in coincidence with any gamma rays above 1.6 MeV, and no levels are postulated between 0.9 and 1.4 MeV. The weak transitions from 0.25 to 0.48 MeV observed in the conversion-electron spectra probably represent transitions between the many levels from 1.4 to 2.6 MeV. Due to lack of coincidence information and uncertainties in energies it was not possible to fit these transitions into the decay scheme in a unique manner. These weak transitions were observed in the conversion-electron spectrum but not in the gamma spectrum. The transition at 0.340 MeV appeared in coincidence with the 1.659-MeV transition and is assumed to originate at the 1.994-MeV level, but this assignment is uncertain. Kenefick and Sheline[20] have recently observed the levels of Sm^{145} populated through the reaction $Sm^{144}(d,p)Sm^{145}$. Their results agree rather well with this work with some exceptions. This is not surprising since the levels were populated by different mechanisms.

Logft values were calculated for the beta transitions using Moszkowski's graphs[21] and allowed approximations. Results indicate that most of the transitions are first-forbidden in character. The first-forbidden unique correction given by Davidson[22] was applied only to the beta transition feeding the ground state. The absolute beta-decay branch intensities are given in Table IV. Also the resulting logft values are compared with those of Zhelov and Muziol.[8] It is evident that their values are consistently lower than the ones given in this work with the exception of the value for the ground state.

The ground-state spin and parity of Sm^{145} is assumed to be $\frac{7}{2}^-$. This is consistent with the single-particle prediction and with the spin and parity of the ground state of Ce^{141} which also contains 83 neutrons and an even number of protons. Since the ground-state positron group is first forbidden unique in character the ground state of Eu^{145} must be $\frac{3}{2}^+$ or $11/2^+$. The value $\frac{3}{2}^+$ was chosen since $11/2^+$ is inconsistent with the predictions of the shell model.

Demeter *et al.*[7] measured the angular correlation between the 0.895- and 0.654-MeV gamma rays obtaining a value of $+0.045\pm0.010$ for the parameter A_2. His result is consistent with spins of $\frac{3}{2}$ and 11/2 for the level at 1.549 and $\frac{3}{2}$, $\frac{5}{2}$, and $\frac{9}{2}$ for the level at 0.895 MeV. Since the logft values for the electron-capture transitions feeding these levels are 7.7 and 7.6, respectively, the spin of the 1.549-MeV level is $\frac{3}{2}$, and the spin of the 0.895-MeV level is $\frac{3}{2}$ or $\frac{5}{2}$. Aleksandrov and Bemer[23] measured the angular correlation between the 0.895- and 0.111-MeV gamma rays. The 0.895- and 1.659-MeV transitions are $M1$-$E2$ in character indicating the levels at 0.895 and 1.659 MeV to have negative parity. The

[20] R. A. Kenefick and R. K. Sheline, Phys. Rev. **139**, B1479 (1965).
[21] S. A. Moszkowski, Phys. Rev. **82**, 35 (1951).
[22] J. P. Davidson, Jr., Phys. Rev. **82**, 48 (1951).
[23] Y. A. Alexsandrov and B. Bemer, Izv. Akad. Nauk SSSR, Ser. Fiz. **26**, 1159 (1962) [English transl.: Bull. Acad. Sci. USSR **26**, 1171 (1963)].

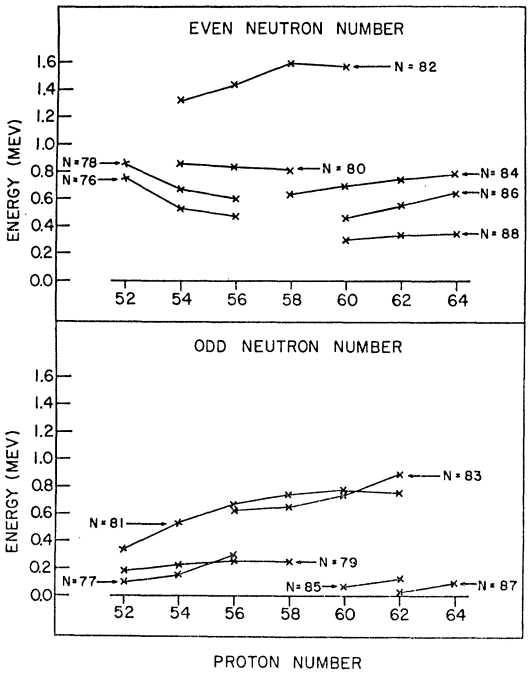

FIG. 10. Energy systematics of first excited states for nuclei with even proton number and neutron number near the closed shell at 82.

0.654- and 0.542-MeV transitions are $E1$ in character indicating the levels at 1.549 and 1.437 MeV to have positive parity. The $M1$-$E2$ character of the 1.083-MeV transition indicates the level at 1.978 MeV to have negative parity. These spin and parity assignments are tentative.

The energies of the first excited states of nuclei with even proton number and a neutron number near 82 are plotted in Fig. 10 as a function of proton number. The energy is about 1.5 MeV for 82 neutrons and decreases slightly with proton number. With the addition of a single neutron above the closed shell at 82 the energy decreases by about a factor of two. The energy also decreases with proton number. The variation of energy with proton number is not consistent with single-neutron excitation. The Sm^{145} first excited state is probably $\frac{3}{2}^-$ or $\frac{5}{2}^-$. Spins of first excited states of other nuclei with 83 neutrons are unknown except for the case of Nd^{143}. In this case the state is $\frac{5}{2}^-$ or $\frac{7}{2}^-$.[12] One would expect the single-neutron state to be $\frac{9}{2}^-$.

The energy for the first excited states of nuclei with 81 neutrons decreases sharply with proton number. This behavior is contrary to the predictions of the shell model even though all of these states are $11/2^-$ in character. As one gets further away from the closed shell of 82 neutrons the first-excited-state energies become progressively lower, and quadrupole forces play an increasingly important role. This trend is evident in Fig. 10.

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