Decay of 5.9-Day ^{145}Eu to Levels in ^{145}Sm†

E. Newman and K. S. Toth
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830
and
I. R. Williams
Knoxville College, Knoxville, Tennessee 37921
(Received 26 April 1970)

The level structure of ^{145}Sm was studied by observing the electron-capture decay of 5.9-day ^{145}Eu. The radioactive source was prepared by bombarding ^{144}Sm with protons accelerated in the Oak Ridge isochronous cyclotron. Both singles and γ-γ coincidence spectra were measured. From these measurements, transition energies were obtained to an accuracy better than previously available and the following new transitions were assigned to the decay of ^{145}Eu: 519.4, 526.2, 713.9, 910.3, 949.9, ~1625, 2340.8, 2508.1, and 2513.0 keV. Because of decay-energy considerations the latter three transitions establish the existence of new ^{145}Sm levels at 2340.8, 2508.1, and 2513.0 keV. From the coincidence data, levels at 1607.6 ($\frac{1}{2}^-$) and 1843.6 ($\frac{1}{2}$, $\frac{3}{2}^-$) keV were also established; these states apparently correspond to those previously observed in ^{144}Sm(d, p) studies at about 1611 and 1854 keV. A survey of available data for $N=83$ isotones (^{137}Xe$\rightarrow$^{147}Gd) indicated a systematic shift in excitation energy for seven rather well-established single-neutron states as their location was traced from nuclide to nuclide. On this basis it was then possible to predict in ^{137}Xe, ^{141}Ce, and ^{147}Gd the approximate excitation energies of some of these so far unreported states.

I. INTRODUCTION

The level structure of ^{145}Sm has been investigated by nuclear-reaction studies and by the electron-capture decay of 5.9-day ^{145}Eu. Information gathered in these studies was summarized in a 1967 compilation[1] and subsequently in a publication by Adam *et al.*[2] An interesting feature observed in the decay of ^{145}Eu is the presence of numerous high-energy transitions that proceed directly to the ^{145}Sm ground state. The recent availability of large-volume Ge(Li) detectors suggested that a new investigation of the ^{145}Eu γ-ray spectrum, with particular emphasis on the high-energy portion, could lead to some new and useful information.

II. EXPERIMENTAL METHOD AND RESULTS

A radioactive source of ^{145}Eu was made via the reaction ^{144}Sm(p, γ) by irradiating samarium oxide, enriched in ^{144}Sm to 94.54%, with 9-MeV protons accelerated in the Oak Ridge isochronous cyclotron. The proton energy was kept below the threshold for the reaction ^{147}Sm$(p, 2n)$ so that the interfering activity, ^{146}Eu (4.6 day), could not be produced. Chemical separations were not made. Short-lived activities produced from oxygen in the target material were of no concern because measurements were begun one day after the end of bombardment. γ rays from the nuclides ^{147}Eu (24 day) and ^{148}Eu (54 day) were observed and recognized because of their distinct half-lives.

Spectra were measured with a 35-cm^3 coaxial Ge(Li) detector and stored in a 4096-channel analyzer. Energy calibrations for these singles measurements were made by using a ^{226}Ra standard source. Up to an energy of 1620 keV, however, the ^{148}Eu present in the source served as an internal calibration standard. Accurate energies and intensities for both ^{148}Eu and ^{226}Ra transitions were taken from the work of Gunnink *et al.*[3] A computer code was used to analyze the spectra and to obtain γ-ray energies and intensities.

Nine new transitions were observed. Four of these can be seen in Fig. 1, which shows a portion ($\gtrsim$1.5 MeV) of a singles spectrum taken a week after bombardment. The previously reported 2510-keV transition is seen in reality to be two transitions with energies of 2508.1 and 2513.0 keV. Two other new transitions can be seen at energies of 2340.8 and ~1625 keV. In the lower-energy part of the singles spectrum the following new transitions were observed: 519.4, 526.2, 713.9, 910.3, and 949.9 keV.

The singles measurements were made intermittently over a period of a month so that isotopic assignments could be made. In the interim periods γ-γ coincidence spectra were obtained to determine γ rays in coincidence with the 893.7-keV transition which deexcites the first-excited state of ^{145}Sm. Measurements were made initially with a 3×3-in. NaI(Tl) crystal spectrometer and a 20-cm^3 Ge(Li) detector. Later, to improve the resolution capabilities of the system, the 35- and 20-cm^3 Ge(Li) detectors were used.

Fourteen coincident γ rays were observed; their energies are as follows: 110.9, 191.4, 519.4, 526.2, 542.6, 653.5, 713.9, 764.8, 838.5, 910.3, 949.9, 1078.6, 1240.5, and 1532.3 keV. Of these, the 519.4-, 526.2-, 713.9-, 910.3-, and 949.9-keV γ rays represent transitions reported for the first time. Also, the 838.5-keV transition has not been reported in any other coincidence measurements. The new information is seen in Fig. 2, where we show the spectrum (from ~0.5 to ~1.3 MeV) observed when the NaI(Tl) spectrometer was used for the energy-gating channel. A singles spectrum is included for comparison. With the improved resolution obtained in the Ge(Li)-Ge(Li) experiment the 519.4- and 526.2-keV γ rays were resolved as shown in the inset in Fig. 2.

Table I summarizes the energies and intensities measured for transitions observed in our γ-ray spectra. Intensities were converted to percent of all decays by utilizing a value of 47.5% for the 893.7-keV γ ray, as reported recently by Chu, Franz, and Friedlander.[4] K-shell conversion-electron intensities for the transitions observed in the present study were taken from published sources (as collated in Ref. 2). These electron intensities were also converted to absolute values by assuming the 893.7-keV transition to be pure $E2$ in character. Conversion coefficients were then calculated in instances where photon and electron intensities were both available. By comparing these coefficients with theoretical ones,[5] probable multipolarity assignments were made for many of the transitions with energies <2 MeV. Uncertainties for the electron intensities[6] of higher-energy transitions are so large that meaningful multipolarities cannot be assigned to them.

III. DECAY SCHEME AND DISCUSSION

The proposed decay scheme (see Fig. 3) incorporates all but four of the transitions listed in Table I. It is based not only on the present results but also on data available from reaction studies and on the e-γ and β^+-γ coincidence measurements

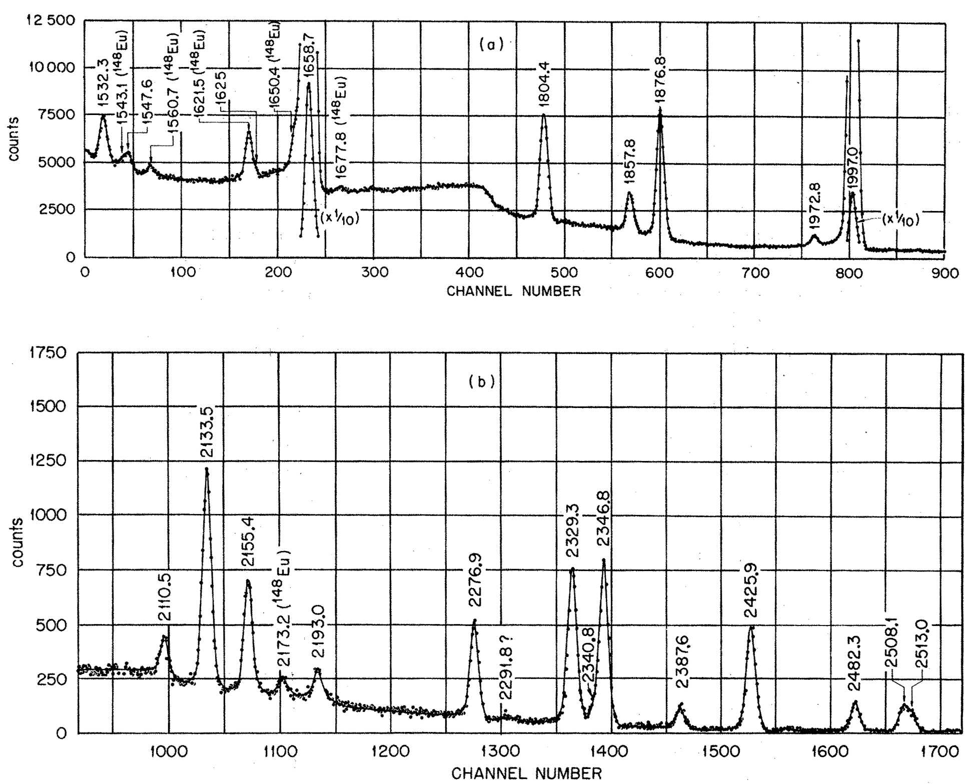

FIG. 1. (a) Singles γ-ray spectrum (from ~1.52 to ~2.05 MeV). Peaks labeled by energy only are assigned to ^{145}Eu decay. (b) Singles γ-ray spectrum (from ~2.05 to ~2.54 MeV). Peaks labeled by energy only are assigned to ^{145}Eu decay.

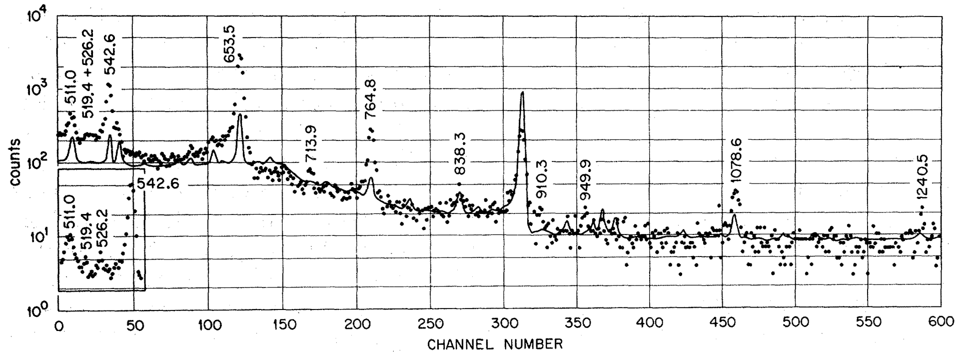

FIG. 2. Portion of a spectrum observed in coincidence with the 893.7-keV transition. A 3×3-in. NaI(Tl) crystal spectrometer was used to set the single-channel window. The full curve, normalized to the data points, is a singles γ-ray spectrum which is included for comparison. The inset shows a small portion of the coincident spectrum measured when a 20-cm^3 Ge(Li) crystal was used to set the energy gate. Peaks labeled by energy are believed to represent true coincidences.

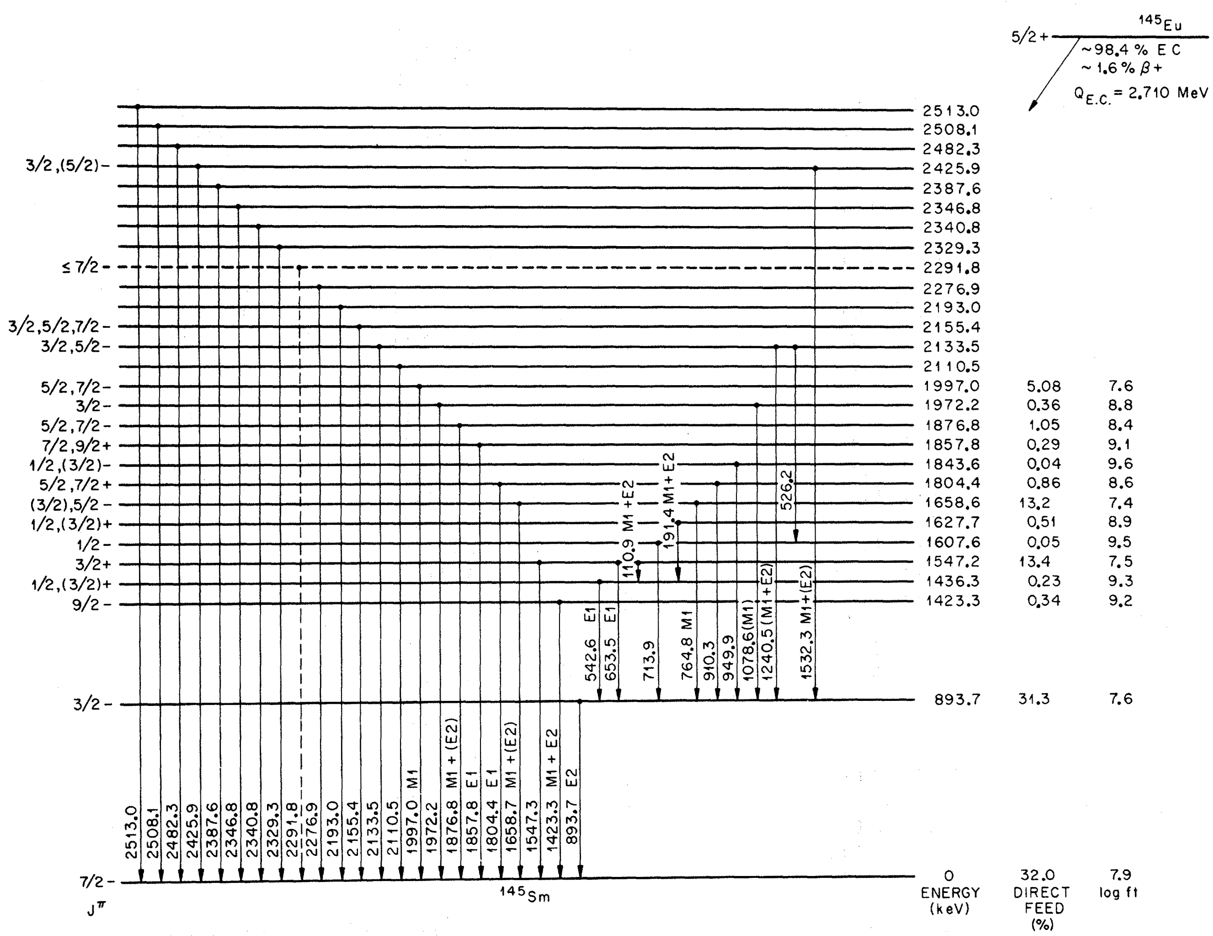

FIG. 3. Proposed ^{145}Eu decay scheme.

of Adam *et al.*[2] In particular, the β^+-γ results show that the ^{145}Eu decay energy is 2.71 MeV. Then, because the ^{145}Sm first excited state is at 893.7 keV, all transitions with energies $\gtrsim$1.82 MeV must proceed directly to ground and must, therefore, establish levels with the same energies. Many of the spin assignments were made by considering (d, p) angular distribution data[7,8] and by requiring that they be consistent with transition multipolarities.

A comparison is made in Table II between the proposed level scheme and the information available from ^{144}Sm(d, p) investigations.[7-9] One striking feature to note in Table II is that the positive-parity states seen in the decay of ^{145}Eu are not populated in the ^{144}Sm(d, p) reaction. This observation is consistent with shell-model considerations because the only positive-parity orbital in the $82 < N \leq 126$ neutron shell is the $i_{13/2}$ orbital, and it should not be excited with an appreciable cross section for low excitations in ^{145}Sm. In fact, no $l=6$ transfers have been observed in the ^{144}Sm(d, p) studies.[7,8] The positive-parity states seen in the present study probably result from neutron couplings to the 3^- core excitation. Evidence in favor of this possibility can be found by

TABLE I. Summary of transition data.

Energy (keV)	I_γ (% of decay)	$10^3 I_K$ (% of decay)	$10^3 \alpha_K$	Multipole order
110.9 ± 0.1	1.14 ± 0.10	1010 ± 50	886 ± 90	$M1+E2$
191.4 ± 0.1	0.41 ± 0.04	90 ± 13	219 ± 44	$M1+E2$
Annih. Rad.	3.12 ± 0.25			
519.4 ± 0.4	0.075 ± 0.020			
526.2 ± 0.2	0.14 ± 0.03			
542.6 ± 0.2	3.04 ± 0.19	9.5 ± 0.9	3.12 ± 0.31	$E1$
653.5 ± 0.1	11.0 ± 0.9	21.0 ± 2.0	1.91 ± 0.29	$E1$
713.9 ± 0.2	0.19 ± 0.04			
764.8 ± 0.2	1.20 ± 0.10	7.9 ± 0.9	6.58 ± 0.99	$M1$
838.5 ± 0.4	0.10 ± 0.03	0.76 ± 0.10	7.60 ± 2.05	
893.7 ± 0.2	47.5 [a]	127 [a]	2.68 [a]	$E2$ [a]
910.3 ± 0.5	0.05 ± 0.01			
949.9 ± 0.5	0.04 ± 0.01			
1078.6 ± 0.3	0.32 ± 0.04	1.2 ± 0.3	3.75 ± 1.15	$(M1)$
1240.5 ± 0.6	0.08 ± 0.02	0.11 ± 0.05	1.33 ± 0.70	$(M1+E2)$
1423.3 ± 0.3	0.34 ± 0.04	0.43 ± 0.10	1.26 ± 0.38	$M1+E2$
1532.3 ± 0.2	0.26 ± 0.04	0.34 ± 0.13	1.31 ± 0.66	$M1+(E2)$
1547.3 ± 0.4	0.11 ± 0.04			
1625.0 ± 1.0	~0.013			
1658.7 ± 0.2	11.9 ± 1.0	10.6 ± 0.9	0.89 ± 0.14	$M1+(E2)$
1804.4 ± 0.2	0.81 ± 0.08	0.29 ± 0.03	0.36 ± 0.05	$E1$
1857.8 ± 0.2	0.32 ± 0.05	0.15 ± 0.04	0.46 ± 0.18	$E1$ or $E2$
1876.8 ± 0.2	1.05 ± 0.10	0.81 ± 0.28	0.76 ± 0.28	$M1+(E2)$
1972.2 ± 0.2	0.04 ± 0.01	0.05 ± 0.03	1.25 ± 0.88	
1997.0 ± 0.2	5.08 ± 0.50	3.8 ± 0.4	0.74 ± 0.11	$M1$
2110.5 ± 0.3	0.035 ± 0.009	0.015 ± 0.015	0.43 ± 0.43	
2133.5 ± 0.2	0.17 ± 0.03	0.14 ± 0.04	0.82 ± 0.33	
2155.4 ± 0.2	0.09 ± 0.02			
2193.0 ± 0.3	0.03 ± 0.01	0.037 ± 0.019	1.23 ± 0.80	
2276.9 ± 0.5	0.08 ± 0.02	0.019 ± 0.014	0.24 ± 0.19	
(2291.8 ± 1.8) [b]	<0.003	0.0066 ± 0.0066		
2329.3 ± 0.3	0.14 ± 0.02	0.057 ± 0.024	0.41 ± 0.20	
2340.8 ± 0.5	0.018 ± 0.006			
2346.8 ± 0.4	0.14 ± 0.02	0.090 ± 0.052	0.64 ± 0.45	
2387.6 ± 0.3	0.021 ± 0.002	0.047 ± 0.023	2.24 ± 1.34	
2425.9 ± 0.3	0.10 ± 0.01	0.089 ± 0.028	0.89 ± 0.31	
2482.3 ± 0.3	0.024 ± 0.004			
2508.1 ± 0.4	0.022 ± 0.003			
2513.0 ± 0.4	0.017 ± 0.002			

[a] Fiducial transition; assumed to be pure $E2$.

[b] Energy taken from the conversion-electron data of Ref. 6.

considering the total intensities of transitions (see Table I) that deexcite the positive-parity levels at 1547.2 and 1627.7 keV. In the case of the $\frac{3}{2}^+$ 1547.2-keV level, the indication is that the 653.5-keV $E1$ transition to the $\frac{3}{2}^-$ state at 893.7 keV is hindered relative to the 110.9-keV $M1+E2$ transition which proceeds to the positive-parity state at 1436.3 keV. Similarly, only the 191.4-keV $M1+E2$ transition to the 1436.3-keV level is observed to deexcite the state at 1627.7 keV; because of the absence of the $E1$ transition to the 893.7-keV state, it too must be retarded. It appears then that these three positive-parity states are similar in character and apparently different from the single-neutron $\frac{3}{2}^-$ state at 893.7 keV.

TABLE II. Comparison of proposed level scheme with data from reaction studies.

Present study Level energy (keV)	Present study J^π	^{144}Sm(d,p) data Level energy (keV) Ref. 9	J^π Ref. 7	J^π Ref. 8
0	$\frac{7}{2}^-$	0	$\frac{7}{2}^-$	$\frac{7}{2}^-$
893.7 ± 0.2	$\frac{3}{2}^-$	895 ± 4	$\frac{3}{2}^-$	$\frac{3}{2}^-$
		1108 ± 4	$\frac{9}{2}^-$	$\frac{9}{2}^-$
1423.3 ± 0.3	$\frac{9}{2}^-$	1427 ± 6	$\frac{9}{2}^-$	$\frac{9}{2}^-$
1436.3 ± 0.4	$\frac{1}{2}, (\frac{3}{2})^+$			
1547.2 ± 0.3	$\frac{3}{2}^+$			
1607.6 ± 0.7	$\frac{1}{2}^-$	1611 ± 9	$\frac{3}{2}^-$	$\frac{1}{2}^-$
1627.7 ± 0.5	$\frac{1}{2}, (\frac{3}{2})^+$			
1658.6 ± 0.2	$(\frac{3}{2}), \frac{5}{2}^-$	1665 ± 8	$\frac{5}{2}^-$	$\frac{3}{2}^-$
		1784 ± 8		$\frac{9}{2}^-$
1804.4 ± 0.2	$\frac{5}{2}, \frac{7}{2}^+$			
		1810 ± 8		
1843.6 ± 0.7	$\frac{1}{2}, (\frac{3}{2})^-$	1854 ± 9	$\frac{3}{2}^-$	$\frac{1}{2}, \frac{3}{2}^-$
1857.8 ± 0.2	$\frac{7}{2}, \frac{9}{2}^+$			
1876.8 ± 0.2	$\frac{5}{2}, \frac{7}{2}^-$	1883 ± 8	$\frac{5}{2}^-$	$\frac{5}{2}, \frac{7}{2}^-$
1972.2 ± 0.2	$\frac{3}{2}^-$	1979 ± 8		$\frac{3}{2}^-$
1997.0 ± 0.2	$\frac{5}{2}, \frac{7}{2}^-$	2002 ± 8	$\frac{5}{2}^-$	$\frac{5}{2}, \frac{7}{2}^-$
2110.5 ± 0.3		2112 ± 14		
2133.5 ± 0.2	$\frac{3}{2}, \frac{5}{2}^-$	2138 ± 9		$\frac{3}{2}, \frac{5}{2}, \frac{7}{2}^-$
2155.4 ± 0.2	$\frac{3}{2}, \frac{5}{2}, \frac{7}{2}^-$	2164 ± 9	$\frac{1}{2}^-$	$\leq\frac{7}{2}^-$
2193.0 ± 0.3		2199 ± 16		
2276.9 ± 0.5				
2291.8 ± 1.8	$\leq\frac{7}{2}^-$	2297 ± 9		$\leq\frac{7}{2}^-$
2329.3 ± 0.3				
2340.8 ± 0.5, 2346.8 ± 0.4 }		2349 ± 10		
2387.6 ± 0.3		2390 ± 10		
2425.9 ± 0.3	$\frac{3}{2}, (\frac{5}{2})^-$	2429 ± 10		$\leq\frac{7}{2}^-$
2482.3 ± 0.3		2488 ± 15		
2508.1 ± 0.4, 2513.0 ± 0.4 }		2512 ± 15		

The decay scheme shown in Fig. 3 is similar to the one proposed in Ref. 2. Aside from improved determinations of level energies, important differences and new pieces of information did come to light as a result of the present investigation.

Firstly, because of decay-energy considerations, three new transitions establish the existence of ^{145}Sm levels at 2340.8, 2508.1, and 2513.0 keV. Previously[1,2] the latter two were thought to be one level at 2510 keV. Kenefick *et al.*[9] saw a level at 2512 ± 15 keV which may correspond to one of the two states. The 2340.8-keV level is new so far as decay studies are concerned; Ref. 9 reports a level at 2349 ± 10 keV which may correspond to this state or the one at 2346.8 keV.

Secondly, our coincidence results establish levels at 1607.6 and 1843.6 keV; these states (reported for the first time in a decay scheme study) apparently correspond to those previously observed in (d, p) studies[7-9] at ~1611 and 1854 keV. The 1607.6-keV level is proposed because the new 713.9-keV γ ray is in coincidence with the 893.7-keV transition. The (d, p) angular distribution data indicate spin assignments of $\frac{1}{2}^-$ (Ref. 8) and $\frac{3}{2}^-$ (Ref. 7). The first assignment seems more probable because of the absence of the 1607.6-keV transition to ground. The evidence for the 1843.6-keV level is somewhat more complicated and must be considered in some detail, together with the previously known[1,2] level at 1857.8 keV. A $(\frac{1}{2}, \frac{3}{2}^-)$ level has been seen in (d, p) studies at ~1854 keV. Up to this time the 1857.8-keV transition has been assumed[1,2] to be the ground-state transition deexciting this particular level. The fact that this low-spin level apparently does not deexcite via a 964-keV transition to the first excited state is hard to understand. A 949.9-keV transition, however, was seen in this study, both in singles and coincidence spectra. Our suggestion then is that the (d, p) level is in actuality at 1843.6 keV and that since the transition to ground was not seen, its spin is $\frac{1}{2}^-$ rather than $\frac{3}{2}^-$. The 1857.8-keV transition, as proposed previously,[1,2] establishes a level of the same energy. Its K-shell conversion coefficient is midway between the theoretical $E1$ and $E2$ values. Regardless of the multipolarity the spin for the state must be high because the transition to the 893.7-keV state was not seen; the spin would be $\geq\frac{9}{2}^-$ for an $E2$ transition and $\frac{7}{2}^+$ or $\frac{9}{2}^+$ if the transition were $E1$ in char-

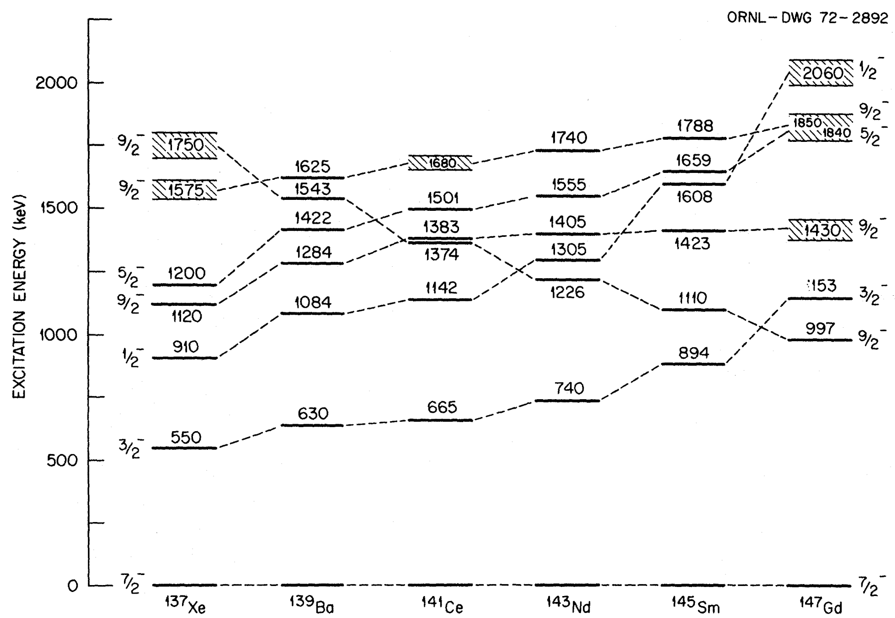

FIG. 4. Excitation energies of negative-parity levels for $N=83$ isotones. Dashed lines connect levels which are assumed to have basically the same neutron configuration. Cross-hatched areas indicate predicted excitation energies of several so far unreported levels.

acter. The positive parity is more probable because: (1) The only $\frac{9}{2}^-$ state observed in decay is the one at 1423.3 keV; (2) a high-spin level at ~1860 keV has not been seen in (d, p) studies; and (3) conversion-electron intensities for high-energy transitions (taken from Ref. 6) appear to be abnormally high so that the $E1$ assignment is probably correct.

Finally, we include a level at 2291.8 keV (shown dashed in Fig. 3) because: (1) A level at about the same energy has been seen in (d, p) studies; (2) a 2291.8-keV transition has been reported in a conversion-electron study[6]; and (3) there is some indication (see Fig. 1) of a peak in our γ-ray spectra at the same energy.

The percentages of direct decay to ^{145}Sm levels below 2 MeV were deduced from an intensity balance. They are shown in Fig. 3 together with $\log ft$ values calculated by using the nomogram and graph shown on pages 62 and 63, respectively, of Ref. 10. The only cascade transitions shown in Fig. 3 are those that could be placed on the basis of coincidence measurements. Possible placements for other low-energy transitions reported elsewhere (see Refs. 1 and 2) were not attempted because: (1) It is not clear which of these transitions do indeed belong to the decay of ^{145}Eu; and (2) within quoted energy limits, most of the transitions cannot be uniquely placed in the decay scheme. The $\log ft$ values calculated for the weakly populated levels below 2 MeV could therefore change drastically. In general, the $\log ft$ values indicated in Fig. 3 are consistent with spin and parity assignments suggested for the various ^{145}Sm states and with the $\frac{5}{2}^+$ assignment for the ^{145}Eu ground state proposed by Newman *et al.*[11]

In Fig. 4 we show negative parity levels of $N=83$ isotones at low and medium energies whose spins have been rather well established.[7,8,12-17] It is apparent that there are systematic shifts in the energies of these levels in going from ^{137}Xe to ^{147}Gd. Dashed lines drawn in the figure follow those states from nucleus to nucleus and are assumed to connect states that have basically the same neutron configuration. It may be noted that as the proton number increases, the excitation energies increase for all but one of these levels. This $\frac{9}{2}^-$ level comes down markedly in energy. On the basis of the systematic behavior, it is possible to predict the position of several unreported or unassigned levels. Their location is indicated by cross-hatched areas in the figure. Specifically the states are as follows: ^{137}Xe: a $\frac{9}{2}^-$ at 1575 ± 40 keV and a second $\frac{9}{2}^-$ at 1750 ± 100 keV; ^{141}Ce, a $\frac{9}{2}^-$ level at 1680 ± 30 keV; ^{147}Gd: two $\frac{9}{2}^-$ levels, one at 1430 ± 40 keV and the second at 1850 ± 50 keV; a $\frac{5}{2}^-$ at 1840 ± 50 keV; and a $\frac{1}{2}^-$ at 2060 ± 50 keV.

† Research sponsored by the U. S. Atomic Energy Commission under contract with Union Carbide Corporation.

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PHYSICAL REVIEW C VOLUME 7, NUMBER 1 JANUARY 1973

Hartree-Fock Calculations with Skyrme's Interaction. II. Axially Deformed Nuclei*

D. Vautherin

Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139,
and Institut de Physique Nucléaire, Division de Physique Théorique, Laboratoire Associé au Centre National de la Recherche Scientifique
91 Orsay, France

(Received 31 July 1972)

Skyrme's interaction is used in deformed Hartree-Fock calculations of some light and rare-earth nuclei. A method of solution is presented, which exploits as much as possible the simple features of the Skyrme force in order to allow calculations of heavy deformed nuclei. In the rare-earth region pairing correlations are taken into account in a simplified but self-consistent way by considering energy functionals depending also on occupation probabilities. Calculations have been made for the two parameter sets which were used in a previous study of double-closed-shell nuclei. The set providing the best fit to ground-state properties of spherical nuclei is also found to give a satisfactory description of nuclear deformations. Comparison is made with other available Hartree-Fock calculations in the case of light nuclei, and a discussion of the importance of various terms in the effective force upon nuclear deformations is given.

I. INTRODUCTION

Skyrme's interaction[1] has been shown in a previous paper[2] to give a very good description of ground-state properties of spherical nuclei in the Hartree-Fock approximation. In particular remarkable fits to binding energies, radii, and elastic electron scattering cross sections have been obtained. Also, single-particle level densities near the Fermi level were found to be reasonably close to the observed ones. Such an agreement has been shown to be related to the density dependence of the Skyrme force. Similar results were indeed obtained from other density-dependent effective forces[3,4] and from realistic Brueckner-Hartree-Fock calculations in the local density approximation.[5,6]

The purpose of this paper is to extend our previous investigations to deformed nuclei. As compared to earlier studies of nuclear deformations in the framework of the Hartree-Fock theory, the present calculations will be shown to achieve at