Isomers of Am^{242}†

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New measurements on the Am^{242} isomers show that the 16-hr activity is the ground state and the 152-yr activity the upper isomer, contrary to earlier evidence. By electrostatic collection techniques some 16-hr americium activity was separated from an aged sample containing the 152-yr isomer. Careful study of the conversion electron spectrum of the sample containing 152-yr Am^{242m} revealed eleven conversion lines of a 48.6-kev transition converted in americium, and the relative M-subshell conversion intensities are only consistent with an $E4$ assignment. This information, coupled with the recent atomic beam measurement of spin 1 for the 16-hr activity, leads to a spin assignment of 5 for Am^{242m}.

The experimental information on these isomers is given a detailed analysis in terms of the Bohr-Mottelson model. The most surprising conclusion of this analysis is that the spin 1 ground state has a K-quantum number of zero, and hence a negative spectroscopic quadrupole moment. Data on levels and decay of the low spin isomers of Ho^{166} and Ta^{180} are also considered and lead to the conclusion that there is generally an energy displacement, between odd and even spin members of $K=0$ rotational bands in odd-odd spheroidal nuclei.

I. INTRODUCTION

WHEN Am^{241} is irradiated with slow neutrons, a pair of isomers of Am^{242} is formed having half-lives of 16 hours and ~100 years.[1] (A more precise half-life measurement of the long-lived isomer is 152±7 years.[2]) Early measurements[3] on the 16-hour isomer showed the presence of L x rays of plutonium, americium, and curium, indicating that the decay included appreciable branching by three modes: electron capture, isomeric transition and β^- emission. Later work[4] showed that the "isomeric transition" was probably spurious, since the americium x rays could be accounted for by self-excitation of the L shell in Am^{241} by its alpha particles. However, the 16-hour isomer was still thought to be the metastable state, since its beta spectrum was found to have an end point slightly higher in energy than that of the long-lived isomer.

The most puzzling aspect of this work was the finding that the decay schemes for beta decay of the two isomers were virtually identical [see Fig. 1(a)]. For each, β^- decay led to the 0+ and 2+ states of the ground state rotational band of Cm^{242}, a situation quite out of keeping with a measurable—indeed, a very long—lifetime for the isomeric transition. The electron-capture branchings of the isomers were also apparently quite similar.

The experiments reported here[5] resolve these discrepancies by showing that the long-lived isomer is the metastable state, and that it decays principally by isomeric transition [see Fig. 1(b)]; hence the beta-decay properties associated with both isomers are simply those of the ground state. The minor differences in β^-/EC ratios for the isomers noted in the older work[4] can be shown to have disappeared in the light of the newer measurements[2,6] and only the apparent small discrepancy in beta-spectrum end points remains.

It may be well to point out why it is difficult to observe the isomeric transition (152-year $Am^{242m} \rightarrow$ 16-hour Am^{242}) unless one designs an experiment specifically with this decay sequence in mind. It happens that the long-lived Am^{242} isomer has a large neutron capture cross section, consequently a maximum concentration of only a few percent by activity can be built up in the Am^{241}. Since Am^{241} has abundant low-energy photon transitions associated with its alpha decay, special pains must be taken to observe the isomeric transition in Am^{242}. In addition, Am^{243} is always present and its decay product, Np^{239}, also obscures the picture.

With the supposition, based on previous work, that the radiations associated with the isomeric transition might be difficult to find, it seemed that the most direct way to establish the relationship was to effect a separation of isomers and to show that 16-hour Am^{242} is present long after conclusion of neutron irradiation. This experiment was successful and is described below. The radiations accompanying the isomeric transition were then found by employing high-resolution electron spectrometry. Part of the impetus for this study and an aid in the interpretation was the recent measurement of the spin of 16-hour Am^{242} by the atomic beam method.[7]

Although much progress has been made in the assignment of particle states in regions of high nuclear de-

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[1] National Nuclear Energy Series, Plutonium Project Record, Vol. *14B*, *The Transuranium Elements* (McGraw-Hill Book Company, Inc., New York, 1949): G. T. Seaborg, R. A. James, and L. O. Morgan, Paper No. 22.1, p. 1525; G. T. Seaborg, R. A. James, and A. Ghiorso, Paper No. 22.2, p. 1554; W. M. Manning and L. P. Asprey, Paper No. 22.7, p. 1595.

[2] R. F. Barnes, D. J. Henderson, A. L. Harkness, and H. Diamond, J. Inorg. & Nuclear Chem. **9**, 105 (1959).

[3] G. D. O'Kelley, G. W. Barton, W. W. T. Crane, and I. Perlman, Phys. Rev. **80**, 293 (1950).

[4] R. W. Hoff, H. Jaffe, T. O. Passell, F. S. Stephens, E. K. Hulet, and S. G. Thompson, Phys. Rev. **100**, 1403 (1955).

[5] A preliminary report of this work was given in the Bull. Am. Phys. Soc. **4**, 461 (1959).

[6] R. W. Hoff, E. K. Hulet, and M. C. Michel, J. Nuclear Energy **8**, 224 (1959).

[7] J. Winocur, R. Marrus, and W. A. Nierenberg, Bull. Am. Phys. Soc. **4**, 451 (1959).

formation,[8,9] little information has been available concerning the coupling of two odd particles in odd-odd nuclei. The information obtained here on Am^{242} has proved to be of importance in handling the general problem and this report contains a discussion of the subject.

II. EXPERIMENTAL

Am^{242} Source

The *long-lived* Am^{242} was prepared by neutron irradiation of Am^{241}. Since we now know that it is the metastable state, we shall henceforth refer to it as Am^{242m} and the 16-hour activity as Am^{242}. Both isomers are formed by slow-neutron capture and the overwhelmingly predominant activity soon after irradiation is 16-hour Am^{242}. However, the material used in the present experiments had aged for several years, so only long-lived activities (and their decay products) were present. Since Am^{242m} has a much higher neutron capture cross section than does Am^{241}, an effective steady-state concentration of about 1% is the highest that can be achieved without resorting to isotope separation.

The pertinent neutron reactions and decay processes are summarized as follows (the decay sequence,

$$Am^{242m} \xrightarrow[IT]{152\text{-year}} Am^{242} \xrightarrow[\beta^-,\,EC]{16\text{-hour}} \cdots$$

is of course the one established by the present study and was not known previously):

$$Am^{241}(n,\gamma)Am^{242m}(n,\gamma)Am^{243} \xrightarrow[\alpha]{} \cdots;$$

$$Am^{241} \xrightarrow[\alpha]{458\text{ yr}} Np^{237} \xrightarrow[\alpha]{} \cdots;$$

$$Am^{242m} \xrightarrow[IT]{152\text{ yr}} Am^{242} \xrightarrow{16\text{ hr}} \begin{cases} \xrightarrow[\beta^-]{84\%} Cm^{242} \xrightarrow[\alpha]{} \cdots, \\ \xrightarrow[EC]{16\%} Pu^{242} \xrightarrow[\alpha]{} \cdots, \end{cases}$$

$$Am^{242m} \xrightarrow[\alpha]{0.48\%} Np^{238} \xrightarrow[\beta^-]{2.1\text{ day}} \cdots;$$

$$Am^{243} \xrightarrow[\alpha]{7950\text{ yr}} Np^{239} \xrightarrow[\beta^-]{2.3\text{ day}} \cdots.$$

Separation of 16-Hour Am^{242}

In order to show that the long-lived isomer of Am^{242} was the metastable state decaying principally by an isomeric transition, it was necessary to separate the short-lived isomer from the equilibrium mixture. Two methods were considered:

(a) Prepare the aqueous ion Am(III) [or Am(VI)] and place it in an oxidizing (or reducing) medium in which thermal chemical reactions would be quite slow. The internal conversion process might rapidly oxidize (or reduce) the 16-hour daughter as it was formed. A chemical separation of hexavalent (or trivalent) americium might then separate the 16-hour isomer from the bulk of the Am^{241} and Am^{242m}.

(b) Prepare a thin sample of americium and collect "recoils" from the internal conversion of the isomeric transition.

The latter method was tried first and worked sufficiently well so that method (a) was not attempted. Since the "recoil" collection efficiency was expected to be very poor, it would be manifestly necessary to perform a chemical purification particularly to remove the neptunium beta emitters which would be collected with high efficiency as alpha-decay recoils.

A thin source containing ~1 microgram total americium was prepared by vacuum vaporization of the chloride solution residue from a white-hot tungsten filament onto a cold platinum plate. The source thickness was probably <1 microgram/cm² and the isotopic composition was determined by Dr. Maynard C. Michel of this Laboratory to be 1.0% Am^{242}, 0.60% Am^{243}, and the remainder Am^{241}. A rough check on the Am^{242} content was obtained by measuring the alpha activity of the Cm^{242} which had grown into the sample.

Recoils from the source were collected on a clean platinum plate which was 3 mm distant from the source and maintained at a negative potential of 300 volts. After collecting for 17 hours the plate contained 400 beta-counts per minute measured in a windowless proportional counter and 25 alpha dis/min. The alpha

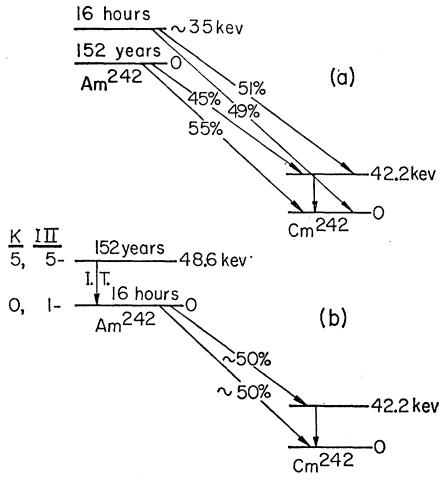

FIG. 1(a). Decay scheme of Am^{242} isomers from previous work; (b) Decay scheme of Am^{242} isomers from this work.

[8] B. R. Mottelson and S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **1**, No. 8 (1959).

[9] F. S. Stephens, F. Asaro, and I. Perlman, Phys. Rev. **113**, 212 (1959).

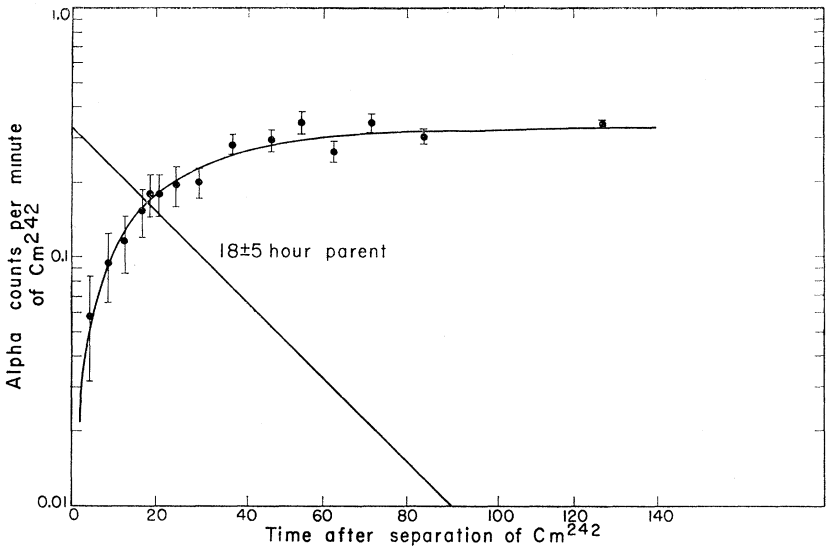

FIG. 2. Decay of purified "recoil" products from americium containing 152-year Am^{242}.

activity is Am^{241} carried from the source as a result of the intense alpha emission. As mentioned, much of the beta activity might be expected to be that of Np^{238} and Np^{239}, so a chemical separation was made. All of the activity was removed from the collector plate with a few drops of $8M$ HCl and run through a Dowex-$A1$ resin column. At this acid concentration, neptunium is retained by the resin and americium passes through. The americium fraction contained 56 net beta counts/min and 20 alpha disintegrations/min.

The decay of the purified americium fraction was measured carefully in the beta counter and found to

TABLE I. Data for the experiment showing growth of Cm^{242} from 16-hour Am^{242} parent.[a]

Source[b]	Recoil sample[c]	Cm^{244} added[d]	Americium fraction: After Am^{242} decay[f] (Initial[e] → decay[f])
Am^{241}	$5\times10^7(\alpha)$	$110(\alpha)$	$13(\alpha)$	$40(\alpha) \rightarrow 40(\alpha)$
Am^{242m}	1.2×10^6	~3		$\sim1 \rightarrow \sim1$
↓ IT				
Am^{242}	$1\times10^6(\beta)$	$\sim500(\beta)$		$\sim170(\beta) \rightarrow \sim1(\beta)$
α ↓ β^-				
Cm^{242}	$1\times10^6(\alpha)$	$\sim6(\alpha)$	$0.5(\alpha)$	$0.30\pm0.05(\alpha) \rightarrow 0.85\pm0.02(\alpha)$ (0.17 ± 0.01) (0.17 ± 0.01)
Np^{238}	$6000(\beta)$	$\gtrsim1\times10^3(\beta)$		
Am^{243}	$1.7\times10^4(\alpha)$	$\sim0.04(\alpha)$		$0.01(\alpha) \rightarrow 0.01(\alpha)$
↓ α				
Np^{239}	$1.7\times10^4(\beta)$	$\gtrsim3\times10^3(\beta)$		
Cm^{244}	...	...	$100(\alpha)$	$2.6\pm0.15(\alpha) \rightarrow 2.78\pm0.04(\alpha)$

[a] Composition: The Am^{241} collected represents the small amount of transfer always noted from a strong alpha source; the Am^{242m} and Am^{243} were estimated to transfer in the same proportion. The Cm^{242} comes both from this mechanism and from β recoils. The Np^{238} and Np^{239} were estimated from known α-recoil efficiencies; accurate values are of no concern to this experiment and in any case these isotopes are removed in subsequent steps.

[b] Approximate composition of americium source; all numbers refer to disintegrations per minute. Actual source consisted of 10 separate thin samples on platinum

[c] The "source" was fastened to the inner surface of an 8-inch diam aluminum hemisphere and recoils collected for 36 hours on a gold foil placed in a central position and maintained at −3000 volts.

[d] After removal of recoil sample from the gold foil with $6M$ HCl, the solution was run through a Dowex-$A1$ resin column to remove dissolved gold, after which the indicated amount of Cm^{244} was added to serve as a monitor for the subsequent americium-curium separation.

[e] Miscellaneous impurities were removed by placing the actinide elements on a Dowex-50 cation exchange column, washing with $2M$ HCl and eluting with $6M$ HCl. The americium fraction was then separated from curium and neptunium on a similar column using alpha-hydroxy isobutyric acid as the eluant. [G. R. Choppin and R. J. Silva, J. Inorg. & Nuclear Chem. 3, 153 (1956); G. R. Choppin, B. G. Harvey, and S. G. Thompson, J. Inorg. & Nuclear Chem. 2, 66 (1959).] The alpha emitters were identified by alpha-energy measurement using a grid ionization chamber and pulse-height analyzer. The amount of Cm^{244} served to show that 0.17 dis/min of Cm^{242} from the recoil sample had remained with the americium after the chemical separation. By difference, 0.13 dis/min Cm^{242} (of the 0.30 dis/min measured) had grown from Am^{242} decay between the time of chemical separation and the first measurement.

[f] This column shows the asymptotic value for Cm^{242} after Am^{242} decay. The entire growth curve is shown in Fig. 2.

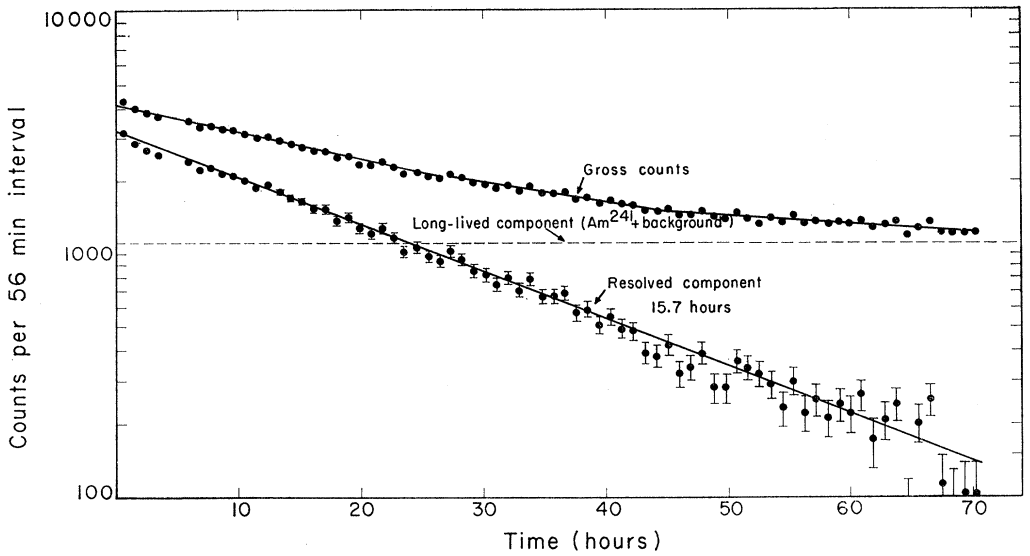

FIG. 3. Curium-242 growth from the purified americium fraction of a "recoil" sample. One alpha count per minute equals two alpha disintegrations per minute.

have a half-life of 15.7 hours after subtracting the long-lived tail due to the Am^{241} alpha particles. The decay curve is shown in Fig. 2. The experiment was repeated and again a 16-hour half-life was obtained.

A different type of experiment was then tried to show conclusively that the 16-hour period belonged to Am^{242}. As Am^{242} decays, one of its products, the 163-day alpha-emitter Cm^{242}, should grow accordingly. However, the ratio of half-lives is such that the Cm^{242} alpha activity from experiments such as this should reach a level of only a fraction of a count per minute. Since several times this quantity of Cm^{242} (see decay reactions above) would be expected to find its way to the collection plate, an americium-curium chemical separation would be necessary before the growth of the Cm^{242} alpha groups could be observed. The actual experiment may best be visualized with recourse to Table I. Here it is shown that it was possible to isolate some 16-hour Am^{242}, to free it initially from Cm^{242} to a low level, and to observe the growth of Cm^{242}. In Table I (last two columns) it is seen that by the time the first measurement was made, 0.30 dis/min of Cm^{242} was present of which 0.17 dis/min was Cm^{242} which had survived the chemical separation. The Cm^{242} grew over a period of days to the asymptotic value of 0.85 dis/min. The entire growth curve showing the origin of Cm^{242} from an $18(\pm 5)$-hour parent is shown in Fig. 3. Since the only possible source of the Cm^{242} is through Am^{242} decay, the 16-hour isomer must exist in equilibrium with the 152-year isomer.

Electron Spectrum for the Am^{242m} Isomeric Transition

About 6×10^6 alpha dis/min of the americium was vaporized onto a 10-mil platinum wire. The wire was used as a source in two photographic-recording permanent magnet beta spectrographs. Three exposures were made in a 100-gauss magnet—for 4, 8, and 21 days. A fourth exposure of 72 days was made in a 50-gauss magnet. The lines observed in the 21-day exposure are shown in Table II. Since Am^{241} accounts for almost all of the activity in the sample, most of the spectrum consists of Np^{237} conversion lines. However, eleven new lines were seen in low intensity which correspond to a 48.6-kev transition converted in americium *L*, *M*, *N*, and *O* subshells. All of the Np^{237} *transitions* were previously known although some new subshell lines were seen. Also seen were conversion lines of the *E*2 transitions in Cm^{242}, Pu^{242}, and Pu^{238} arising from the beta decay of Am^{242}, electron capture decay of Am^{242}, and alpha decay of Cm^{242}, respectively. Fourteen Auger lines from Np^{237} were also identified but are not listed in Table II.

Another exposure of 21 days was made on the same permanent magnet with a comparable Am^{241} source containing less than 0.01% Am^{242} by mass. All of the lines assigned to Np^{237} in Table II were observed, but none of the lines assigned to Am^{242} or its daughters were seen.

Of course, the information of primary interest here concerns the 48.6-kev isomeric transition in Am^{242}. The relative intensities of the various Am^{242m} conversion lines and the pertinent theoretical conversion coefficients[10,11] are listed in Table III. Particular interest is attached to the four Am *M*-subshell conversion lines because their relative intensities define the multipolarity

[10] M. E. Rose, *Internal Conversion Coefficients* (North-Holland Publishing Company, Amsterdam, Interscience Publishers, Inc., New York, 1958).

[11] L. A. Sliv and I. M. Band, Leningrad Physico-Technical Institute Report, 1956 [translation: Reports 57*ICC K*1 and 58*ICC L*1 issued by Physics Department, University of Illinois, Urbana, Illinois (unpublished)].

TABLE II. Electron lines from the 21-day exposure of the $Am^{241,242,243}$ sample in a 100-gauss magnet.

Visual intensity[a]	Electron energy (kev)	Subshell	Binding energy	Gamma-ray energy (kev)	
	Np^{237} lines ($Am^{241} \rightarrow Np^{237}$)				
VW	8.76	Np L_{III}	17.61	26.37	
W	20.66	M_I	5.74	26.40	
	Obscured by L_I of 43.44	M_{II}			
	Obscured by L_{II} of 43.44	M_{III}			
VW	22.52	M_{IV}	3.85	26.37	
VW	22.72	M_V	3.66	26.38	
W	24.88	N_I	1.50	26.38	
W	25.06	N_{II}	1.32	26.38	
VW	25.29	N_{III}	1.08	26.37	
			Average	26.38	
W-M	10.84	L_I	22.41	33.25	
W-VW	11.69	L_{II}	21.59	33.28	
W	15.63	L_{III}	17.61	33.24	
M-S	27.46	M_I	5.74	33.20	
W-M	27.83	M_{II}	5.36	33.19	
W-M	28.78	M_{III}	4.43	33.21	
M-S	31.72	N_I	1.50	33.22	
VVW	31.90	N_{II}	1.32	33.22	
VW	32.13	N_{III}	1.08	33.21	
M-W	32.96	O_I	0.34 est	33.30	
			Average	33.21	
M-S	21.03	L_I	22.41	43.44	
M-S	21.85	L_{II}	21.59	43.44	
M-S	25.85	L_{III}	17.61	43.46	
	Obscured by L_{II} of 59.58	M_I and M_{II}			
M	39.02	M_{III}	4.43	43.45	
	Obscured by L_{III} of 59.58	N_I			
VW	42.17	N_{II}	1.32	43.49	
W	42.37	N_{III}	1.08	43.45	
W	43.23	O_{III}	0.21 est	43.44	
			Average	43.45	
M-W	33.12	L_I	22.41	55.53	
M-W	33.97	L_{II}	21.59	55.36	
	Obscured by L_{II} of 59.6	L_{III}			
W	49.88	M_I	5.74	55.60 55.62	
W	50.21	M_{II}	5.36	55.57	
W	51.15	M_{III}	4.43	55.58	
			Average	55.57	
VS	37.18	L_I	22.41	59.59	
VVS	38.03	L_{II}	21.59	59.62	
S	41.97	L_{III}	17.61	59.58	
S	53.84	M_I	5.74	59.58	
VS	54.25	M_{II}	5.36	59.61	
S-M	55.13	M_{III}	4.43	59.56	
W-M	55.71	M_{IV}	3.85	59.56	
W-M	55.90	M_V	3.66	59.56	
M-S	58.25	N_I	1.32	59.57	
	Np^{237} lines ($Am^{241} \rightarrow Np^{237}$)				
M-S	58.12	N_{II}	1.50	59.62	
W-M	58.50	N_{III}	1.08	59.58	
W-VW	58.75	N_{IV}	0.82	59.57	
M	59.29	O_{II}	0.27 est	59.56	
VW	59.53	P_{II}	0.03 est	59.56	
			Average	59.58	
VVW	76.56	L_I	22.41	98.97?	
W-M	77.37	L_{II}	21.59	98.96	
W-M	81.41	L_{III}	17.61	99.02	
VW	93.64	M_{II}	5.36	99.00	
VW	94.54	M_{III}	4.43	98.97	
			Average	98.98	
	Am^{242} Lines ($Am^{242m} \rightarrow Am^{242}$)				
W	25.70	Am L_{II}	22.94	48.64?	Resolved from L_{III} of 43.4
W-M	30.11	L_{III}	18.52	48.63	
W	42.88	M_{II}	5.75	48.63	
W	43.91	M_{III}	4.70	48.61	
W	44.52	M_{IV}	4.11	48.63	
W	44.76	M_V	3.90	48.66	
W-VW	47.17	N_{II}	1.45	48.62	
VVW-VW	47.50	N_{III}	1.18	48.68	
W	47.78	N_V	0.86	48.64	(could contain N_{IV})
B {*VVW*	48.50	$O_{IV,V}$	0.13 est	48.63	
B {*VVW*	48.32	O_{II}	0.29 est	48.61	
			Average	48.63	
	Pu^{238} Lines ($Cm^{242} \rightarrow Pu^{238}$)				
VW	38.61	Pu M_{II}	5.56	44.17	
VVW-VW	39.57	M_{III}	4.56	44.13	
	Obscured by L_{II} of Np 43.4	L_{II}			
VW	26.06	L_{III}	18.06	44.12	May contain some $O_{I,II}$ of 26.38 of Np
			Average	44.14	
	Cm^{242} Lines ($Am^{242} \rightarrow Cm^{242}$)				
VW-W	18.54	Cm L_{II}	23.63	42.17	
W	23.22	L_{III}	18.99	42.21	
W	36.25	M_{II}	5.95	42.20	
VW	37.40	M_{III}	4.84	42.24	Resolved from L_I of Np 59.58
			Average	42.20	
	Pu^{242} Lines ($Am^{242} \rightarrow Pu^{242}$)				
VW	22.30	Pu L_{II}	22.25	44.55	
VVW	26.53	L_{III}	18.06	44.59?	
			Average	44.55	

[a] Symbols: *B*—broad; *M*—moderate; *V*—very; est—estimated; *S*—strong; *W*—weak; ?—questionable line.

of the transition unambiguously. These are compared in Table III with theoretical *M*-subshell conversion coefficients (relativistic, point nucleus, unscreened) by Rose.[10] The experimental ratios $M_I:M_{II}:M_{III}:M_{IV}:M_V$ are $<0.2:1.3:1.0:0.8:1.0$ within an accuracy of roughly 30%, and it is seen that only an *E*4 assignment is possible. For all magnetic multipolarities there exist subshell ratios which are different from the observed values by at least a factor of 50, and for electric transitions the closest other possible fit is for *E*5, but here $M_{IV}/M_{III}=6$. The M_I line could not be seen and its maximum intensity could be set at less than 15% of that of the M_{II} line.

The maximum amount of *M*5 admixture in the *E*4 radiation can be calculated from the subshell intensity ratios and the theoretical conversion coefficients. From the L_{II}/L_{III} ratio the minimum half-life for *M*5 radiation is 7×10^{10} years corresponding to 0.3% admixture. From the *M*-subshell ratios the minimum half-life is 3×10^{11} years corresponding to a 0.06% admixture.

Decay Scheme

With the information already discussed and summarized here, the partial decay scheme shown in Fig. 1(b) results: (1) The 152-year isomer is the metastable state, (2) the isomeric transition energy is 48.6 kev, (3) the transition is *E*4, (4) 16-hour Am^{242} has spin 1, (5) as a consequence of (3) and (4), the metastable state has the same parity as the ground state and probably has spin 5, and (6) the previous evidence on the direct beta decay of 152-year Am^{242} must be disregarded. The signs of the parities and the *K* quantum number assignments will be explained in the following section on the interpretation of these results.

TABLE III. Subshell conversion coefficients in americium for a 48.6-kev gamma ray.

Sub-shells	Theoretical values α_1	α_2	α_3	α_4	α_5	β_1	β_2	β_3	β_4	β_5	Experimental relative intensities (accuracy ~30%)[a]
L_I	0.20	8.4	2.1×10^2	2.85×10^3	3.2×10^4	37	1.2×10^3	1.4×10^4	1.4×10^5	1.15×10^6	<0.6
L_{II}	0.23	220	9.2×10^3	1.7×10^5	2.1×10^6	4.6	5.3×10^2	9.7×10^2	9.7×10^3	9.4×10^4	1.7
L_{III}	0.25	180	7.0×10^3	1.3×10^5	1.9×10^6	0.20	8.2×10	7.2×10^4	2.4×10^6	4.6×10^7	1.8
M_I	0.071	4.7	2.1×10^2	4.3×10^3	7.9×10^4	22	650	1.3×10^4	2.3×10^5	3.9×10^6	<0.2
M_{II}	0.067	97	6.2×10^3	1.8×10^5	3.6×10^6	2.4	52	1.0×10^3	1.6×10^4	2.6×10^5	1.3
M_{III}	0.077	86	4.8×10^3	1.1×10^5	2.0×10^6	0.085	330	4.9×10^4	2.4×10^6	8.5×10^7	1.0
M_{IV}	0.018	1.9	5.2×10^2	1.5×10^5	1.2×10^7	0.013	7.2	9×10^2	4.9×10^4	1.8×10^6	0.8
M_V	0.021	1.0	9.6×10^2	1.6×10^5	1.0×10^7	0.006	0.28	1.5×10^3	5.5×10^5	5.3×10^7	1.0
N_I											<0.2
N_{II}											0.6
N_{III}											0.4
$N_{IV,V}$											0.8
O											~0.6

[a] The relative intensities of the L_{II} and L_{III} subshell lines should be accurate to ~30% as should the relative intensities of the lines from higher shells. The ratio of $L/(M+N+O)$ conversion, however, could be in error by a larger amount.

The beta-decay properties of Am^{242} and Am^{242m} are of importance to the interpretation of their quantum states and are summarized in Table IV. The experimental data upon which the logft values were calculated come from work other than ours as indicated[12–17] in Table IV. However, our reinterpretation of the decay schemes and measurement of the isomeric transition energy have introduced substantial changes in the electron capture decay energy of Am^{242} and in the energy available for the unobserved beta transitions of Am^{242m}. It may be noted that the K-capture logft values for Am^{242} look much like those for the corresponding β-decay modes. This is as it should be because the corresponding nuclear configurations of the daughter nuclides are the same. The data upon which the K-capture logft values are based, however, are not as accurate as the β-decay values and should be given less weight in any detailed interpretations.

The limit which can be set on the β^- decay of the 152-year Am^{242m} considers only the transition to the 4+ state of Cm^{242}. From our knowledge of the level structure of Cm^{242} and from the finding in the present study that Am^{242m} undoubtedly has spin 5, this transition should be the one most easily discernible. By means of beta-gamma coincidence measurements Stephens[12] obtained the information upon which is based the upper limit of beta decay which appears in Table IV. From this, the value logft>13 was calculated. Since the beta transition involves only a spin change of 1 unit, the large ft value is of great importance in the assignment of the states.

The $E4$ isomeric transition turns out to be highly hindered. The total conversion coefficient can be estimated[11] to be 1.3×10^6. From this the radiative lifetime is 2×10^8 years, which is 10^6 times longer than that

TABLE IV. Beta-decay properties of Am^{242} and Am^{242m}.

Isomer	Decay mode	Product-state	Decay energy[a]	Relative intensity[b] %	Logft
16-hour Am^{242}	β^- 83.6%	Cm^{242}, 0+	0.667	34	7.1
		Cm^{242}, 2+	0.625	50	6.8
	EC 16%	Pu^{242}, 0+	0.72	~6 (K-cap., 4.4)	~7.6
		Pu^{242}, 2+	0.67	~10 (K-cap., ~7.6)	~7.3
152-year Am^{242m}	β^-	Cm^{242}, 4+	0.578	<2% of IT	>13

[a] Am^{242} β^- decay from reference 13; Am^{242} EC decay, values from reference 14 corrected by our reinterpretation of decay scheme; Am^{242m} β^- decay to Cm^{242} 4+ state, Q_{β^-} taken as 0.667+0.049 Mev and position of 4+ state as 0.138 Mev from reference 15.

[b] Am^{242} β^- groups from reference 13; Am^{242} EC to the 2+ level was taken from reference 13; the EC to the 0+ state was taken as the difference between this number and the total EC of 16.4% (reference 6). The K-capture intensities were calculated from the theoretical K/L and $L/\Sigma(M+N+\cdots)$ ratios (reference 16). Am^{242m}, the value was obtained from an upper limit on the intensity of any 100-kev radiation associated with the β decay of Am^{242m}, .01% (reference 12), and the theoretical $E2$ conversion coefficients (reference 10). The ft values were calculated from the equation and graphs given by Moszkowski (reference 17).

[12] F. S. Stephens, Jr. (unpublished).

[13] S. A. Baranov and K. N. Shlyagin, in *Proceedings of the Conference of the Academy of Sciences of the U.S.S.R. on the Peaceful Uses of Atomic Energy*, Moscow, July 1–5, 1955 (Akademiia Nauk, S.S.S.R. Moscow, 1955) [English translation by Consultants Bureau, New York: U. S. Atomic, Energy Commission Report TR-2435, 1956], Vol. 1, p. 183.

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[16] A. H. Wapstra, G. J. Nijgh, and R. Van Lieshout, *Nuclear Spectroscopy Tables* (North Holland Publishing Company, Amsterdam, 1959).

[17] S. A. Moszkowski, Phys. Rev. **82**, 35 (1951). Logf_0t was calculated from the equations and log$C$ was taken from the graphs.

calculated by the single-proton formula as given by Moszkowski.[18]

The minimum half life of 3×10^{11} years for $M5$ radiation as determined from the M-subshell intensities is about an order of magnitude larger than the value calculated from the single-proton formula.

III. THEORETICAL INTERPRETATION

Beta Decay of Am^{242m}

Am^{242} lies in a region of large prolate nuclear deformation; for nuclei in such regions, K, the projection of total angular momentum on the nuclear symmetry axis, is very nearly a constant of the motion. K-selection rules operate on the deformed nuclei such as to impose on transitions one or two orders of magnitude retardation for each unit by which $|\Delta K|$ exceeds the total angular momentum associated with the radiation.[19]

Am^{242m} with spin 5 probably has $K=5$. For direct beta decay to the 4+ state in Cm^{242}, 578 kev of energy is available and $\Delta I=1$. Hence, the beta decay would be allowed or first-forbidden, depending on whether the parity of Am^{242m} is even or odd. We prefer *odd parity*, but *even parity* cannot be ruled out on the basis of existing information. The normal logft value for $\Delta I=1$, yes, transition is around 7.5, yet from Table IV the logft is >13. The reason for the retardation is surely the violation of the K-selection rule, for here $\Delta K=5$. Beta decay via the unique Gamow-Teller ($\Delta I=2$, yes) matrix element would be retarded by 3 orders of K forbiddenness. Accepting a value of 8 as the normal logft for this type of transition, we would expect a logft value well above 11, perhaps nearer 14, consistent with the experimental limit. The decay of long-lived Lu^{176} (probably spin 7)[15] to the spin-6 member of the ground-state rotational band in Hf^{176} ($K=0$, $I=6$) with a logft of 18.5 presents a closely related example.

Am^{242} Beta Decay and K Assignment

Normally, one would assume the spin-1 ground state to have $K=1$, but we were stimulated, mainly by atomic-beam moment measurements, to consider also the possibility of $K=0$ for this nucleus.

The traditional test for the quantum number K involves comparisons of branching ratios of beta or gamma radiation to different members of the same rotational band, the reduced transition probabilities being proportional to the square of a Clebsch-Gordan coefficient, $\langle I_iLK_iK_f-K_i|I_iLI_fK_f\rangle^2$. The subscripts refer to initial and final states and L is the angular momentum associated with the transition. For the case of a spin-one odd nucleus, the beta decay to ground and first excited state should be predominantly $L=1$, whichever the parity of the initial state. Thus, there are two possibilities to be tested, $K_i=0$ and $K_i=1$. In the former case the reduced transition probability (reciprocal of ft value) favors the 2+ first excited state by a factor of two, and if $K_i=1$, the reduced transition probability to ground is favored by a factor of two. The test in Am^{242} may be applied to both the β^- and the electron-capture branches.

It is seen from Table IV that the $K=0$ assignment is clearly indicated. The smaller logft value applies to the 2+ state and the difference corresponds closely to a factor of 2 in reduced transition probabilities. The electron-capture ratios are also in good agreement with this interpretation.

Later in this paper we will discuss the theoretical implications of the surprising appearance of spin 1 as the lowest member of a $K=0$ band.

Gamma-Ray Lifetime of the Isomeric Transition

As already pointed out, the $E4$ isomeric transition probability is a factor of 10^6 slower than the Moszkowski single-proton formula estimate. With a K change of 5 this transition is once K forbidden. As mentioned earlier, one or two orders of magnitude retardation are generally associated with each order of K forbiddenness for the strongly deformed nuclei. This simple rule obviously does not account for the retardation observed. For further understanding of the retardation it will be necessary to consider the particular admixtures of $K=1$ in the ground-state wave function and of $K=4$ in that of the long-lived isomer.

Single Particle Orbitals of Am^{242}

To make any further progress in the theoretical consideration of the Am^{242} isomers we must consider the proton and neutron orbitals involved, in the manner of Gallagher and Moszkowski.[20] From the state assignments of odd-mass nuclei proposed by Mottelson and Nilsson[8] and by Stephens, Asaro, and Perlman,[9] the most likely neutron orbital in Am^{242} is the $5/2+[622]$ ground state of isotones Pu^{241} and Cm^{243}. The quantum designation is the usual one, $\Omega\pi[N,n_z,\Lambda]$, appropriate to particles in spheroidal nuclei: Ω is the projection of the particle angular momentum on the nuclear cylindrical symmetry axis; π, the parity; N, the total oscillator quantum number; n_z, the number of nodal planes of the wave function perpendicular to the symmetry axis; Λ, the projection of the orbital angular momentum on the symmetry axis. The intrinsic spin projection, Σ, which is $\pm1/2$, is simply $\Omega-\Lambda$. For this neutron orbital $\Sigma=+1/2$.

The most likely proton orbital is $5/2-[523]$, for which $\Sigma=-1/2$, the ground state of Am^{241} and Am^{243}.

[18] S. A. Moszkowski, in *Beta- and Gamma-Ray Spectroscopy*, edited by Kai Siegbahn (Interscience Publishers, Inc., New York, North Holland Publishing Company, Amsterdam, 1955), Chap. XIII.

[19] B. R. Mottelson and S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Skrifter **1**, No. 8, 9 (1959).

[20] C. J. Gallagher and S. A. Moszkowski, Phys. Rev. **111**, 1282 (1958).

The orbital 5/2+[642], however, is rather near-lying and is also a possibility.

The quantum number K is the projection of the total angular momentum on the nuclear symmetry axis, and with two unpaired particles of $\Omega=5/2+$ and $\Omega=5/2-$, the values $K=0-$ and $K=5-$ are possible. According to the Nordheim coupling rules modified by Gallagher and Moszkowski,[20] the intrinsic spins of proton and neutron prefer a parallel orientation; therefore the $K=0-$ state should lie below the $K=5-$ state. This agrees with our assignments based on experiment. The choice of 5/2+[642] for the proton orbital would lead to the opposite prediction, but in view of the curious displacement of odd and even spin values of the $K=0$ band, the 5/2+ proton orbital cannot really be ruled out on this basis.

The classification of beta-decay ft values for odd-mass spheroidal nuclei has been quite successful. It seems reasonable to try to extend this classification to beta decay of low-spin odd-odd nuclei, at least for beta groups to and from the ground rotational band of even-even nuclei where there is no K forbiddenness. Such beta decay, assuming that the paired orbitals do not change, may be considered as proceeding by one of the odd nucleons transforming itself into the paired partner of the other odd nucleon. That is, for β^- decay the odd neutron must transform to the paired partner of the odd proton.

For the β^- or electron-capture decay of the $I=1-$, $K=0$, isomer we would have the following changes in asymptotic quantum numbers (i.e., just the difference of numbers in odd proton and neutron orbitals):

$$\Delta\Omega=0,\quad \Delta N=\mp 1,\quad \Delta n_z=0,\quad \Delta\Lambda=\pm 1,\quad \Delta\Sigma=\mp 1.$$

There is no violation of the asymptotic selection rules for first-forbidden beta decay, given first by Alaga.[21] Thus, this beta decay would be classified first forbidden, unhindered, ($1u$). For 17 $1u$ transitions in odd-mass nuclei with $Z>89$ the average logft is 6.5 with average deviation ± 0.5 and extreme values of 5.7 and 7.3.[9] The logft values of 7.1 and 6.8 for the beta groups of Am^{242} fall on the high side of the average. In fact, the logft values for the same nucleon states in the decay of U^{239}, Pu^{241}, and Am^{239} are $\sim$5.8, 5.9, and 5.7, respectively. It has been suggested to us by Stephens[22] that the greater logft value in the Am^{242} case may arise because there are certain beta-decay matrix elements which can contribute in odd-A cases with $\Delta I=0$ but cannot contribute to Am^{242} decay where $\Delta I=1$.

Nuclear Moments

Atomic beam measurements[23] have fixed precisely the absolute value of the ratio of the magnetic moments of Am^{242} and Am^{241}, 0.236, and also the absolute value of the ratio of their spectroscopic quadrupole moments, 0.562. Furthermore, the measurements have established that either the magnetic moment or the quadrupole moment of Am^{242} is of opposite sign to the corresponding moment of Am^{241}. The optical spectrographic data of Manning, Fred, and Tomkins[24] for Am^{241} gives $\mu=+1.4$ nuclear magnetons (nm) and $Q_{\text{spec}}=+4.9$ barns. Combining this information with that from the atomic beam measurements, we obtain for Am^{242}, $\mu=\pm 0.33$ nm and $Q_{\text{spec}}=\mp 2.75$ barns.

These nuclear moments may now be compared with the theoretical expectations for the $I=1$, $K=0$ assignment. An abundance of evidence established the intrinsic quadrupole deformations of nuclei in the region of americium as prolate (positive). However, for nuclear states with $K^2<I(I+1)/3$ the signs of the intrinsic and spectroscopic moments will be opposite. The relation between these moments is as follows:

$$Q_{\text{spec}}=\frac{3K^2-I(I+1)}{(I+1)(2I+3)}Q_0;$$

for $I=1$, $K=0$, $Q_{\text{spec}}=-Q_0/5$. If we assume that Q_0 for Am^{242} is the same as that for Am^{241}, the $K=0$ assignment gives $Q_{\text{spec}}=-2.74$ barns, which is in excellent agreement with the value ∓ 2.75 barns obtained as mentioned above. If, on the other hand, we assume $K=1$ for Am^{242}, then Q_{spec} should be $+1.4$ barns.

The magnetic moment may also be analyzed. For the $K=0$, $I=1$ assignment the angular momentum is directed perpendicular to the symmetry axis, and there is no specific contribution to the magnetic moment from the odd nucleons. In this case we would expect a magnetic moment $\mu=g_R I$, where g_R is the gyromagnetic ratio for collective motion, usually estimated as $+Z/A$,[25] the fraction of protons in the nucleus. From this we get $\mu=+0.39$ nm, which agrees in sign and magnitude with the measured value ($\mu=+0.33$ nm) if the sign for Q_{spec} is taken to be negative in accord with our theoretical prediction.

If we consider the assignment $I=1$, $K=1$, we must first of all postulate some possible orbital assignments for the neutron and proton. The most likely are 5/2−[523] (or 5/2+[642]) for the proton as before and 7/2+[624] for the neutron. This neutron orbital appears as a state at 172 kev in Pu^{241}. If the magnetic moments are calculated from Nilsson wave functions,[8,26] (with a deformation parameter, η, of 4.8),[27] the values for 5/2−[523] and 5/2+[642] proton orbitals are 0.2 nm and −1.2 nm, respectively. Thus the measured magnetic moment is not consistent with a $K=1$ assign-

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[22] F. S. Stephens, Jr. (private communication).
[23] R. Marrus, W. A. Nierenberg, and J. Winocur, Phys. Rev. (to be published).
[24] T. E. Manning, M. Fred, and F. S. Tomkins, Phys. Rev. **102**, 1108 (1956).
[25] See discussion in reference 8, p. 12.
[26] S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **29**, No. 16 (1955).
[27] The deformation parameter was taken from a Nilsson diagram for protons (see references 8 and 9).

ment with proton orbital 5/2+[642] but cannot be used by itself to rule out $K=1$ with proton orbital 5/2−[523]. With the latter assignment, however, the ratio of μ/Q_{spec} would be positive, in disagreement with the experimental results. It is seen, therefore, that not only is the magnitude of the measured quadrupole moment in better agreement with theory for $K=0$ than for $K=1$, but the sign of the ratio μ/Q_{spec} (as determined from theory) can only be negative for $K=0$. Thus, the atomic beam measurements reinforce the $K=0$ assignment.

Measurement of the magnetic moment of the spin-5 isomer would offer the best hope for distinguishing between the alternative odd and even parity assignments discussed earlier. For the choice of odd-parity proton orbital 5/2−[523] the theoretical magnetic moment of Am^{242m} is +0.3 nm, as calculated from the Nilsson wave functions for $\eta=4.8$. For an even parity assignment involving proton orbital 5/2+[642] the theoretical magnetic moment is +2.6 nm. The quadrupole moment in either case should be about 7.9 barns.

Ho^{166}

For Ho^{166} one expects the proton orbital 7/2−[523] and the neutron orbital 7/2+[633].[20] The coupling rules of Gallagher and Moszkowski predict the ground state to have $K=7-$ and an upper state, $K=0-$. Isomers with beta-decay half-lives of 27 hours and >30 years are known, although the relative positions of the states are not clear. The 27-hour isomer has been assigned spin zero, odd parity, by spectrum shape of the beta group leading to the 2+ state of Er^{166} and by the beta-gamma angular correlation involving this group.[28] Spin zero has been measured recently by atomic beam methods.[29] Logft values to the 0+ and 2+ states of Er^{166} are 8.1 and 8.0, respectively. For the long-lived isomer all that can be said of interest here is that its complex decay scheme and long half-life are consistent with a high spin and K-quantum number.

It is obvious that for the Ho^{166} isomer with $K=0$, the $I=1$ rotational state does not lie at lower energy than the $I=0$ state. Of great interest are recent independent studies of the decay of Dy^{166} to Ho^{166} by Geiger, Graham, and Ewan,[30] and by Helmer and Burson,[31] who find evidence for a rotational band with level sequence 0-, 2- (54.2 kev), 1- (82.5 kev). In this case the even- and odd-spin members are also displaced, but the odd member is displaced upward. This point will be returned to in the following section. There are no ft values (with $\Delta I=2$, yes or $\Delta I=0$, yes) for odd-mass beta decay with the asymptotic classifications obtaining in Ho^{166}, so that a valid comparison of our absolute beta-decay rates is not possible.

Ta^{180}

A nucleus which seems to be analogous to Am^{242} is Ta^{180}. The most likely orbital assignments from examination of neighboring odd-mass nuclei are either 7/2+[404] or 9/2−[514] for the proton and 9/2+[624] for the neutron. There are two isomers known: a very long-lived one whose decay has not been observed, and an 8.15-hour isomer which decays by β^- emission and electron capture. For either of the proton assignments the coupling rules would predict that the high spin ($K=8$ or 9) would be lowest. The low-spin isomer decays to the 2+ and 0+ states of W^{180}, favoring somewhat the 2+ state. The corresponding logft values are 6.5 and 6.8 for the transitions to the 2+ and 0+, respectively.[32] This pattern suggests an $I=1$, $K=0$ assignment, just as was the case for Am^{242}, but it would be well to have a careful redetermination of the branching ratios of beta decay and electron capture to the ground and first excited states. This assignment would call for the 9/2−[514] proton orbital and the 9/2+[624] neutron orbital. The asymptotic classification of the beta decay is thus first forbidden, unhindered, and the logft values are near the average for the first-forbidden, unhindered, beta decay of odd-mass nuclei.

Eu^{152m} would fall in the same category as Ho^{166}, but there may be some questions as to its being of stabilized spheroidal shape.

The short-lived Lu^{176} isomer may be analogous to Am^{242} and Ta^{180}. Atomic beam measurements[33] show spin 1, and the beta-decay branching to the first excited state is somewhat greater than that to ground.[34]

Displacement of Odd and Even Rotational States

Let us summarize the evidence on displacement of odd- and even-spin members of probable $K=0$ rotational bands in spheroidal odd-odd nuclei. In Ho^{166} the odd-spin members are displaced upward and in Ta^{180} and Am^{242} they are displaced downward, making $I=1$ lower than $I=0$. We may see how this displacement can arise by writing out the wave function properly symmetrized to remain invariant with respect to a rotation of 180° about any axis through the center of the nucleus and perpendicular to the main symmetry axis:

$$\psi=\left(\frac{2I+1}{16\pi^2}\right)^{\frac{1}{2}}[\chi_\Omega\chi_{\Omega'}D_{M,K}{}^I(\theta_i) + (-)^{I-i_p-i_n}\chi_{-\Omega}\chi_{-\Omega'}D_{M,-K}{}^I(\theta_i)],$$

where $\Omega+\Omega'=K$ (Ω may be positive or negative here), and χ_Ω is the odd-proton wave function with respect to

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[29] L. S. Goodman, W. J. Childs, R. Marrus, I. P. K. Lindgren, and A. Y. Cabezas, Bull. Am. Phys. Soc. **5**, 344 (1960).
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[33] M. B. White, S. S. Alpert, and E. Lipworth, Bull. Am. Phys. Soc. **5**, 273 (1960).
[34] J. K. Poggenburg and J. O. Rasmussen (unpublished).

the nuclear coordinate system, j_p is the proton angular momentum, and Ω its projection on the symmetry axis. The primed quantities refer to the odd neutron. Where j is not a good quantum number, the different components of the wave function must be separately symmetrized. We note when $\Omega=-\Omega'$ and $K=0$ that the wave function may be factored as follows:

$$\psi=\left(\frac{2I+1}{16\pi^2}\right)^{\frac{1}{2}}[\chi_\Omega(p)\chi_{-\Omega}(n) +(-)^{I-i_p-i_n}\chi_{-\Omega}(p)\chi_\Omega(n)]D_{M0}{}^I(\theta_i).$$

If we now consider a residual force acting between neutron and proton, it will in general give rise to an energy term with sign alternating with spin, I. This energy term is a cross term connecting the first and second parts of the wave function and is essentially due to a component of the force which scatters the proton and neutron into states with equal and opposite projections of the angular momentum. Whether the odd or even spins are elevated in energy depends on details of the wave functions. Further theoretical study will aim to predict the sign and magnitude of the displacement. In the special case of $K=0$ and $|\Omega|=|\Omega'|=1/2$ there will be an additional odd-even displacement energy due to a term $(\hbar^2/\mathcal{I})\mathbf{j}_p\cdot\mathbf{j}_n$ in the collective rotational part of the Hamiltonian. The combination of both proton and neutron $|\Omega|=1/2$ orbitals may occur in the short-lived isomer of Pa^{234}.

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Rare $E2$ Transition in C^{13}†

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By means of a coincidence method it is shown that the $\frac{5}{2}+$ state of C^{13} at 3.86 Mev has an $E2$ branch of relative strength $(9.3\pm2.0)\times10^{-3}$ to the $\frac{1}{2}+$ state at 3.09 Mev. From consideration of the likely strengths of the competing $E1$ transition to the $\frac{3}{2}-$ state at 3.68 Mev and the $M2$ transition to the ground state it is deduced that this branching ratio implies an $E2$ transition speed of the order of a single-particle (proton) unit. This in turn demands the substantial participation of at least one excited state of C^{12} in the parentage of at least one of the C^{13} states with respect to the $1d$ or $2s$ neutron. This eliminates in particular a jj-coupling description of C^{13} in which the two states in question are $1d_{\frac{5}{2}}$ and $2s_{\frac{1}{2}}$ neutron states and more generally a weak-coupling model in which the ground state of C^{12} is the unique parent for the C^{13} states (with respect to $1d$ and $2s$ neutrons).

INTRODUCTION

ELECTRIC quadrupole transitions in the light elements are of considerable interest. Although the independent-particle model (IPM) in intermediate coupling gives a generally excellent account of level schemes, magnetic moments, and dipole transition probabilities in the $1p$ shell and just beyond,[1] it fails badly in its account of the $E2$ rates. The sense of the failure is that the predicted rate is too low and this has suggested that configuration mixing must be an essential ingredient in our IPM account of the light nuclei; an alternative description is in terms of some form of collective model and a good beginning has been made in establishing the relationship between the two descriptions.[2] Any extension of our knowledge of $E2$ transitions in the light elements, particularly in the $1p$ shell where our account of the level schemes via the IPM is seen at its most successful, is very welcome and valuable.[3] The present investigation is to establish one such transition in C^{13} and to determine its probability relative to competing $E1$ and $M2$ transitions. It is the $E2$ transition between the $\frac{5}{2}+$ state at 3.86 Mev and the $\frac{1}{2}+$ state at 3.09 Mev.

This particular $E2$ transitions has an additional interest because it takes place in C^{13}. Although the IPM analysis[1] of $A=13$ gives the best account at $a/K\sim5$ it has frequently been suggested that in fact C^{12} is close to jj coupling. In this case we should primitively attempt to describe these $\frac{5}{2}+$ and $\frac{1}{2}+$ states as single-particle neutron states $1d_{\frac{5}{2}}$ and $2s_{\frac{1}{2}}$, respectively. This view is in fact encouraged by the empirical observation that the fractional parentage coefficients for the ground

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[1] See, e.g., D. Kurath, Phys. Rev. **101**, 216 (1956); **106**, 975 (1957). J. P. Elliott and B. H. Flowers, Proc. Roy. Soc. (London) **A229**, 536 (1955); **A242**, 57 (1957). A. M. Lane Proc. Phys. Soc. **A66**, 977 (1953); **A68**, 189 and 197 (1955).
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