Decay of Sm^{156}†

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(Received 13 February 1963)

The radiations following the decay of 9.4±0.2 h Sm^{156} have been studied using techniques of scintillation spectrometry and 4π beta counting. The isotope was produced by fissioning natural uranium in a high neutron flux and except for Sm^{153}, was separated from other fission products by radiochemical techniques. The following gamma-ray energies were observed in the decay of Sm^{156}: 38 keV, x rays (~20%), 87 keV (40%), 165 keV (18%), 203 keV (29%), 252 keV (5%), and 290 keV (3%). The 87-keV gamma transition was found to be coincident with both the 165- and 203-keV gamma transitions. Its K-shell conversion coefficient is 0.35±0.02. Angular correlation studies indicated the 87-203 keV gamma anisotropy to be about −0.25 and the 87–165 keV gamma anisotropy to be $0<A<0.1$. Fermi plots of the beta spectra coincident with the 165- and 203-keV gamma rays produced identical end points of 430±10 keV. Another beta group, 45% in abundance, had an end point of 715±15 keV and presumably goes to the ground state of Eu^{156}.

INTRODUCTION

THE radioisotope Sm^{156} was first reported by Winsberg[1] as a β^- emitter with a 9.0-h half-life. Subsequently very little has been reported on the decay of this even-even nuclide in spite of the potential interest in the excited states of its odd-odd daughter nuclide. By irradiating natural uranium in a neutron field we have produced and isolated this isotope and have partially characterized its decay. In the present studies, its half-life was found to be 9.4±0.2 h from both beta and gamma decay. The identification of this isotope with mass number 156 is also consistent with its fission yield with respect to Sm^{153} fission yield. Further, the Eu^{156} activity was observed to grow in at a rate consistent with the Sm^{156} decay.

Source Production and Purification

About 0.1 g of natural uranium in the acetate form was irradiated for 10–15 min in a neutron flux of 5×10^{13} n/cm^2 sec. After a 5-h "cooling" period to allow short-lived activities to decay, the uranyl acetate was dissolved in a HCl solution containing Sr^{2+}, Zr^{4+}, and Nd^{3+} carriers. A chemical separation procedure was used to remove most of the extraneous fission products from Y^{3+} and the rare earths, from which the samarium isotopes were isolated by ion-exchange column technique. A more detailed description of the chemical separation procedure is given in the Appendix.

RESULTS

Gamma-Ray Scintillation Studies

Studies of the gamma and x-ray radiations were made using a 3-in.×3-in. solid and a 3-in.×3-in. well-type NaI crystal. Coincidences were observed by using a "fast-slow" coincidence circuit ($2\tau\sim0.2$ μsec) in conjunction with a single- and multichannel analyzer. Six gamma radiations were found with the following energies (in keV): 38, 87, 165, 203, 252, and 290. The total gamma-ray spectrum, including radiations due to contaminate Sm^{153} activity, is shown in Fig. 1. The unavoidable presence of the 47-h Sm^{153} activity made it somewhat difficult to obtain accurate information on the low-energy gamma radiations of Sm^{156}. Curve a of Fig. 2 shows the composite Sm^{153} and Sm^{156} low-energy spectrum. After the shorter lived Sm^{156} decayed away, the gamma spectrum due to Sm^{153} (shown as curve b) was corrected for decay and subtracted from the composite curve. This difference is shown as curve c which is now due to the Sm^{156} low-energy radiations alone. Since Sm^{153} has only very low intensity radiations above 100 keV, the higher energy gamma rays of Sm^{156} were unobscured by Sm^{153} activity.

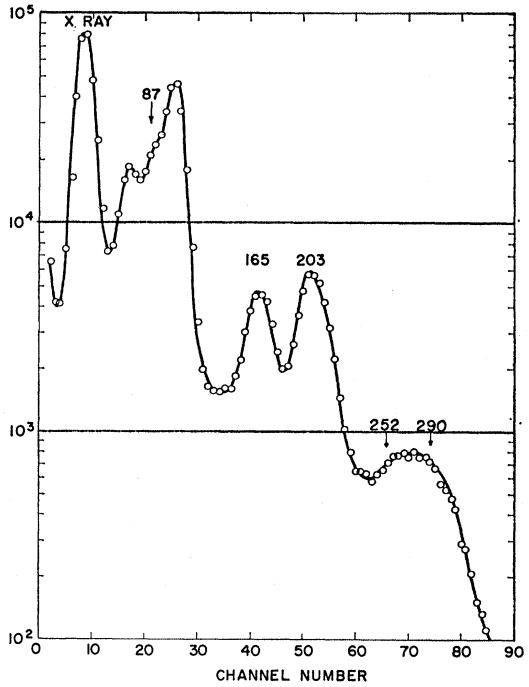

FIG. 1. Gamma-ray energy spectrum of the Sm^{153} and Sm^{156} activities.

† This work was supported by the U. S. Air Force Office of Scientific Research under Contract AF 49(638)-815.
[1] L. Winsberg, Natl. Nucl. Energy Ser. Div. IV 9, 1302 (1951).

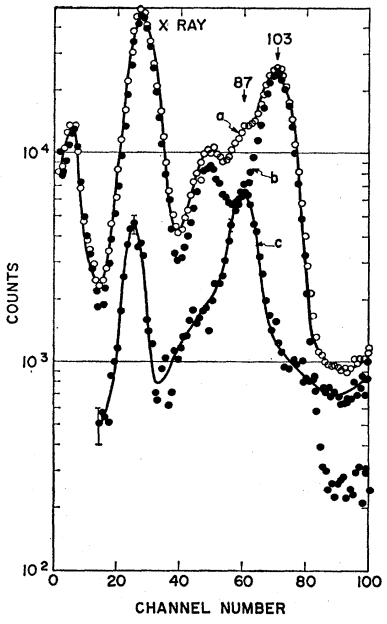

FIG. 2. Composite Sm^{153}-Sm^{156} low gamma-ray energy spectrum (curve a) and the resolved Sm^{153} and Sm^{156} spectra (curves b and c, respectively).

Absolute gamma-ray intensity data were obtained by assaying the samarium activities with a 4π beta-proportional counter and by using a 3-in.×3-in. NaI crystal which had been previously calibrated for photopeak counting efficiency.[2] The gamma-ray energies and intensities are summarized in Table I.

TABLE I. Gamma-ray energies and intensities.

Energy (kev)	Intensities (%)
38	...
x ray (41 keV)	20
87	40±2
165	18.5±1
203	29±1
252	5
290	3

Coincidence Studies

Coincidence spectra indicated that the 165- and 203-keV gamma rays are both in coincidence with the 87-keV transition, but not in coincidence with each other. By an accurate comparison of the yield of 87-keV gamma rays and 41-keV europium x rays in coincidence with the 165- and 203-keV gamma rays, an α_k electron conversion value of 0.35±0.02 was obtained for the 87-keV transition. The theoretical α_k value for a pure $E1$ transition of this energy is 0.34 according to the tables of internal conversion coefficients as given by Rose.[3]

An additional coincidence gamma ray of 38 keV was observed when the source was placed in close proximity to one crystal and the resulting "sum peak" of the 87- and 165-keV gamma rays was used for gating the multichannel analyzer. The intensity of the 38-keV gamma ray was quite low, which is probably due to the high conversion of this transition.

Angular correlation studies were also made on some of the coincidence gamma rays. Measurements for the anisotropy found in the case of the 87–203 angular correlation are shown in Fig. 3. Since the 87-keV transition was shown above to be an $E1$ transition, the expression for the γ-γ directional correlation is, therefore, of the form $W(\theta)=1+A_2P_2(\cos\theta)$. Incorporating corrections for the solid angles used in the experiment,[4] a value of $A_2=-0.18\pm0.03$ was determined by a least-square fit of this equation to the data shown in Fig. 3. The anisotropy A, is therefore -0.25. Only a few combinations of nuclear spin values and gamma-ray multipolarities result in such a large negative anisotropy.

Data on the 87–165 keV angular correlation were not accurate enough to warrant careful analysis. However, it was apparent that the anisotropy was less than $+0.1$.

Beta-Ray Studies

Analyses of the beta emissions were made using a hollow plastic scintillator.[5] Non-Gaussian-type instrument resolution corrections[6] were applied to all of the spectra. Curves a and b in Fig. 4 are Fermi plots of beta spectra coincident with the 165- and 203-keV gamma rays, respectively. Their identical end point of 430±10 keV shows that the same beta transition appears to be responsible for both the gamma transitions. Curve c is a Fermi plot of the higher energy portion of the total beta spectrum. A large Sm^{153} contribution to the original data has been subtracted and is responsible for the relatively large fluctuations in

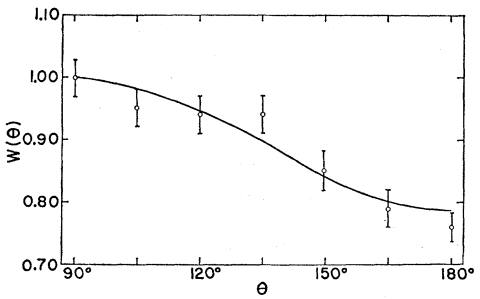

FIG. 3. Angular correlation of the 87- and 203-keV gamma rays.

[2] Ray Gunnink and A. W. Stoner, Anal. Chem. **33**, 1311 (1961).
[3] M. E. Rose, in *Beta- and Gamma-Ray Spectroscopy*, edited by Kai Siegbahn (North-Holland Publishing Company, Amsterdam, 1955), Appendix IV.
[4] H. I. West, Jr., Lawrence Radiation Laboratory Report, UCRL-5451, 1959 (unpublished).
[5] D. G. Gardner and W. W. Meinke, J. Appl. Radiol. Isotopes **3**, 232 (1958).
[6] M. S. Freedman, T. B. Novey, F. T. Porter, and F. Wagner, Jr., Rev. Sci. Instr. **27**, 716 (1956).

the data. This Sm^{156} beta group of 715±15 keV presumably populates the ground state of Eu^{156}.

No attempts were made to study the conversion electrons since it was somewhat impractical to separate the quantities of Sm^{156} activity necessary for such a study.

DISCUSSION AND INTERPRETATION OF DATA

Two alternative decay schemes for Sm^{156} are presented in Fig. 5. It is not possible to unambiguously determine the proper decay sequence because none of the intermediate energy levels of Eu^{156} are appreciably populated by direct beta decay.

Examination of the known ground-state spins of the neighboring Sm^{155} and Gd^{157} nuclides indicates that the odd neutron in Eu^{156} should have a ground-state spin and parity of $\frac{3}{2}$- corresponding to the [521] Nilsson neutron level.[7] The odd proton of the heavier europium nuclides all seem to have a spin and parity of $\frac{5}{2}$+ corresponding to the [413] Nilsson proton level.[7] Since the ground state of Eu^{156} is appreciably populated by direct beta transition from the 0+ Sm^{156} ground state ($\log ft = 6.1$) this level is best described by the *difference* of the neutron and proton components of angular momentum, resulting in a 1- nuclear ground-state spin. This value is consistent with some studies on the decay of Eu^{156}.[8,9] However, a value of 3- has been mentioned in connection with the ground state of Eu^{156}.[10]

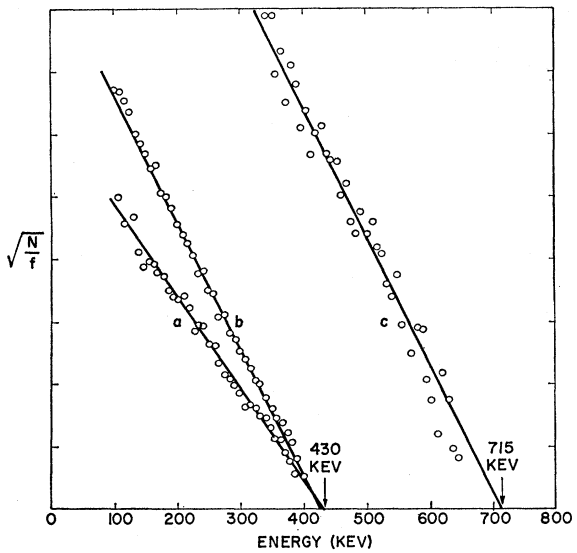

FIG. 4. Fermi plots of beta spectra coincident with the 165- and 203-keV gamma rays (lines a and b) and the high-energy portion of the total beta-ray spectrum (line c).

[7] B. R. Mottelson and S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat. Fys. Skrifter **1**, No. 8 (1959).
[8] J. E. Cline and R. L. Heath, Nucl. Phys. **22**, 598 (1961).
[9] G. T. Ewan, R. L. Graham, and J. S. Geiger, Bull. Am. Phys. Soc. **5**, 21 (1960).
[10] D. R. Smith, L. M. Langer, and D. A. Howe, Bull. Am. Phys. Soc. **5**, 254 (1960).

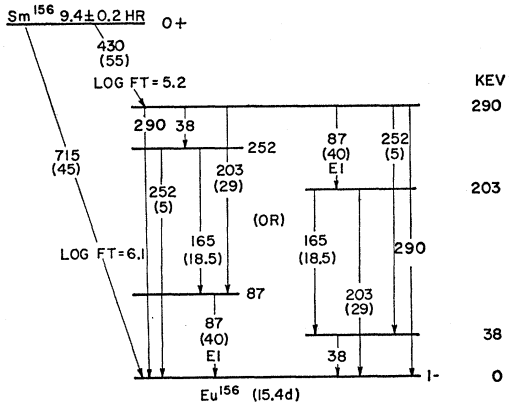

FIG. 5. Two possible decay schemes for Sm^{156}. Absolute gamma-ray intensities (%) are in parentheses.

The $\log ft$ value of 5.2 for the 430-keV beta group populating the 290-keV level of Eu^{156} would indicate that the spin of this level is 0 or 1 with positive parity. Assuming a ground-state spin of 1, angular correlation data indicate that the 290-keV level spin is 0. Such a state could arise from an excited $\frac{5}{2}$+ [642] neutron coupled with the $\frac{5}{2}$+ [413] proton.

At the present time, one can only speculate as to the spin values of the other states. However, the absence of any appreciable amount of beta population of these intermediate states indicates that the beta transitions must be forbidden.

APPENDIX

The following is the chemical scheme used in separating samarium activities from other fission products:

(1) The $UO_2(C_2H_3O_2)_2 \cdot 2H_2O$ was dissolved in a 6*M* HCl solution containing 5 mg each of Sr^{2+}, Zr^{4+}, and Nd^{3+} carrier elements.

(2) After the uranium was dissolved, the solution was brought to pH=1 with NH_4OH. $KMnO_4$ reagent was then added to oxidize the neptunium present to the +6 state and was then heated.

(3) The solution was brought to pH 8–9 with NH_4OH to precipitate the insoluble hydroxides. (The solution should be carefully buffered so that strontium is not precipitated.)

(4) After the precipitate was washed, it was dissolved in HCl and HF was added to precipitate the Y^{3+} and rare-earth fluorides.

(5) The precipitate was washed and dissolved in a 10*M* HNO_3 solution saturated with H_3BO_3.

(6) Sr^{2+} and Zr^{4+} were again added and steps 2–5 repeated.

(7) Excess NH_4OH was added to precipitate the rare-earth hydroxides from solution.

(8) After the precipitate was washed, it was dissolved in dilute HCl and adsorbed onto Dowex-50 cation-

exchange resin which was placed on top of a 50-cm column. The column was eluted with 3.5 pH ammonium lactate solution.[11]

[11] W. E. Nervik, J. Phys. Chem. **59**, 690 (1955).

(9) After the samarium activities were eluted from the column, they were re-adsorbed on the top and again run through the column to insure radiochemical purity from the other rare earths and, in particular, from the yttrium activities.

PHYSICAL REVIEW VOLUME 131, NUMBER 1 1 JULY 1963

Distorted-Wave Calculations of Light Nuclei (d,p) Angular Distributions*†

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(Received 25 February 1963)

Deuteron-stripping angular distributions have been calculated for 14 light-target reactions ($A \leq 48$) over a range of bombarding energies, using the distorted-wave Born approximation with diffuse-well optical-model nuclear potentials. A fair degree of agreement with experiment has been obtained, though in many cases the results, which depend strongly on the particular reaction considered, are inferior. In some of the latter instances the data are not well fitted; in others the agreement between elastic-scattering and stripping parameters, or between parameters for stripping leading to different residual levels of the same final nucleus, is poor. For reactions with $L_N=0$ it appears that the angular distributions can be reasonably fitted in the neighborhood of the Coulomb barrier as the bombarding energy is raised only if the deuteron real potential depth is appreciably increased.

INTRODUCTION

In a previous paper[1] results of calculations for deuteron stripping differential cross sections based on the distorted-wave Born approximation with diffuse-well optical model nuclear potentials were presented for 14 reactions for nuclei with $A \geq 59$. The present study extends this work to 14 reactions for light nuclei with $A \leq 48$. The main purpose of the investigation, as previously, was to ascertain the degree of applicability of the distorted-wave Born approximation with optical potentials in the determination of stripping differential cross sections. In particular, it was hoped that a set of optical-model parameters having only limited and systematic variations could be found which would yield agreement, over a wide range, with experimental data for light nuclei. This search has only been partially successful. Appreciable and nonsystematic variations in the optical parameters are obtained in many cases, in contrast to the results found for most of the heavier nuclei previously studied,[1] and the consistency in the results for different reactions is generally poor. In some instances, more than one acceptable set of parameters is determined, even under conditions in which the usual VR^2 ambiguity can be excluded.

Thus, the results presented here for light nuclei are to be accepted only with a considerable degree of caution. Not only does the distorted-wave Born approximation with optical potentials seem poorer than for the heavier nuclei, but the complexity of the calculations makes it entirely possible that in many cases more extensive work will disclose the existence of parameter regions yielding appreciably better results than obtained here.[2]

CALCULATIONAL PROCEDURE

It has been shown previously[1] for heavier targets ($A \geq 59$) that (1) optical-model parameters yielding agreement with the stripping data exist which do not vary appreciably from one reaction to the next, and (2) these parameters are in close accord with those obtained from elastic-scattering data. Such consistency between various reactions, unfortunately, has not been found for light targets ($A \leq 32$). Hence, it was considered advisable to adopt an approach in the stripping calculations for light nuclei somewhat different from that used in reference 1.

Because of the lack of over-all consistency, and the VR^2 ambiguity, the potential radii have been kept fixed at certain values for all of the light nuclei reactions. The following somewhat arbitrary values based on preliminary calculations have been adopted[3]:

$$R_{0p}=1.25 \text{ F}, \quad R_{0d}=1.4 \text{ F},$$

* This work was supported in part by the U. S. Atomic Energy Commission.
† Based on a dissertation (W. R. Smith) submitted in partial fulfillment of the requirements for the Ph.D. degree at the University of Texas.
[1] W. R. Smith and E. V. Ivash, Phys. Rev. **128**, 1175 (1962).

[2] Approximately 3000 angular distributions for light nuclei have been obtained; however, 14 parameters are involved in the calculation, not including at least two necessary to take into account spin-orbit effects.
[3] The notation used in this article agrees with that of reference 1.