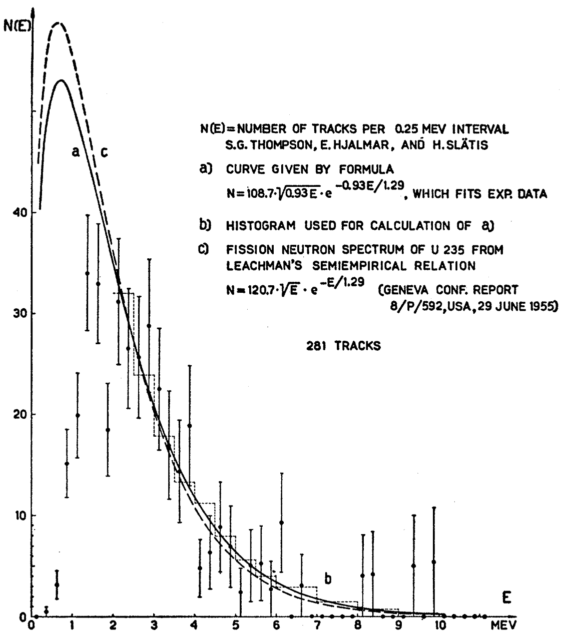

FIG. 1. Energy spectrum of neutrons from spontaneous fission of Cf^{252}.

irradiation of Pu^{239} in the Materials Testing Reactor at Arco, Idaho.[1] The source also contained some Cf^{250}, similarly produced in the irradiation. The spontaneous fission rate of the source was approximately 30 per minute and essentially all fissions were produced by Cf^{252} (the spontaneous fission half-lives are 66 years for Cf^{252} and 15 000 years for Cf^{250} [2,3]). The alpha-particle disintegration rate of the source was about 1000 per minute. The number of neutrons per fission in Cf^{252} is 3.87.[4]

The purpose of our investigation was to determine the energy spectrum of the neutrons. The essentially weightless source was prepared by the evaporation of a solution of the californium isotopes on a thin platinum foil which was covered with another foil in order to prevent alpha particles from escaping. The diameter of the active deposit was about 3 mm. The source was placed in the center of a wooden box of dimensions 35×35×50 cm on an Ilford photographic emulsion, Type C.2 of 100μ thickness (5×10 cm), and the plate was exposed to the neutrons for 14 days. After the emulsion was developed, it was examined for proton recoil tracks using an Ortholux research microscope (magnification 300). Since a small number of tracks was observed, it was necessary for the measurements to take into account all tracks, for which $|v| \leq 20°$ and $|\varphi| \leq 40°$. (v is the angle between the proton track and the emulsion plane, and φ is the projection on the emulsion plane of the angle ϑ between the direction of motion of the neutron and that of the proton, $\cos\vartheta = \cos v \cos\varphi$. The sample is mounted next to the emulsion so that the neutron paths lie in the emulsion plane.) The energies of the protons were computed using the range-energy relation of Lattes, Fowler, and Cuer,[5] and the neutron energies were obtained from the relation $E_n = E_p/\cos^2\vartheta$. A total of 281 tracks fullfilled the conditions described above. The number of neutrons per energy interval was corrected for finite emulsion thickness and for the variation of neutron cross section with energy. The shape of the resulting neutron energy spectrum as shown in Fig. 1 is similar to that for neutrons from thermal fission of U^{235}.[6,7] However, the neutron energies from Cf^{252} seem to be slightly larger than from U^{235}, possibly by about 8%. This work is being continued with the objective of obtaining a more accurate energy spectrum.

[1] See for example Thompson, Ghiorso, Harvey, and Choppin, Phys. Rev. **93**, 908 (1954).
[2] Ghiorso, Thompson, Choppin, and Harvey, Phys. Rev. **94**, 1081 (1954).
[3] Diamond, Magnusson, Mech, Stevens, Friedman, Studier, Fields, and Huizenga, Phys. Rev. **94**, 1083 (1954).
[4] Diven, Martin, and Terrell, according to reference 6.
[5] Lattes, Fowler, and Cuer, Proc. Roy. Soc. (London) **59**, 883 (1947).
[6] R. B. Leachman, Proceedings of the Geneva Conference on the Peaceful Uses of Atomic Energy, A/CONF. 8/P/592, USA, 1955.
[7] B. E. Watt, Phys. Rev. **87**, 1037 (1952).

Radiations from 1− States in Even-Even Nuclei*

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IT has become well established that for even-even nuclei in the region well above the closed shell of 82 protons and 126 neutrons, there exist low-lying energy levels with spin and parity assignments 0+, 2+, 4+, etc.[1,2] Such a sequence of levels is described as a rotational band because the spins, parities, and energy spacing conform with the expectations of rotational states according to the Bohr-Mottelson unified

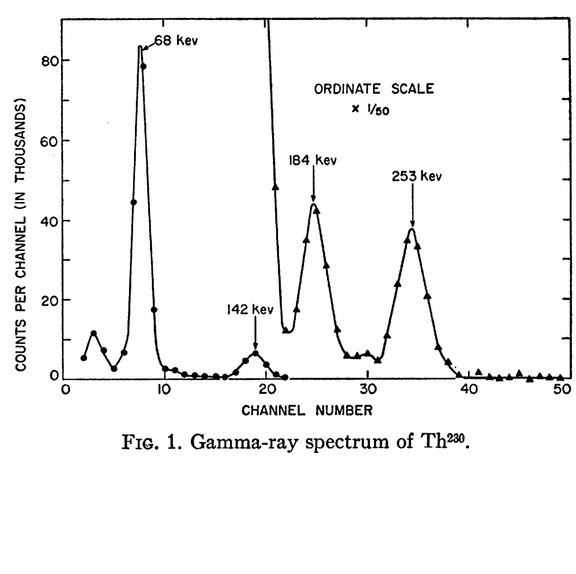

FIG. 1. Gamma-ray spectrum of Th^{230}.

nuclear model.[3] Recently, additional low-lying states have been found in this region which are apparently not members of this rotational band. They have spin 1 and odd parity and were the subject of a previous paper[4] in which the evidence for this assignment was presented. Briefly, this evidence consisted of conversion coefficient data in the case of Th^{228} decay,[5] as well as rather unambiguous alpha-gamma angular correlation data in the decay of Th^{226}, Th^{228}, and U^{230}.[4] In each case where a 1− state was positively identified the state was de-excited by gamma transitions both to the 0+ and 2+ states.

In addition to the three alpha emitters just mentioned, two others, Th^{230} and U^{232}, were included in the earlier paper[4] as cases which led to a probable 1− state although angular correlation measurements were not made. To this group should now be added Cm^{242}. For those cases in which angular correlation data could not be obtained, the main evidence for this assignment was the observation of a pair of gamma rays in almost equal intensity which differed in energy by just the energy of the first excited state (2+). For example, in Cm^{242} decay, gamma rays of 605 and 562 kev were found[6] and these differ by 43±5 kev, which agrees with 44.11 kev[7] measured for the first excited state of Pu^{238}. For Th^{230} and U^{232} decay, not only did the energy difference of two gamma rays agree with the spacing of the 2+ state, but the gamma ray of lower energy of each pair was found to be in coincidence with the 2+→0+ transition.

The gamma-ray spectrum of Th^{230} taken with a sodium iodide scintillation spectrometer is shown in Fig. 1 as typical of the group. The two probable *E*1 gamma rays are at 184 and 253 kev. In Fig. 2, the decay scheme of Th^{230} is shown, and again this is typical except that in some cases the 1− state lies slightly below the 4+ state and in one instance (excited states of Th^{226}) the two levels are within a few kev of each other and have not yet been resolved.

From gamma-ray spectra such as that shown in Fig. 1, the relative intensities of the two *E*1 transitions were obtained by integration of the two respective photopeaks. Corrections for counting efficiency, escape peak, and background radiations were made. It was then

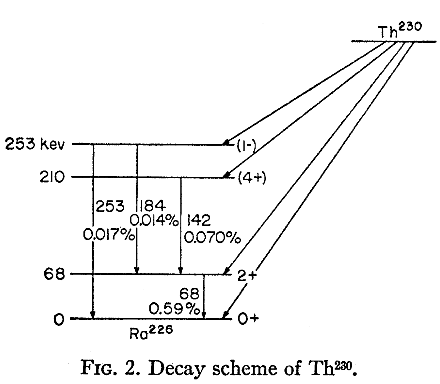

FIG. 2. Decay scheme of Th^{230}.

TABLE I. Reduced gamma-ray transition probabilities from 1− states.[a]

Parent emitter	Daughter nucleus	Energy γ_0	Energy γ_2	Red. trans. prob. γ_0/γ_2	References for γ-ray energies and abundances	Hindrance factors for α groups to 1− states
Cm^{242}	Pu^{238}	605	562	0.60±0.15	b	1000
U^{232}	Th^{228}	326	268	0.43±0.08	c,d	70
Ac^{226},U^{230}	Th^{226}	232	159	0.51±0.15	e,f	11
Th^{230}	Ra^{226}	253	184	0.49±0.08	g	40
Th^{228}	Ra^{224}	217	133	0.36±0.15	g	10
Th^{226}	Ra^{222}	242	130	0.48±0.15	e	4.0

[a] γ_x represents the transition from the 1− state to the state of spin *x*.
[b] See reference 6.
[c] F. Asaro and I. Perlman, Phys. Rev. 99, 37 (1955).
[d] Scharff-Goldhaber, der Mateosian, Harbottle, and McKeown, Phys. Rev. 99, 180 (1955).
[e] F. Asaro and I. Perlman (unpublished data).
[f] J. R. Grover and G. T. Seaborg (unpublished data).
[g] Stephens, Asaro, and Perlman (unpublished data).

possible to obtain the reduced transition probabilities by removing the expected third-power Weisskopf energy dependence. The result of this treatment is shown in column 5 of Table I and the significance will be discussed presently.

Although the limits of error are rather large, the data are all consistent with a value of 0.5 for the ratio γ_0/γ_2 of the reduced transition probabilities. The large limits of error are due to the difficulties in obtaining good gamma-ray intensity data; however, an attempt is being made to improve the limits on some of the more favorable cases.

The type of configuration for an odd-parity state at an excitation of only a few hundred kev in an even-even nucleus has not yet come up for discussion. A suggestion has been made,[8] however, that this state may have the same intrinsic structure as the ground state and represents a collective distortion in which the nucleus is pear-shaped. On this basis this state would belong to the quantum number $K=0$ configuration of the ground state, a supposition which can be checked by comparing gamma-transition probabilities to the 0+ and 2+ states. Following the treatment of Alaga, Alder, Bohr, and Mottelson,[9] the reduced transition probabilities of gamma rays leading from a particular state to two members of a rotational band would depend simply upon the geometrical factors of the transition and are expressed by the vector addition coefficients. In the present case the two gamma rays are electric dipole and the question is whether the 1− state belongs to $K=0$ or $K=1$. It turns out that if $K=0$ the reduced transition probability ratio γ_0/γ_2 is 0.5, and if $K=1$ the ratio is 2.0. Clearly, from the data shown in Table I, $K=0$ satisfies all cases and $K=1$, none.

All of the 1− states which we have observed have been populated to some extent by alpha emission. If we compare the abundance of the alpha group to the ground state with that of the group to the 1− state and remove the energy dependence by spin-independent alpha-decay theory,[10] we have a ratio of reduced alpha-particle transition probabilities more commonly known as "hindrance factors." These hindrance factors are also shown in Table I (column 7).

No explanation can be advanced at present as to why some of these analogous alpha transitions are relatively highly favored compared with others. The data do seem to correlate with atomic number and with neutron number for a given element.

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[1] I. Perlman and F. Asaro, Ann. Rev. Nuc. Sci. **4**, 157 (1954).
[2] A. Bohr, Phys. Rev. **90**, 717 (1953).
[3] A. Bohr and B. R. Mottelson, Kgl. Danske Videnskab. Selskab Mat.-fys. Medd. **27**, No. 16 (1953); A. Bohr, *Rotational States of Atomic Nuclei* (Ejnar Munksgaard, Copenhagen, 1954).
[4] Stephens, Asaro, and Perlman, Phys. Rev. **96**, 1568 (1954).
[5] Asaro, Stephens, and Perlman, Phys. Rev. **92**, 1495 (1953).
[6] Asaro, Harvey, and Perlman (unpublished data).
[7] W. G. Smith and J. M. Hollander, University of California Radiation Laboratory Unclassified Report No. UCRL-2974-Rev., 1955, (unpublished).
[8] A. Bohr (private communication of a suggestion by R. Christy).
[9] Alaga, Alder, Bohr, and Mottelson, Kgl. Danske Videnskab. Selskab, Mat-fys. Medd. (to be published).
[10] I. Kaplan, Phys. Rev. **81**, 962 (1951).

Angular Distribution of Gamma Rays in Coulomb Excitation*

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PREVIOUSLY reported calculations[1,2] of the angular correlation coefficient a_2 for Coulomb excitation of the 330-kev level in Pt^{194} have been expanded to include a_4, and similar calculations have been carried out for the 550-kev level of Cd^{114}. The formulas used were those in the literature[3] with signs corrected according to Breit, Ebel, and Russell.[4]

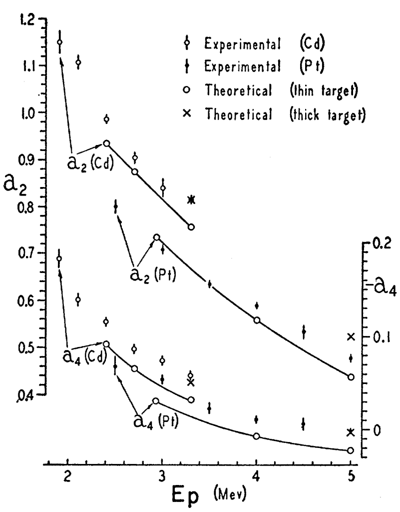

FIG. 1. Angular correlation coefficients a_2 and a_4 plotted against proton energy E_p. Circled points give thin target theoretical values for Pt^{194} and Cd^{114}. Experimental points are given by dots (Pt) or circles (Cd) with vertical spreads. The crosses give theoretical values corrected for thickness of target and admixture of Pt^{196}. The scale for a_2 is at the left, that for a_4 at the right.

The semiclassical approximation for radial matrix elements was used[5] and checked against direct calculation in typical cases. The error in a_2 is estimated to be about one percent, that in a_4 may be larger due to stronger cancellation. It proved sufficient to limit the calculation to values of angular momentum $L \leq 40$. The coefficients given here for Cd^{114} agree with those of Goldstein *et al.*[6]

Thick-target corrections have been roughly estimated for the highest proton energy in each case following McGowan and Stelson.[7] Use was made of their values of the energy loss weighting factor φ and the multiple scattering attenuation coefficients. For Pt a rough allowance for the presence of Pt^{196} with a 358-kev level has been included with the thick target corrections. In Fig. 1, the theoretical results are plotted together with the experimental values for Pt[7] and Cd.[8] The thin-target coefficients have the correct dependence on energy and on nuclear charge. The thick-target correction brings about agreement with experiment in some cases but not in all.

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[1] Breit, Ebel, and Benedict, Phys. Rev. **100**, 428 (1955).
[2] F. D. Benedict, Phys. Rev. (to be published).
[3] L. C. Biedenharn and C. M. Class, Phys. Rev. **98**, 691 (1955).
[4] Breit, Ebel, and Russell (to be published).
[5] K. A. Ter-Martirosyan, J. Exptl. Theoret. Phys. (U.S.S.R.) **22**, 284 (1952); G. Breit and P. B. Daitch, Phys. Rev. **96**, 1447 (1954); Benedict, Daitch, and Breit, Phys. Rev. (to be published), and references in last mentioned paper.
[6] Goldstein, McHale, Thaler, and Biedenharn, Phys. Rev. **100**, 435 (1955).
[7] F. K. McGowan and P. H. Stelson, Phys. Rev. **99**, 127 (1955).
[8] F. K. McGowan and P. H. Stelson (private communication to Professor G. Breit).

Anomalous Neutral *V*-Particles*

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IN view of the current interest in the problem of whether there exist neutral curious particles which undergo three-body decay, and if so what is the nature of these particles, a search has been made for the so-called anomalous neutral decays among photographs of *V*-particles obtained from the Princeton dual cloud chamber at Echo Lake, Colorado.[1] Much of the previous work in this field has been summarized by Astbury.[2]