Ratios of Independent Yields of the Isomers $Te^{131-131m}$ and $Te^{133-133m}$ in Fission*

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The independent yield ratios of (30-h Te^{131m})/(25-min Te^{131}) and of (53-min Te^{133m})/(12.5-min Te^{133}) were measured in the following types of fission: U^{235} with thermal neutrons, and Th^{232} and U^{238} with 18-MeV deuterons and with 33-MeV He^4 ions. The fractional independent chain yields of the isomers were measured by determining the growth curves of the daughter iodine activities extracted at successive time intervals from aliquots of samples containing tellurium activities quickly separated from fission induced in short irradiations, and correcting for contributions from precursors. The isomer-yield ratios for independent formation for 30-h Te^{131m}/25-min Te^{131} and for 53-min Te^{133m}/12.5-min Te^{133}, respectively, are as follows: 1.8 ± 0.4 and 1.55 ± 0.5 for $U^{235}(n_{th},F)$, 3.3 ± 0.5 and 2.8 ± 1.7 for $Th^{232}(\alpha_{33},F)$, 2.7 ± 0.5 and 1.7 ± 0.9 for $Th^{232}(d_{18},F)$, 5.0 ± 1.0 and 3.1 ± 2.0 for $U^{238}(\alpha_{33},F)$, and 3.3 ± 0.5 and 1.8 ± 1.1 for $U^{238}(d_{18},F)$. The fractional independent chain yield of $Te^{131m}+Te^{131}$ was measured as 0.124 ± 0.014 for $U^{235}(n_{th},F)$. The fraction of decay of Sb^{131} to Te^{131m} was measured and found to be $6.8\pm1\%$. On the basis of the measured isomer ratios, the intrinsic spin of the primary fragment (leading by the emission of neutrons and γ rays to the secondary fragments studied) was estimated. The calculations indicate that in thermal-neutron fission an appreciably larger spin ($\sim5\hbar$) than that of the compound nucleus must be assigned to the heavy primary fragment in order to explain the observed isomer ratios in Te^{131} and Te^{133}. Similar reasoning in the 33-MeV He^4-ion fission of Th^{232} indicates that the primary fragment must be given an intrinsic spin value roughly $7\hbar$.

I. INTRODUCTION

DURING the past few years efforts have been made to obtain information on the distribution of angular momentum in the fission process. A measure of the orbital angular momentum between the fission fragments is obtained from angular distributions of the fission fragments.[1–6] From these measurements it is indicated that, in general, a small fraction of the angular momentum of the compound nucleus is distributed as orbital angular momentum between the fragments for low or medium energy neutron, deuteron, or helium-ion fission. The rest of the angular momentum should appear as intrinsic spins of the two fragments.

A more direct measure of the intrinsic spin of the fragments can in principle be obtained from measurements of the ratios of yields of isomers of the fragments. Relatively few careful measurements of this type have been done.[7–11] Most of the work reported refers to medium- or high-energy fission. Due to the short β^--decay chains in these cases, independent isomer ratios could in some cases be determined directly or inferred from cumulative-yield measurements. A trend of increasing high-to-low-spin isomer ratio with increasing energy of the bombarding particle is observed. This result is to be expected because the amount of angular momentum deposited in the compound nucleus increases with increasing energy and mass of the projectile. No independent yield ratios in thermal neutron fission have been published in detail.

In this work the isomer ratios of Te^{131m}/Te^{131} and Te^{133m}/Te^{133} in thermal neutron fission of U^{235} were measured and compared with the results from medium-energy charged-particle-induced fission. The charged-particle reactions chosen[12] were $Th^{232}(\alpha_{33},F)$ [leading to the same compound system as $U^{235}(n_{th},F)$], $Th^{232}(d_{18},F)$, $U^{238}(\alpha_{33},F)$, and $U^{238}(d_{18},F)$. The fraction of β^- decay of Sb^{131} to Te^{131m} was measured because knowledge of this quantity is required for the calculation of the independent Te^{131m} and Te^{131} yields.

II. EXPERIMENTAL PROCEDURE

A. Irradiations and Bombardments

Targets of ~200 mg of natural uranium as ammonium uranyl carbonate were irradiated in the thermal neutron flux of the MIT reactor. Use of the pneumatic tube system made possible quick access to the irradiated samples, which were available for chemical operations within 15 to 25 sec after the end of the irradiation.

For the charged-particle experiments, foils of natural

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[2] J. R. Huizenga and R. Vandenbosch, in *Nuclear Reactions*, edited by P. M. Endt and P. B. Smith (North-Holland Publishing Company, Amsterdam, 1962), Vol. 2, Chap. 2.

[3] I. Halpern and V. M. Strutinski, in *Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958* (United Nations, Geneva, 1958), Vol. 15, p. 408.

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[11] H. Warhanek and R. Vandenbosch, J. Inorg. Nucl. Chem. **26**, 669 (1964).

[12] F refers to fission and the subscript to the energy of the projectile in MeV or "th" for thermal.

uranium (137 mg/cm^2) and thorium (70.9 mg/cm^2) were bombarded in the external beam of the Brookhaven National Laboratory cyclotron. The reduction of the energy of the deuteron and He^4-ion beams by the target wrapping and the target foils was determined from range-energy curves.[13] The average energies of the deuterons and He^4 ions causing fission in the reactions $U^{238}(d,F)$, $Th^{232}(d,F)$, $Th^{232}(\alpha,F)$, and $U^{238}(\alpha,F)$ were 18.1, 18.6, 33.3, and 33.4 MeV, respectively.

In the thermal neutron experiments, the irradiation times were 45 sec; in the deuteron experiments, 10 to 20 sec; and in the He^4-ion experiments, 1 min.

B. Chemistry

Branching-Ratio Experiments

The branching fraction of Sb^{131} decaying to Te^{131m} was measured in experiments in which antimony was cleanly separated from tellurium, tin, and iodine activities of freshly made fission products. From the antimony in solution, the granddaughter I^{131} was extracted at appropriate growth times, and the growth curves were constructed after correction for iodine chemical yield.

The irradiated ammonium uranyl carbonate samples were dissolved in 40 ml of concentrated HCl containing ~20 mg Sb(III), 10 mg Te(IV), 10 mg Te(VI), 20 mg I^-, and 20 mg Mo(VI) carriers in a separatory funnel. Oxidation was achieved by adding 5 ml of 5% NaOCl solution, followed by extraction with 20 ml of isopropyl ether saturated with concentrated HCl. The antimony was back-extracted as Sb(III) by shaking with 10 ml of 15% hydrazinium hydrochloride (N_2H_5Cl-HCl) solution containing 50 mg KSCN. The aqueous phase was washed with 10 ml of isopropyl ether; then 10 mg of mixed-valence tellurium carrier was added, and the solution was boiled. The precipitated tellurium was filtered and discarded, and the separation time was taken as the middle of the filtration. The filtrate containing the Sb(III) was collected in a 100-ml volumetric flask containing 200 mg I^- in alkaline solution. From aliquots of this solution, I_2 was extracted at appropriate times by the standard CCl_4 extraction methods[14] and counted for I^{131}.

Isomer-Ratio Experiments

The tellurium isomer ratios were determined in experiments in which tellurium was quickly separated from fission products, free from antimony and iodine activities. This was done by dissolving the target material in boiling 3*M* HCl solution (15 ml) containing 20 mg each of Te(IV), Te(VI), I^-, and Sb(III). To the target solution, 5 ml of a 15% solution of N_2H_5Cl-HCl was added, and SO_2 was bubbled through to precipitate elemental tellurium. The reaction vessel, with fritted bottom, was connected with a bell-type vacuum-filtering apparatus in which a 100-ml volumetric flask collected the filtrate without intermediate transferring. The tellurium separation time was taken as the middle of filtration. The elemental tellurium was dissolved in aqua regia after three washings with 3*M* HCl solution. From suitable aliquots of this solution, containing 200 mg I^- carrier and kept alkaline, I_2 was extracted[14] at appropriate times. These samples containing the iodine carrier as I^-, were kept for about 50 h, then boiled to expel the xenon activities formed, and promptly counted for I^{131} and I^{133}. Data were taken for times of about 5, 10, 18, 35, 70, and 140 min, and at five more times up to 300 h, after tellurium separation.

In the thermal neutron experiments the tellurium separation times were between 1 and 1.5 min after the end of irradiation. In the charged-particle experiments, separation times were from 3 to 4 min, due to foil dissolution problems. The longer times in the latter case could be tolerated, however, because of the higher Te^{131} and Te^{133} fractional chain yields in the charged-particle cases.

C. Counting

The method applied here was the construction of the integral growth curve of I^{131} and I^{133} obtained in the decay of the two isomeric pairs Te^{131m}, Te^{131} and Te^{133m}, Te^{133}. The counting of the iodine samples was chosen to provide only two-component gross decay curves (without perturbation from 12-day Xe^{131m}, 5.3-day Xe^{133}, 2.3-day Xe^{133m}, and 9.1-h Xe^{135}). A few hours after the separation of iodine from tellurium, the main radiations come from 6.7-h I^{135}, 20.8-h I^{133}, and 8.05-day I^{131} (here the 2.3-h I^{132} and 52-min I^{134} do not interfere), but at later times the xenon activities mentioned above build up. By allowing 50- to 60-h decay time and boiling the samples, the interference from 6.7-h I^{135} and 9.1-h Xe^{135} was eliminated. A survey of the decay schemes of the nuclides in question[15] showed that by counting the γ rays falling in the energy band 170 to 2000 keV, all other interfering activities (in particular the abundant 80-keV γ ray from 5.3-day Xe^{133}) were eliminated.

The detectors used were 2.0-×2.0-in. well-type NaI(Tl) crystals. No counting efficiency corrections were needed as only relative disintegration rates were required. The total chain activities were measured by separating the iodine activities from an aliquot of the target solution after complete decay of the mass 133 and 131 chains to 20.8-h I^{133} and 8.05-day I^{131}. Thus, after appropriate corrections for growth-decay and chemical yields, the fractional chain yields were obtained as the ratio of the activity of the iodine from the quickly separated tellurium to that in the sample representing the total chain activity.

In the charged-particle experiments the samples were

[13] M. Rich and R. Madey, University of California Radiation Laboratory Report UCRL-2301, 1954 (unpublished).

[14] J. Kleinberg and G. A. Cowan, *Nuclear Science Series Report* NAS-NS 3005 (National Academy of Sciences-National Research Council, 1960), p. 31.

[15] *Nuclear Data Sheets*, compiled by K. Way *et al.* (National Academy of Sciences—National Research Council, Washington, D. C., 1962).

simultaneously followed for decay by recording the γ rays in the bands 170 to 2000 keV and 380 to 2000 keV. The latter type of counting gave a higher 20.8-h I^{133} component than the 8.05-day I^{131} component (which gives mostly 350-keV γ rays), which allowed for more accurate determination of the 20.8-h I^{133}. This procedure was necessary because the fractional chain yield of the Te^{131} increases more than that of the Te^{133} as we go from thermal-neutron- to charged-particle-induced fission.

The analysis of the iodine decay curves into the 20.8-h and 8.05-day components was performed by the least-squares technique using the FRANTIC computer program.[16]

The counting of the iodine samples for the Sb^{131} branching to Te^{131m} was done using the same counting system discussed above.

III. RESULTS

A. Analysis of the Isomer-Ratio Data

In view of the fact that a large number of activities having similar half-lives is involved in this problem, the milking procedure outlined above was used in the determination of the fractional chain yields of the Te^{131} and Te^{133} isomeric pairs. From the integral growth curves for I^{131} and I^{133}, one can determine the activities of Te^{131m}, Te^{131} and Te^{133m}, Te^{133} in the following way. Consider, as an example, the results from $U^{235}(n_{th},F)Te^{131}$. In Fig. 1, curve B gives the growth curve for I^{131}, which was constructed from the I^{131} activities extrapolated to the milking time after correction for iodine chemical yield. Curve A is the asymptote of B having a half-life of 8.05 days and is obtained from points that are off the abscissa scale in Fig. 1. Curve C, also plotted as D on the upper time scale is curve A minus B, and E is its short-lived component. It can be seen that the difference of B from A yields C or D, a two-component decay curve with half-lives of 30-h Te^{131m} (C) and 25-min Te^{131} (E). The effective zero-time (tellurium separation) activities $A_m{}^{\text{eff}}(0)$, $A_g{}^{\text{eff}}(0)$ are related to the true Te^{131m} and Te^{131} zero-time activities $A_m(0)$, $A_g(0)$ through the relations given in Appendix A. Figure 2 gives typical growth curves obtained in $U^{235}(n_{th},F)Te^{131m,131}$, $Th^{232}(\alpha_{33},F)Te^{131m,131}$, $U^{238}(\alpha_{33},F)Te^{131m,131}$, and the hypothetical curve corresponding to Te^{131m}/Te^{131} produced in the relative amounts of secular equilibrium $[A_g{}^{\text{eff}}(0)=0]$. This shows that the relative amount of ground state falls on going from thermal fission to charged-particle fission.

Since the nuclides under study are not shielded, corrections must be applied for the contribution to the measured activities due to decay of precursors during irradiation and subsequent decay to the time of the tellurium separation. In order to avoid serious errors, the corrections were evaluated using the exact equations for growth during irradiation and subsequent decay to the separation time. The antimony and tin precursors for both mass numbers 131 and 133 were included in the calculations. These corrections were evaluated using a computer program[17] written for

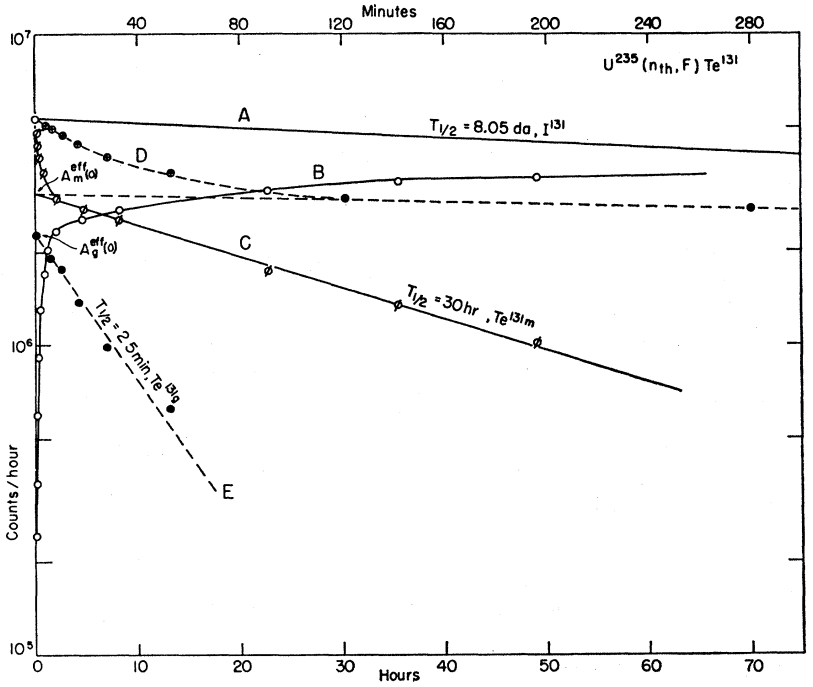


FIG. 1. Analysis of the I^{131} growth curve obtained in the decay of $Te^{131m}+Te^{131}$, which was quickly separated from the fission products in $U^{235}(n_{th},F)$. Curve A is the asymptote of the growth curve, and is obtained by extrapolation of points that are off scale (refer to bottom time scale). Curve B is the I^{131} growth curve (refer to bottom scale). Curve C is the decay curve of $Te^{131m}+Te^{131}$ obtained by subtracting B from A (refer to bottom scale). Curve D is the decay curve C plotted in the upper time scale. Curve E is the decay curve of Te^{131g} plotted in the upper time scale.

[16] P. C. Rogers, Massachusetts Institute of Technology Laboratory for Nuclear Science, Technical Report No. 76 (NYO-2303), 1961 (unpublished).

[17] D. G. Sarantites, Ph.D. thesis, Massachusetts Institute of Technology, 1963 (unpublished).

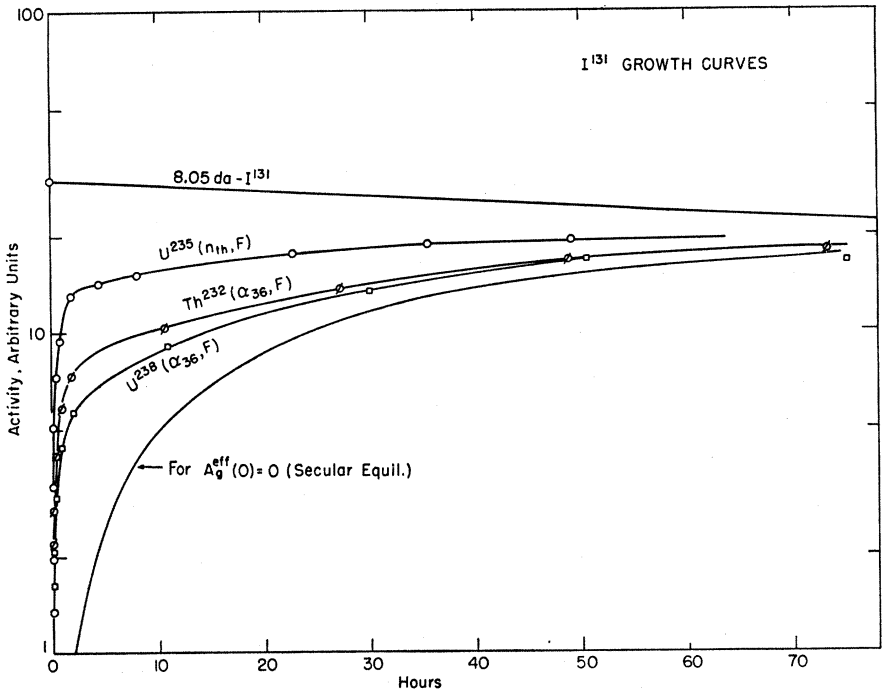


FIG. 2. Normalized I^{131} growth curves obtained in the decay of $Te^{131m}+Te^{131g}$ from $U^{235}(n_{th},F)$, $Th^{232}(\alpha,F)$, and $U^{238}(\alpha,F)$. These curves are normalized to the same asymptotic activity.

the Bateman equations in the general form, including possible branching in the chain. The use of this program made possible the investigation of the effects upon the corrected isomer-yield ratios of uncertainties in the decay properties of the nuclides involved and of uncertainties in choice of most probable charge Z_P for the two chains. Here a Gaussian charge dispersion was used for the fractional chain yield f^i, namely,

$$f^i=(\pi C)^{-1/2}\exp[-(Z-Z_P)^2/C] \qquad (1)$$

with $C=0.94$ (see, for example, Ref. 18). The values of the most probable charge, Z_P, in the charged-particle cases were taken from the data of Storms[19] on the chains 135 and 133 by extrapolation to 131 and correction for the excitation energy according to the prescription given by Coryell, Kaplan, and Fink.[20]

The necessary data and the results are presented in Table I. The fourth and fifth columns of Table I give $A_m^{\text{eff}}(0)$ and $A_g^{\text{eff}}(0)$, the effective activities for the

TABLE I. Experimental data and results on the independent yield ratios of $Te^{131m,131}$ and $Te^{133m,133}$.

Reaction		Irrad. time (min)	Separ. time (min)	$A_m^{\text{eff}}(0)$ (10^6 counts/h)	$A_g^{\text{eff}}(0)$ (10^6 counts/h)	Z_P	$f_m^i+f_g^i$ $C=0.94$ (calc.)	f_m/f_g (uncorrected)	σ_m/σ_g
$U^{235}(n_{th},F)Te^{131}$	No. 1	0.75	1.00±0.10	3.10± 0.05	2.29± 0.05	50.75	0.110[a]	1.097	1.65
$U^{235}(n_{th},F)Te^{131}$	No. 2	0.75	1.45±0.20	3.95± 0.10	2.55± 0.10	50.75	0.110[a]	1.239	2.00 } 1.8 ±0.4
$U^{235}(n_{th},F)Te^{131}$	No. 3	1.00	1.25±0.20	2.23± 0.15	1.40± 0.20	50.75	0.110[a]	1.249	1.90
$Th^{232}(\alpha_{33},F)Te^{131}$		1.00	4.0 ±0.5	2.40± 0.10	0.60± 0.10	52.23	0.545	2.970	3.3±0.5
$Th^{232}(d_{18},F)Te^{131}$		0.16_7	4.0 ±0.5	1.25± 0.05	0.38± 0.05	52.16	0.567	2.494	2.7±0.5
$U^{238}(\alpha_{33},F)Te^{131}$		1.00	3.5 ±0.5	1.70± 0.05	0.29± 0.05	52.24	0.545	4.371	5.0±1.0
$U^{238}(d_{18},F)Te^{131}$		0.33_3	3.5 ±0.5	1.37± 0.05	0.37± 0.05	52.01	0.582	2.800	3.3±0.5
$U^{235}(n_{th},F)Te^{133}$	No. 1	0.75	1.00±0.10	314 ±12	144 ±8	51.57	0.430	1.77	1.59 } 1.55±0.5
$U^{235}(n_{th},F)Te^{133}$	No. 2	0.75	1.45±0.20	297 ±23	162 ±30	51.57	0.430	1.53	1.50
$Th^{232}(\alpha_{33},F)Te^{133}$		1.00	4.0 ±0.5	5.1 ± 0.3	1.3 ± 0.8	52.79	0.300	2.7	2.8±1.7
$Th^{232}(d_{18},F)Te^{133}$		0.16_7	4.0 ±0.5	4.7 ± 0.2	2.0 ± 1.0	52.59	0.400	1.7	1.7±0.9
$U^{238}(\alpha_{33},F)Te^{133}$		1.00	3.5 ±0.5	3.5 ± 0.3	0.8 ± 0.6	52.78	0.303	3.0	3.1±2.0
$U^{238}(d_{18},F)Te^{133}$		0.33_3	3.5 ±0.5	3.9 ± 0.2	1.6 ± 1.0	52.56	0.412	1.8	1.8±1.1

[a] Value taken from Ref. 18.

[18] A. C. Wahl, R. L. Ferguson, D. R. Nethaway, D. E. Troutner, and K. Wolfsberg, Phys. Rev. **126**, 1112 (1962).
[19] H. A. Storms, Ph.D. thesis, Massachusetts Institute of Technology, 1962 (unpublished).
[20] C. D. Coryell, M. Kaplan, and R. D. Fink, Can. J. Chem. **39**, 646 (1961).

metastable and ground state at the tellurium separation time as obtained from the analysis of the iodine decay curves. The seventh column gives the values for the total independent chain yield for the tellurium isomers $f_{Te}{}^{i}=f_{Tem}{}^{i}+f_{Teg}{}^{i}$, obtained using the Z_P values of column six. The last two columns in Table I give the isomer yield ratios, uncorrected and corrected for precursor decay, respectively. The ratio of the independent yields $f_m{}^{i}/f_g{}^{i}$ is equal to the ratio of the cross sections σ_m/σ_g. The magnitude of corrections for precursor decay in the cases of the metastable and the ground state were about 1% and 40 to 50% in $U^{235}(n_{th},F)Te^{131}$, respectively, and less than 1% and 15 to 25%, respectively, for the rest of the cases in Te^{131}. In the Te^{133} case the corrections were invariably less than 10%. The half-lives and branching fractions used in the calculations are given in Table II.[21,22,23] The corrected isomer ratios were found to be rather insensitive to small variations in the branching fraction of Sb^{131} to Te^{131m}, to the half-life of Sn^{131}, and to the assumed Z_P. In the thermal neutron case only, the ratio is rather sensitive to the half-life of Sb^{131}. For example, in the worst case [Run No. 2 of $U^{235}(n_{th},F)Te^{131}$ in Table I], using a half-life of 19.4 min for Sb^{131} increases σ_m/σ_g by 30% over the value obtained with the assumed 23-min half-life. The assigned errors in the results cover the changes which might arise from these uncertainties.

The fractional chain yield of $Te^{131m}+Te^{131}$ for thermal neutron fission was found to be 0.124 ± 0.014, compared with 0.110 used for the Z_P calculations.[18]

The analysis of the growth curves of I^{131} for the $Te^{131m-131}$ yields was straightforward, as shown in Fig. 1, and from three thermal neutron runs independent corroboration of the half-lives was also obtained: Te^{131m}, 30 ± 2 h, and Te^{131}, 25 ± 2 min. The runs for $Te^{133m-133}$ were more difficult to analyze because the half-lives are shorter and closer together. During the course of this investigation, Dr. Prussin[23] informed us of his study of Te^{133g} which provides the half-life 12.45 ± 0.3 min, replacing the older value[21] of 2 min. The growth curves for I^{133} were analyzed by computer[16] for three components: a positive amount $A_I{}^{eff}(0)$ of I^{133} decaying with half-life of 20.8 h, and negative amounts $-A_m{}^{eff}(0)$ and $-A_g{}^{eff}(0)$ decaying with half-lives of 53 min and 12.45 min. The computer program was also modified to introduce the constraint, $A_I{}^{eff}(0)-A_m{}^{eff}(0)-A_g{}^{eff}(0)=0$, required by the decay laws. This modification reduces the degrees of freedom by one and seemed to give unsatisfactory results for the very limited number of points available. The values of $A_I{}^{eff}(0)$ and $A_m{}^{eff}(0)$ were rather well determined by the unmodified program. It was decided to take $A_g{}^{eff}(0)$ as the difference between these, assigning a rather large uncertainty in the value. The better runs gave independent evidence for the 12.45-min half-life of Te^{133}; Dr. C. E. Bemis of our laboratory has also confirmation of the species.

TABLE II. Decay properties used in the calculation of the independent isomer ratios.

Nuclide	Half-life	Branching fraction to
Sn^{131}	3.4 min[a]	
Sn^{133}	30 sec[b]	
Sb^{131}	23 min[a]	Te^{131m}, 6.8%[c]
Sb^{133}	2.64 min[b]	Te^{133m}, 72%[a]
Te^{131m}	30 h[a,c]	Te^{131}, 19%[d]
Te^{131}	25 min[a,c]	
Te^{133m}	53 min[a]	Te^{133}, 13%[d]
Te^{133}	12.45 min[e]	
I^{131}	8.05 day[a]	
I^{133}	20.8 h[a]	

[a] See Ref. 21. [b] See Ref. 22. [c] This work. [d] See Ref. 15. [e] See Ref. 23.

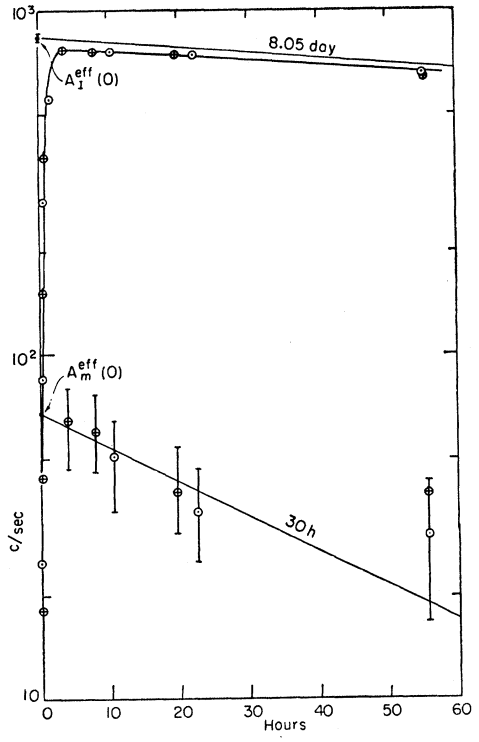


FIG. 3. Analysis of the growth curve of I^{131} obtained in the decay of Sb^{131} data from two independent experiments for the branching of Sb^{131} to the Te^{131} isomers. The asymptotic curve with slope of 8.05 days is based on two points that are off scale. ⊙ data from Experiment No. 1. ⊕ data from Experiment No. 2.

B. Sb^{131} Branching-Ratio Experiments

For the measurement of the branching of Sb^{131} to Te^{131m}, the growth curve of the granddaughter I^{131} was determined as discussed in Sec. IIB. Figure 3 shows the result of two experiments normalized to the same asymptotic activity. The asymptotic activity with half-life of

[21] S. Katcoff, Nucleonics 18, 201 (1960).
[22] P. O. Strom, paper given at the Discussion on Nuclear Chemistry (Fission and Other Low Energy Nuclear Processes), University of Oxford, 1962 (unpublished).
[23] S. G. Prussin (private communication).

TABLE III. Independent isomer-yield ratios in fission.

Target	Projectile	Projectile energy (MeV)	Isomer pair	Spin of isomers m	Spin of isomers g	σ_m/σ_g	$\frac{\sigma_m}{\sigma_m+\sigma_g}$
U^{238} [a]	α	42	Cs^{134}	8	4	4.27	0.81
U^{238} [a]	α	30	Cs^{134}	8	4	2.33	0.70
U^{235} [a]	α	42	Cs^{134}	8	4	3.35	0.77
U^{235} [a]	α	42	Cs^{134}	8	4	1.38[d]	0.58[d]
U^{235} [a]	α	27	Cs^{134}	8	4	1.27	0.56
U^{235} [a]	d	21	Cs^{134}	8	4	1.63	0.62
U^{233} [a]	α	42	Cs^{134}	8	4	2.23	0.69
U^{233} [a]	α	42	Cs^{134}	8	4	1.94[d]	0.66[d]
U^{233} [a]	γ	16	Cs^{134}	8	4	0.75[d]	0.43[d]
U^{235} [b]	n	thermal	Te^{131}	11/2	3/2	1.80	0.64
U^{235} [c]	n	thermal	Te^{131}	11/2	3/2	1.7	0.63
Th^{232} [b]	α	33	Te^{131}	11/2	3/2	3.3	0.77
Th^{232} [b]	d	18	Te^{131}	11/2	3/2	2.7	0.73
U^{238} [b]	α	33	Te^{131}	11/2	3/2	5.0	0.83
U^{238} [b]	d	18	Te^{131}	11/2	3/2	3.3	0.77
U^{233} [c]	n	thermal	Te^{131}	11/2	3/2	2.1	0.68
Pu^{239} [c]	n	thermal	Te^{131}	11/2	3/2	3.4	0.77
U^{235} [b]	n	thermal	Te^{133}	11/2	3/2	1.55	0.61
Th^{232} [b]	α	33	Te^{133}	11/2	3/2	2.8	0.74
Th^{232} [b]	d	18	Te^{133}	11/2	3/2	1.7	0.63
U^{238} [b]	α	33	Te^{133}	11/2	3/2	3.1	0.76
U^{238} [b]	d	18	Te^{133}	11/2	3/2	1.8	0.64

[a] See Ref. 11.
[b] This work.
[c] See Ref. 24.
[d] Isomer ratio determined by anticoincidence counting.

8.05 days is determined from points that are off the scale. Extrapolation of this asymptotic activity to the time of purification of antimony yields $A_1^{\text{eff}}(0)$. The difference of the later part of the growth curve ($t>5$ h) from its asymptote yields a decay curve with the half-life of 30-h Te^{131m} having an extrapolated value $A_m^{\text{eff}}(0)$. It is shown in Appendix B that in this particular case the fraction of the decay of Sb^{131} to Te^{131m} is given by

$$F_1=0.835R/(1-0.152R),$$

where $R=A_m^{\text{eff}}(0)/A_1^{\text{eff}}(0)$. The experimental values for $A_m^{\text{eff}}(0)$ and $A_1^{\text{eff}}(0)$ were 68 ± 10 and 840 ± 20 arbitrary units, giving $F_1=6.8\pm1.0\%$. This is in accord with $5.5\pm0.5\%$ communicated by Dr. Glendenin,[24] in contrast with the old value[21] of 15%.

IV. DISCUSSION

The available data in the literature on the *independent* isomer-yield ratios in low-energy fission are summarized in Table III. It should be noted that there are many other reported isomer-yield ratios; however, these have been omitted for one of two reasons. On the one hand, for many of the ratios reported for low-energy fission, the yield of at least one of the isomers is partially a chain yield, set principally by β branching. On the other hand, at high energies, where Z_P has moved to the isomer pair in question or even closer to the line of β stability, effects of precursor decay can essentially be eliminated. However, in these cases, the identity of the fissioning nuclides and the mechanisms for their formation are too ambiguous to permit interpretation of the results. An example of both problems is given by the studies of the Cd^{115m}/Cd^{115} yield ratio by Hicks and Gilbert[7] and by Sharp and Pappas.[8]

Our data for Te^{131} in thermal neutron fission of U^{235} indicate the major fraction, 0.64 ± 0.05, yields Te^{131m} of spin 11/2− in preference to Te^{131g} of spin 3/2+. This result is in excellent agreement with the privately communicated[24] value of the Argonne group, 0.63 ± 0.03, also in Table III. This group finds the isomer fraction to be about the same for $U^{233}(n_{\text{th}},F)$ and higher for $Pu^{239}(n_{\text{th}},F)$. Our data for Te^{133} show a similar fraction, $0.61_{-0.10}^{+0.06}$, yielding the high-spin Te^{133m}.

The data on Cs^{134} indicate an increase in the high-spin fraction with increasing energy of the bombarding particle. An increase in the fraction for Te^{131} and Te^{133} is observed when the bombarding particle is changed from 18-MeV deuterons to 33-MeV He^4 ions. (Note that the excitation energy of the initial compound nucleus is less than 2 MeV greater for the He^4-ion bombardment than with the deuterons. Of course, the initial compound nucleus is greater by one neutron and one proton in the former case.) Similarly, for Te^{131}, the fraction increases in going from thermal-neutron fission to that induced by charged particles. In the case of Te^{133} isomers, the

[24] M. Talat-Erben, L. E. Glendenin, H. C. Griffin, and E. P. Steinberg (private communication).

trend is observed for the He^4-ion fission and the expected increase may well be within the limits of error on the deuteron measurements (see Table I). The trends observed, that is, increase in the high-spin fraction with increasing energy and/or mass of the bombarding particle, are to be expected because of the increase in angular momentum deposited in the compound nucleus.

We have attempted to make a careful quantitative investigation of the dependence of the fragment isomer-yield ratios upon the assumed spin distribution of the primary fission fragments.[25] First, it is necessary to estimate the "primary parentage" of the given secondary fragment, i.e., the contribution to the yield of secondary species (Z,A) by emission of no neutrons from primary (Z,A), the contribution by emission of one neutron from primary $(Z,A+1)$, etc. We have determined primary parentage and energies of emitted neutrons by means of Monte Carlo calculations similar to those of Dostrovsky *et al.*,[26] except that we have ignored charged-particle emission.

In the model presented below, there are many possible reasonable assumptions. Unfortunately, in many cases, there are no experimental data upon which a choice can be made among the assumptions. The choices we have made below are reasonable, but not unique. We have tested the model by comparison of various results of the calculations with experimental data. Some of the comparisons are noted below and are discussed in more detail in Ref. 27.

The Monte Carlo calculations were performed for a wide range of fragment mass numbers around mass 132 and in the complementary light-mass region.[27] The primary yield-mass curve was taken from the time-of-flight data of Milton and Fraser.[28] Primary fractional chain yields were assumed to be given by Eq. (1) with $C=0.94$. Original estimates of the primary Z_P values suggested by Wahl *et al.*[18] were adjusted slightly to reproduce better the experimental secondary Z_P values.

In order to estimate the distribution of number of prompt neutrons emitted by the various primary species, the following procedure was used. The most-probable sum $\bar{E}$ of the excitation energies of the complementary light and heavy primary species, (Z_L,A_L) and (Z_H,A_H), respectively, was taken as

$$\bar{E}=\Delta M(U^{236*})-(\Delta M_L+\Delta M_H)-\langle KE\rangle_{av}(A_H/A_L), \quad (2)$$

where the mass excess ΔM of excited U^{236} was obtained from Foreman and Seaborg's table,[29] those for the fragments from Seeger's mass formula,[30] and the average kinetic energy release, $\langle KE\rangle_{av}$, for divisions into mass ratio A_H/A_L was obtained from Milton and Fraser's results.[28] From the assumptions made in Eq. (2), we have for the dispersion of energies:

$$\sigma_E=\sigma_{KE}, \quad (3a)$$

and we further assume that

$$\sigma_{E_L}{}^2+\sigma_{E_H}{}^2=\sigma_E{}^2, \quad (3b)$$

where σ_{E_L} and σ_{E_H} are dispersions of the excitation energies of the individual fragments. There are several implicit assumptions contained in Eqs. (2), (3a), and (3b). Instrumental studies give $\langle KE\rangle_{av}$ and σ_{KE} as a function of A_H/A_L, but for a given A_H/A_L the dependence of $\langle KE\rangle_{av}$ and σ_{KE} upon Z_H/Z_L are not known. The total energy release, $E_T[=\Delta M(U^{236*})-(\Delta M_L+\Delta M_H)]$, for a given A_H/A_L has approximately parabolic dependence on Z_L, generally having its maximum near Z_{P_L}. As implied in Eq. (2), we have assumed that the KE distribution is the same for each charge division for a given mass division and equal to the KE distribution found by instrumental studies for the given mass division. Thus, changes in E_T with Z_H/Z_L require changes in $\bar{E}$. Presently, there are no experimental data upon which to make a choice between Eq. (2) and the opposite assumption, namely, that the change in E_T with Z_H/Z_L affects $\langle KE\rangle_{av}$ while leaving $\bar{E}$ approximately constant. The truth probably lies somewhere between these extremes.

Equation (3b) implies that there is no correlation between the excitation energies received by the two fragments of a given event. Again we have made what we consider to be a reasonable assumption in the absence of experimental data. If there is a negative correlation between fragments, the standard deviations for the individual fragments will be larger than indicated by Eq. (3b). On the other hand, deviations from the assumption implied by Eq. (2), as discussed in the preceding paragraph, will decrease the standard deviations.

Values of σ_{KE} were taken from the semiconductor-detector measurements by Gibson, Thomas, and Miller.[31] We further assume that

$$(\sigma_{E_H}{}^2/\sigma_{E_L}{}^2)=(\bar{E}_H/\bar{E}_L)\equiv F(A_H/A_L), \quad (4)$$

where $\bar{E}_L$ and $\bar{E}_H$ are the most-probable excitation energies of the light and heavy complementary fragments, respectively. The relationship between σ's and $\bar{E}$'s was assumed on general statistical grounds. In principle, one could obtain $F(A_H/A_L)$ from a complete theory of the fission process. In the absence of any

[25] By primary fragments, we denote fragments prior to prompt-neutron emission.

[26] I. Dostrovsky, Z. Fraenkel, and G. Friedlander, Phys. Rev. **116**, 683 (1959).

[27] G. E. Gordon, N. K. Aras, and L. A. Wilson, Massachusetts Institute of Technology, Laboratory for Nuclear Science Progress Report, MIT-2098-No. 64, 1964 (unpublished); N. K. Aras, M. P. Menon, and G. E. Gordon (unpublished); G. E. Gordon and N. K. Aras, to be presented at the International Atomic Energy Agency Symposium on the Physics and Chemistry of Fission, Salzburg, Austria, 1965.

[28] J. C. D. Milton and J. S. Fraser, Can. J. Phys. **40**, 1626 (1962).

[29] B. M. Foreman, Jr. and G. T. Seaborg, J. Inorg. Nucl. Chem. **7**, 305 (1958).

[30] P. A. Seeger, Nucl. Phys. **25**, 1 (1961).

[31] W. M. Gibson, T. D. Thomas, and G. L. Miller, Phys. Rev. Letters **7**, 65 (1962); also, W. M. Gibson (private communication).

TABLE IV. Parentage and neutron energies in formation of Te^{131} and Te^{133} secondary fragments.

Product nuclide	Parent	No. of neutrons emitted	Contribution to product yield	Av. neutron kinetic energies (MeV) 1st	2nd	3rd	Av. γ-ray energy release (MeV)
Te^{131}	Te^{131}	0	0.378	...	...	...	4.0
	Te^{132}	1	0.468	0.71	...	...	3.3
	Te^{133}	2	0.154	1.01	0.54	...	2.6
Te^{133}	Te^{133}	0	0.269	...	...	...	4.3
	Te^{134}	1	0.384	0.84	...	...	3.6
	Te^{135}	2	0.286	1.57	0.73	...	3.2
	Te^{136}	3	0.061	1.45	1.33	0.53	2.6

satisfactory theory, we have left it as a parameter to be adjusted freely until it approximately reproduced the experimental value[32] of the ratio $\bar{\nu}_{A_H}/\bar{\nu}_{A_L}$ of average number of prompt neutrons emitted by heavy fragments of mass A_H to that for the complementary light fragments of mass A_L. The implications of the assumptions made above are discussed in more detail in Ref. 27.

The first step in each iteration for a given species was the selection of an excitation energy from the distribution constructed as described above. The selections were made via the Monte Carlo rejection technique.[33] The number and kinetic energies of neutrons emitted were determined by the same technique as discussed in Ref. 26. The nuclear level density was assumed to be proportional to $\exp[2(aE)^{1/2}]$, with $a=A/\gamma$, the value of γ being left as a free parameter. Neutron separation energies and δ values (to correct for odd-even effects on level density, see Ref. 26) were taken from Seeger's mass formula and the smooth curve of pairing energy as a function of A, respectively.[30]

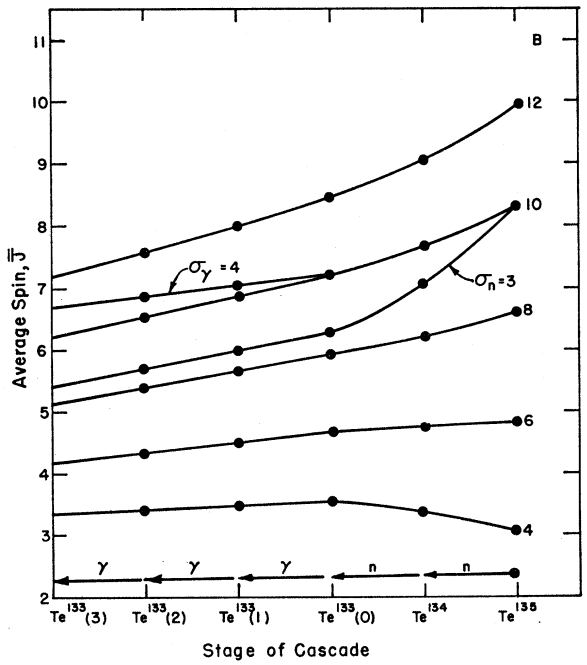


FIG. 4. Calculated average spin for the species in the cascade $Te^{135} \rightarrow Te^{133}+2n$ for various B values. The notation $Te^{133}(0)$, $Te^{133}(1)$, · · · refers to Te^{133} after emission of 0, 1, etc. γ rays. Except where noted for $B=10$, the values of σ_n and σ_γ are 4 and 3, respectively.

A number of calculations were performed with 50 to 200 iterations per nuclide in order to find the best values of the parameters, in particular the charge-dispersion parameter C, primary Z_P values, γ, and $F(A_H/A_L)$. Results were compared with various experimentally known quantities, notably secondary Z_P and $\bar{\nu}_A$ values, the gross neutron kinetic energy spectrum, and the average prompt γ-ray energy release. For the mass region of interest, the experimental quantities were well fitted using $\gamma=13$ MeV, $C=0.94$, and primary Z_P values close (within 0.3 charge units) to those suggested by Wahl *et al.*[18] For example, the calculated fractional chain yield for $Te^{131m}+Te^{131}$ is 0.109, in good agreement with the experimental value 0.124 ± 0.014 given above. Results of the calculations on primary parentage of Te^{131} and Te^{133} are listed in Table IV.

It is not possible to determine the spin distribution of the primary fragments from the observed isomer-yield ratios of the secondary fragments. However, if we assume a functional form of the primary spin distribution, we can determine approximately the average primary fragment spin that corresponds to the observed isomer-yield ratio. As suggested by Warhanek and Vandenbosch on statistical grounds, we assume that the angular-momentum distribution of the primary fragments is given by

$$P(J_c)=(2J_c+1)\exp[-J_c(J_c+1)/B^2], \qquad (5)$$

in which $P(J_c)$ is the probability for primary frgaments of spin J_c and B is a parameter somewhat analogous to a spin-cutoff factor.[11]

We have used the statistical treatment of neutron emission developed by Vandenbosch and Huizenga[34] to determine the change in the spin distribution caused by the emission of neutrons. In these calculations we have used values for barrier-transmission coefficients, $T_l(E_n)$, obtained from optical-model calculations based on a

[32] J. Terrell, Phys. Rev. **127**, 880 (1962).
[33] H. Kahn, Atomic Energy Commission Report No. AECU-3259, 1954 (unpublished).
[34] R. Vandenbosch and J. R. Huizenga, Phys. Rev. **120**, 1313 (1960).

potential of the type described by Bjorklund and Fernbach[35] and the neutron kinetic energies given in Table IV. The parameter σ_n of the spin distribution (see Ref. 34) was taken as constant and equal to 4. For the γ-ray de-excitation process, we assumed that only dipole radiations are emitted and that three γ rays are emitted in each cascade. The latter is based on the relationship given by Strutinski *et al.*[36] for the average number of γ rays emitted, $\bar{N}_\gamma$, from a nucleus of excitation energy E_γ:

$$\bar{N}_\gamma=(aE_\gamma)^{1/2}/(l+1), \quad (6)$$

where l is the assumed multipolarity, and a is the level-density parameter which we take to be $A/13$ MeV^{-1}. Under the assumption of dipole radiation, we find a range of $\bar{N}_\gamma$ from 2.6 to 3.3 for the $\bar{E}_\gamma$ values listed in Table IV. Of the distribution resulting from emission of two γ rays, we assume that all nuclei having $J<7/2$ decay to the lower isomer $(3/2+)$, all with $J>7/2$ decay to the upper isomer $(11/2-)$, and those with $J=7/2$ divide equally between the isomers upon emission of the third γ ray. From the work of Huizenga and Vandenbosch,[37] the value of the spin-cutoff factor, σ_γ, for γ-ray de-excitation is expected to be about 3 or 4. We have used both values and taken an average of the results.

Before comparing the calculations with experimental results, we first investigate the sensitivity of the calculations to changes in the values of the parameters for the typical reaction $Te^{135}\rightarrow Te^{133}+2n$. In Fig. 4 we have plotted the average spin $\bar{J}$ of the primary and succeeding species in the de-excitation chain for various values of B. We see that the average spin value does not change strongly with the emission of neutrons and γ rays, particularly for B values below 10. Also, in Fig. 4 we show the effects of variations in σ_n and σ_γ, the effect of the former being appreciably greater than that of the latter. In Fig. 5, we show the dependence of the calculated fraction of high spin for $Te^{135}\rightarrow Te^{133}+2n$ as a function of neutron kinetic energy, here assumed to be the same for the first and second neutrons, for two values of B. In this calculation we have used neutron transmission coefficients taken from the calculations of Feld *et al.*[38] We see that the high-spin fraction is very insensitive to neutron kinetic energy, particularly for the lower B value. This is also rather insensitive to the number of γ rays emitted, N_γ; for example, for $Te^{135}\rightarrow Te^{133}+2n$ and $B=10$, the calculated fraction varies from 0.83 to 0.80 for N_γ equal to 1 and 4, respectively. That the calculated fraction is not strongly dependent upon the number of neutrons emitted is demonstrated in Table V in which we list the calculated fractions for Te^{131} and Te^{133} resulting from the various primary parents, all having an assumed primary spin distribution given by Eq. (5) with $B=10$.

TABLE V. Calculated high-spin fractions of Te^{131} and Te^{133} resulting from the various primary parents.[a]

Product nuclide	Parent	No. of neutrons emitted	Contributions to product yield	$\sigma_m/(\sigma_m+\sigma_g)$
$Te^{131m,g}$	Te^{131}	0	0.378	0.836
	Te^{132}	1	0.468	0.823
	Te^{133}	2	0.154	0.814
	Weighted average			0.826
$Te^{133m,g}$	Te^{133}	0	0.269	0.836
	Te^{134}	1	0.384	0.820
	Te^{135}	2	0.286	0.809
	Te^{136}	3	0.061	0.793
	Weighted average			0.820

[a] Calculated with $B=10$, $\sigma_n=4$, average of $\sigma_\gamma=3$ and 4, $N_\gamma=3$, dipole radiation only, average neutron kinetic energies from Table IV, and transmission coefficients from optical-model calculations (see text).

Taking into account the various uncertainties in the values of the parameters and the effects of such uncertainties upon the calculated fraction of high spin for a given B value, as discussed in the preceding paragraph, we estimate that for a given observed fraction, the uncertainty in determining the corresponding B value is about ±1.5 units at the most. As the average initial spin varies more slowly than B (see Fig. 4), the uncertainty in average initial spin value is only about $\pm1.2\hbar$ in the range of interest here. Including the uncertainty in the experimental value of the high-spin fraction raises the uncertainty in the average initial spin value to 1.4 and $1.5\hbar$, respectively, for Te^{131} and Te^{133}. Thus, in spite of the complexity of the calculations and the uncertainties in the values of the parameters involved, we may obtain a meaningful estimate of the average spin of the primary fragments from the observed isomer-yield ratios. The root-mean-square average $\langle J^2\rangle_{\rm av}^{1/2}$ is a little higher. In the limit of large B,

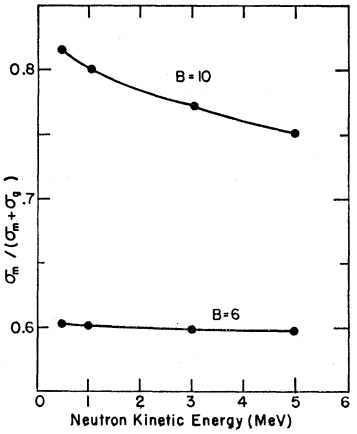


FIG. 5. Calculated high-spin fraction, $\sigma_m/(\sigma_m+\sigma_g)$, for Te^{133} resulting from emission of two neutrons from Te^{135}, as a function of the average kinetic energies of the two neutrons (here assumed the same for both). Calculated using transmission coefficients from Feld *et al.* (Ref. 38), with parameters $\sigma_n=4$, $\sigma_\gamma=3$, $N_\gamma=3$.

[35] F. Bjorklund and S. Fernbach, Phys. Rev. **109**, 2951 (1958).
[36] V. M. Strutinski, L. V. Groshev, and M. K. Akimova, Nucl. Phys. **16**, 657 (1960).
[37] J. R. Huizenga and R. Vandenbosch, Phys. Rev. **120**, 1305 (1960).
[38] B. T. Feld, H. Feshbach, M. L. Goldberger, H. Goldstein, and V. F. Weisskopf, Atomic Energy Commission Report NYO-636, 1951 (unpublished).

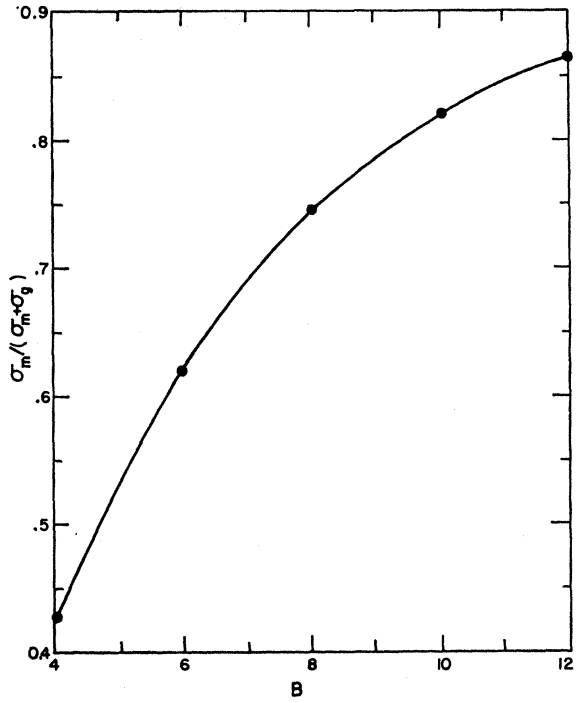


FIG. 6. Calculated high-spin fraction, $\sigma_m/(\sigma_m+\sigma_g)$, for Te^{133} as a function of B. The parameters are the same as those given in Table V, footnote a.

$\bar{J}=\pi^{1/2}B/2$ and $\langle J^2\rangle_{av}{}^{1/2}=B$. For B equal 5 or 10, the most-probable J value is 3.16 or 6.85, $\bar{J}$ is 3.94 or 8.37, and $\langle J^2\rangle_{av}{}^{1/2}$ is 4.58 or 9.56.

In Fig. 6 we have plotted the calculated Te^{133} isomer-yield ratio as a function of B, using our best estimates of the parameters. The corresponding curve for Te^{131} isomers is almost indistinguishable and has not been shown. The measured fractional yields of high spin, $\sigma_m/(\sigma_m+\sigma_g)$, of 0.64 ± 0.05 and $0.61_{-0.10}{}^{+0.06}$ for production of Te^{131} and Te^{133}, respectively, in thermal neutron fission of U^{235} correspond to B values of 6.0 ± 1.5 and 5.9 ± 1.5, or average initial spin values of $(5\pm1.5)\hbar$ for both. These results are in agreement, within the limits of experimental error, with the value $(7\pm2)\hbar$ found for gross fission fragments from thermal neutron fission of U^{235} by Hoffman,[39] who determined angular correlations between γ rays and fragments. Also, from the isomer-yield ratio Cs^{134m}/Cs^{134} from photofission of U^{233}, Warhanek and Vandenbosch[11] have inferred a root-mean-square angular momentum of the primary parents of about $7.4\hbar$, corresponding to $\bar{J}$ of about $6.5\hbar$.

As the spins of the fissioning nuclei are 3 or $4\hbar$ (assuming s-wave neutron capture) to be distributed between the fragments, the high average spins of the primary fragments are at first rather surprising. Hoffman's results further indicate that the fragment spin vectors are directed preferentially perpendicular to

[39] M. M. Hoffman, Phys. Rev. **133**, B714 (1964).

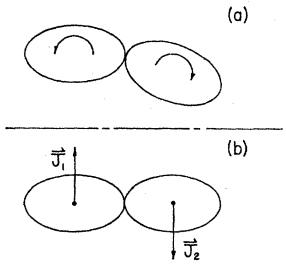


FIG. 7. Hoffman explanation (Ref. 39) for the origin of fragment spins. (a) Typical asymmetry of a type that can produce torques by electrostatic repulsion. (b) Orientation of resulting spin vectors.

the fragment direction of motion. He has made a reasonable explanation of both the magnitudes and orientations of the fragment spin vectors on the basis of torques applied to the fragments by electrostatic repulsion if, near the time of scission, the fragment system has an asymmetry of the type shown in Fig. 7(a). His calculation predicts an average primary fragment spin of 5.5 to $7\hbar$ for fragments in the region of $A=134$, in good agreement with our results. On the basis of his model, it is easy to see how both complementary fragments can have spins J_L and J_H greater than that of the fissioning nucleus as there is a strong tendency for $\mathbf{J}_L$ and $\mathbf{J}_H$ to be approximately antiparallel, thus largely cancelling each other. In addition, it should be noted that some of the angular momentum of the fissioning system can be carried off as mutual orbital angular momentum, l; however, for thermal neutron fission, l would generally be quite small.[3]

In the discussion of charged-particle-induced fission we shall consider the case of $Th^{232}(\alpha_{33},F)Te^{131}$, with the same compound nucleus as for $U^{235}(n_{th},F)$. In this case we start with a compound nucleus having an average angular momentum of $12.7\hbar$. This value was calculated using the empirical relations given by Halpern and Strutinski.[3] Here the excitation energy is high enough to cause neutron emission prior to fission. The prefission neutrons carry away a relatively small fraction of the angular momentum of the compound nucleus. Still, the average angular momentum in the fission processes competing with neutron emission will be much higher than that in the thermal-neutron case. If we assume that the number of prompt neutrons emitted to yield the secondary Te^{131} is roughly two, as indicated by Britt and Whetstone,[40] we can estimate the average spin value of the primary fragment to be roughly equal to $7\hbar$ from the observed high-spin isomer fraction 0.74.

In this case we have some additional information about the fragment spins. From the anisotropy of the fission-fragment angular distribution,[5] we can use Halpern and Strutinski's model[3] to find the average value of K, the projection of the spin of the fissioning nucleus, $\mathbf{J}_f$, along the symmetry axis of the fissioning nucleus. According to the model, the fragments are emitted in the direction of the symmetry axis; therefore, the component of $\mathbf{J}_f$ perpendicular to the symmetry axis be-

[40] H. C. Britt and S. L. Whetstone, Jr., Phys. Rev. **133**, B603 (1964).

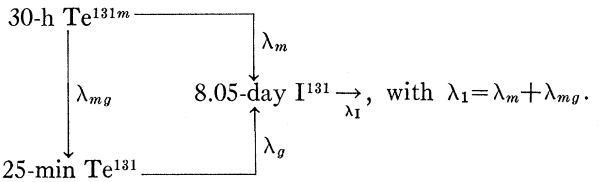
comes the orbital-angular momentum of the fragments, and the fragment intrinsic spins add vectorially to give a vector of length K along the symmetry axis. The anisotropy, $[\sigma(0°)/\sigma(90°)]$, of about 1.6 for $Th^{232}(\alpha_{30},F)$, gives an average K of about $8\hbar$. From the average value of $\bar{J}_H=7\hbar$ found above, we see that, again, there is apparently some cancellation of $\mathbf{J}_H$ by $\mathbf{J}_L$, assuming that J_L is also about $7\hbar$. There is little more that can be said. The Hoffman[39] model which successfully reproduces the observations on thermal-neutron fission of U^{235} is also plausible in the case of $Th^{232}(\alpha_{33},F)$; however, there is no evidence in the latter case that the fragments are aligned preferentially perpendicular to the direction of fragment motion. Perhaps the most interesting qualitative result is the observation that in going from $U^{235}(n_{th},F)$ to $Th^{232}(\alpha_{33},F)$ the average spin of the fissioning nucleus goes from about 3.5 to $13\hbar$; however, the average spin of the primary fragments in the mass 134 region increases by only about $2\hbar$, from 5 to $7\hbar$. Thus, the spins of the two fragments apparently do not line up as nearly antiparallel as in the case of $U^{235}(n_{th},F)$.

ACKNOWLEDGMENTS

The authors wish to thank Dr. Richard W. Dodson and Dr. James F. Mollenauer who arranged for the cyclotron bombardments at the Brookhaven National Laboratory, and Dr. Charles P. Baker for providing the deuteron and helium-ion bombardments. We thank Dr. Curtis E. Bemis, Jr., for his assistance in some of the experiments, and Professor John W. Irvine, Jr., and Dr. Lawrence E. Glendenin for information and advice. The IBM-7090 computer of the MIT Computation Center, the CDC-1604 computer of the Oak Ridge National Laboratory, and the IBM-7072 computer of the Washington University were used in the analysis of data in this work.

APPENDIX A

Consider the chain of mass number 131:



It can be shown that the difference of the growth equation for I^{131} from its asymptote (growth equation for $t\geq 10$ days) is given by

$$A_I(t)=A_g^{\text{eff}}(0)e^{-\lambda_g t}+A_m^{\text{eff}}(0)e^{-\lambda_I t}, \tag{A1}$$

where

$$A_m^{\text{eff}}(0)=A_m{}^0\frac{\lambda_I(\lambda_g-\lambda_m)}{(\lambda_1-\lambda_I)(\lambda_g-\lambda_1)}, \tag{A2}$$

and

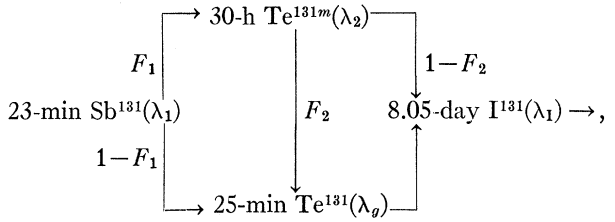
$$A_g^{\text{eff}}(0)=A_g{}^0\frac{\lambda_I}{(\lambda_g-\lambda_I)}-A_m{}^0\frac{\lambda_{mg}\lambda_g\lambda_I}{\lambda_1(\lambda_g-\lambda_1)(\lambda_g-\lambda_I)}; \tag{A3}$$

$A_m^{\text{eff}}(0)$, $A_g^{\text{eff}}(0)$ are the effective zero-time (tellurium purification time) activities of Te^{131m}, Te^{131}, respectively; $A_m{}^0$, $A_g{}^0$ are the true zero-time activities of Te^{131m}, Te^{131}, respectively; and the λ's are as indicated above.

Similar expressions hold for the chain of mass number 133.

APPENDIX B

Consider the chain



where F_1 is the fraction of Sb^{131} decaying to Te^{131m}, and F_2 is the fraction of Te^{131m} decaying by isomeric transition. It can be shown that, for $\lambda_1 t$, $\lambda_g t>15$, the activity of I^{131} grown from an initial activity $A_1(0)$ of Sb^{131} is given as

$$A_I(t)=A_I^{\text{eff}}(0)\,e^{-\lambda_I t}-A_m^{\text{eff}}(0)\,e^{-\lambda_2 t}, \tag{B1}$$

where

$$A_I^{\text{eff}}(0)=A_1(0)\left[F_1\frac{\lambda_2\lambda_I}{(\lambda_2-\lambda_I)(\lambda_1-\lambda_I)}\left(1+\frac{\lambda_I}{\lambda_g-\lambda_I}F_2\right)+(1-F_1)\frac{\lambda_g\lambda_I}{(\lambda_g-\lambda_I)(\lambda_1-\lambda_I)}\right], \tag{B2}$$

and

$$A_m^{\text{eff}}(0)=A_1(0)F_1\frac{\lambda_2\lambda_I}{(\lambda_2-\lambda_I)(\lambda_1-\lambda_2)}\left[1+\frac{\lambda_2}{\lambda_g-\lambda_2}F_2\right]. \tag{B3}$$

As discussed in the text, $A_I^{\text{eff}}(0)$ and $A_m^{\text{eff}}(0)$ are obtained from the experiment.

Dividing (B2) by (B3) one has

$$\frac{A_I^{\text{eff}}(0)}{A_m^{\text{eff}}(0)}\equiv\frac{1}{R}=\left(\frac{\lambda_1-\lambda_2}{\lambda_1-\lambda_I}\right)\frac{B_2}{B_1}\left[1+\frac{(1-F_1)\lambda_g(\lambda_2-\lambda_1)}{F_1B_2\lambda_2(\lambda_g-\lambda_I)}\right], \tag{B4}$$

where

$$B_1=1+\frac{\lambda_2}{\lambda_g-\lambda_2}F_2 \quad \text{and} \quad B_2=1+\frac{\lambda_I}{\lambda_g-\lambda_I}F_2.$$

Thus, $1/R$ is insensitive to λ_1, F_2, λ_g and depends linearly on $1/F_1$. Using the above half-lives and solving for F_1, one finds $F_1=0.835R/(1-0.152R)$.

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Proton Polarization in the $Sr^{88}(d,p)Sr^{89*}$(1.05-MeV) Reaction*

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The polarization of protons from the $Sr^{88}(d,p)Sr^{89*}$ reaction exciting the 1.05-MeV state in Sr^{89} has been measured at 14 laboratory angles from 12 to 131° using a deuteron bombarding energy of 11 MeV. In this reaction, which involves no orbital-angular-momentum transfer by the captured neutron, spin-orbit terms in the optical-model potentials describing the interactions of the incident and exit particles are considered to be responsible for the polarization. The measurements were made using a heavy-particle magnetic spectrometer to select the desired proton group and focus it on the carbon second scatterer. This scatterer was viewed to the "right" and the "left" by a pair of scintillation counters set at a mean laboratory angle of 40°. The sign of the polarization seems to correspond to the sign of the slope of the angular distribution, being negative at the forward angles with apparent sign changes at the subsequent minima and maxima. This behavior is in approximate agreement with the "derivative rule" for stripping reactions with $l_n=0$ orbital-angular-momentum transfer. The polarization changes most rapidly near the stripping minima and becomes largest at the backward angles (−28% at 95°).

I. INTRODUCTION

ANGULAR distributions of protons emitted in deuteron stripping reactions have been successfully fitted by the distorted-wave Born approximation,[1] in which the waves describing the incoming deuterons and outgoing protons are distorted by an optical-model potential. While theoretical fits to the angular distributions yield useful information with regard to the reaction process, a more sensitive test of the theoretical formulation is obtained when the polarization of the outgoing nucleons is considered. Since polarized particles do not result if plane waves are assumed in the formulation, measurements showing nonzero proton polarizations from stripping reactions clearly emphasize the necessity for using a distorted-wave-Born-approximation (DWBA) treatment.

Newns[2] was the first to suggest a measurement of the proton polarization resulting from a deuteron stripping reaction. He postulated that the nucleus receives a net oriented pulse of orbital angular momentum (l_n) due to unequal absorption of the incoming and outgoing beams of particles. Hence, for a given angular-momentum transfer to the nucleus (j_n), the emitted particle is expected to be polarized since the neutron and proton spins are coupled in the deuteron. These absorptive distortion effects alone are not sufficient to account for the polarizations observed experimentally, however. Neglecting spin-dependent interactions, distorted-wave calculations[3,4] predict polarizations restricted in magnitude to $\leq 33\%$. The sign of the polarization is expected to conform to the rule that $P=\pm$ for $j_n=l_n\pm\frac{1}{2}$, assuming deuterons are more strongly absorbed than protons in nuclear matter. (The direction of positive polarization is taken to be $\mathbf{n}=\mathbf{k}_d\times\mathbf{k}_p$ in accordance with the Basel convention.) A further consequence of these calculations is the absence of polarization for $l_n=0$ neutron transfers. Previousp olarization measurements have

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[1] Examples of these fits and references to others are given in W. Tobocman and W. R. Gibbs, Phys. Rev. **126**, 1076 (1962); R. H. Bassel, R. M. Drisko, and G. R. Satchler, Oak Ridge National Laboratory, Physics Division Annual Progress Report, ORNL-3085, 1961 (unpublished); B. Buck and P. E. Hodgson, Nucl. Phys. **29**, 496 (1962); W. R. Smith and E. V. Ivash, Phys. Rev. **131**, 304 (1963).
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