PHYSICAL REVIEW C VOLUME 29, NUMBER 5 MAY 1984

Independent isomeric yield ratios and primary angular momenta in the photofission of $^{235,238}U$ with 12–30-MeV bremsstrahlung

D. De Frenne, B. Proot, H. Thierens, P. De Gelder, E. Jacobs, and A. De Clercq
Laboratorium voor Kernfysica, B-9000 Ghent, Belgium

(Received 16 January 1984)

The independent isomeric yield ratios for ^{129}Sn, ^{130}Sb, ^{131}Sn, ^{132}Sb, ^{133}Te, and ^{136}I for the photofission of ^{235}U with 12–30-MeV bremsstrahlung and for ^{126}Sb, ^{129}Sn, ^{130}Sb, ^{131}Sn, ^{132}Sb, ^{133}Te, and ^{136}I for the photofission of ^{238}U have been determined using radiochemical techniques and gamma spectrometry of fission product catcher foils and irradiated uranium samples. The root-mean-square values of the primary angular momenta of the corresponding fission fragments, $J_{\rm rms}$, were calculated with the statistical procedure of Huizenga and Vandenbosch and with the more elaborate deexcitation model of Min and Martinot. Both procedures gave, except for ^{130}Sb, almost the same $J_{\rm rms}$ values. Our experimental results show a near independency of $J_{\rm rms}$ on the spin and excitation energy of the compound nucleus. An increase of the $J_{\rm rms}$ values with the excitation energy of the fragments is observed. In addition, a significant proton odd-even effect on the $J_{\rm rms}$ values is present for the photofission of ^{235}U as well as ^{238}U. Our experimental photofission results show a qualitative agreement with the theoretical calculations of Dietrich and Zielinska-Pfabé.

I. INTRODUCTION

It is well known that studies of angular momenta of fission fragments provide useful information on the scission configuration and consequently lead to a better understanding of the fission process.[1] In the past, several experimental techniques, as e.g., measurements of the anisotropy[2] and number[3] of emitted gamma rays, ground state band populations in even-even fission products,[4] and isomeric yield ratios,[5] have been used to obtain information on primary angular momenta of fission fragments produced in different fissioning systems.

It has been well established that in fission most of the fragments are formed with much higher angular momenta than those of the fissioning nuclei (see, e.g., Ref. 1). In the framework of the liquid drop model[6] this generation of angular momentum is explained by the excitation of the "bending" and "wriggling" modes during the descent from saddle to scission point. In addition, some supplementary angular momentum can be induced by Coulomb excitation of the fragments after scission.

Recently Denschlag *et al.*[7] and Bocquet *et al.*[8] have shown that for ^{235}U$(n_{\rm th},f)$, the initial angular momenta of the fission fragments strongly depend on the excitation energy of those fragments. For the spontaneous fission of ^{252}Cf, Wilhelmy *et al.*[4] found a much weaker dependence of the primary spins on the kinetic energy of the fragments.

The results of Denschlag *et al.*[7] and Bocquet *et al.*[8] for the primary angular momenta of several fission fragments produced in the ^{233,235}U$(n_{\rm th},f)$ and ^{239}Pu$(n_{\rm th},f)$ reactions were confirmed by Fujiwara *et al.*[9] In the same study,[9] a striking proton odd-even effect of the primary angular momenta, was also observed for the investigated fission fragments.

In this paper we present the results of our systematic study on isomeric yield ratios and deduced $J_{\rm rms}$ values of primary angular momenta of fission fragments produced in the photofission of ^{235,238}U with 12–30-MeV bremsstrahlung. The independent chain yields were determined using the catcher-foil technique, direct gamma spectrometry of irradiated uranium foils, and chemical separation techniques. These yields have been published in a previous paper on the charge distribution in the photofission of ^{235,238}U (Ref. 10). For all details concerning the measurement and calculation of the independent chain yields we refer to that paper.

II. EXPERIMENTAL RESULTS AND DISCUSSION

A. Isomeric yield ratios

For the isomeric pairs produced in the photofission of ^{235}U and ^{238}U, the isomeric ratios $\sigma_H/(\sigma_H+\sigma_L)$ (σ_H and σ_L are, respectively, the independent chain yields of the high- and low-spin isomers) deduced from the experimentally determined independent chain yields of Ref. 10 are summarized in Tables I and II, respectively. In these tables two different values are given for the isomeric yield ratio of the isomeric pair $^{131}\mathrm{Sn}(\frac{3}{2}^+)$-$^{131}\mathrm{Sn}(\frac{11}{2}^-)$, corresponding to two extreme hypotheses for the absolute intensities of the gamma rays from the decay of ^{131}Sn. Recently the decay of ^{131}Sn was investigated by Huck *et al.*[14] and Schussler *et al.*[15] In the latter study more detailed information on the half-lives of the two tin isomers and the number, energy, and relative intensity of the observed gamma rays is given. However, the values for the absolute intensities of the gamma rays cannot be used because the normalization procedure employed by the authors is not reaction independent. On the other hand, in the work of Huck *et al.*,[14] it is not always evident which levels of ^{131}Sb are fed by the two tin isomers. This means

TABLE I. Isomeric yield ratios $\sigma_H/(\sigma_H+\sigma_L)$ for the photofission of ^{235}U with 12-, 15-, 20-, and 30-MeV bremsstrahlung.

Isomeric pairs \ E_e (MeV)	12	15	20	30
^{129}Sn($\frac{11}{2}^-$)-^{129}Sn($\frac{3}{2}^+$)	0.67±0.09	0.62±0.07	0.64±0.08	0.67±0.10
^{130}Sb(8^-)-^{130}Sb(5^+)	0.53±0.14	0.53±0.10	0.57±0.09	0.52±0.08
^{131}Sn($\frac{11}{2}^-$)-^{131}Sn($\frac{3}{2}^+$)	0.36±0.06[a] 0.54±0.07[b]	0.42±0.04[a] 0.59±0.06[b]	0.31±0.05[a] 0.47±0.05[b]	0.34±0.05[a] 0.51±0.05[b]
^{132}Sb(8^-)-^{132}Sb(4^+)	0.40±0.06	0.32±0.05	0.29±0.05	0.33±0.07
^{133}Te($\frac{11}{2}^-$)-^{133}Te($\frac{3}{2}^+$)	0.70±0.07	0.69±0.05	0.72±0.06	0.71±0.07
^{136}I(6^-)-^{136}I(2^-)	0.70±0.05	0.76±0.07	0.72±0.05	0.71±0.05

[a] Calculated with $I_{798}^{\text{abs}}=0.523$ and $I_{1226}^{\text{abs}}=1.0$ (Ref. 14).

[b] Calculated with $I_{798}^{\text{abs}}=0.680$ and $I_{1226}^{\text{abs}}=0.729$ (Ref. 14).

that only two extreme hypotheses for the absolute intensity of the 798 and 1226 keV gamma lines can be considered:

(i) All not unambiguously identified gamma transitions belong to the decay of ^{131}Sn^g ($T_{1/2}=39$ s; $J^\pi=\frac{3}{2}^+$) which leads to a value of 0.68 for the absolute intensity of the 798 keV gamma line and of 0.73 for the 1226 keV line.

(ii) On the contrary, the assumption that the same transitions belong to the decay of ^{131}Sn^m ($T_{1/2}=50$ s; $J^\pi=\frac{11}{2}^-$) isomer leads to a value of 0.52 for the 798 keV gamma ray and 1.0 for the 1226 keV gamma ray.

The values in Tables I and II for the isomeric yield ratios of the ^{131}Sn isomeric pair are calculated with these two extreme hypotheses. Although from our experiments it is not possible to determine the half-lives of both ^{131}Sn isomers very accurately, our results are consistent with those of Schussler *et al.*,[15] $T_{1/2}=39$ s for ^{131}Sn^g ($J^\pi=\frac{3}{2}^+$) and $T_{1/2}=50$ s for ^{131}Sn^m ($J^\pi=\frac{11}{2}^-$), but disagree with the values of Huck *et al.*,[14] who reported a half-life $T_{1/2}\simeq60$ s for both isomers. For the calculation of the independent chain yields of the tin isomers we used the half-life values for both tin isomers given by Schussler *et al.*[15]

Since no other photofission data are available in the literature for these isomeric pairs, we have compared in Table III our results with those obtained for the same isomers in other low energy fissioning systems.[7,8,16–18] As can be seen from Tables I–III, in general, there is good agreement between our photofission data and those for the other low energy fissioning systems. However, for the isomeric pair ^{132}Sb(8^-)-^{132}Sb(4^+), there is good agreement between our results and those of Denschlag *et al.*,[7] but no agreement with those of Imanishi *et al.*[17] An explanation for this discrepancy is not obvious. For the isomeric pairs ^{126}Sb(8^-)-^{126}Sb(5^+) and ^{129}Sn($\frac{3}{2}^+$)-^{129}Sn($\frac{11}{2}^-$) no data are available in the literature for other fissioning systems.

B. Primary angular momenta

From the measured isomeric yield ratios of Tables I and II, the corresponding root-mean-square values of the primary angular momenta (J_{rms}) for the fission fragments produced in the photofission of ^{235,238}U were calculated using a statistical model analysis for the deexcitation of the fission fragments as discussed by Huizenga and Vandenbosch[19,20] and also with a more generalized deexcitation model developed by Min and Martinot[21] (computer code MAMI). The use of the latter procedure was already described in a previous paper.[13] Except for ^{130}Sb, both methods gave almost identical J_{rms} values. Only those obtained with the MAMI code are given in Tables IV and

TABLE II. Isomeric yield ratios $\sigma_H/(\sigma_H+\sigma_L)$ for the photofission of ^{238}U with 12-, 15-, 20- and 30-MeV bremsstrahlung.

Isomeric pairs \ E_e (MeV)	12	15	20	30
^{126}Sb(8^-)-^{126}Sb(5^+)		0.42±0.07	0.42±0.07	0.43±0.05
^{129}Sn($\frac{11}{2}^-$)-^{129}Sn($\frac{3}{2}^+$)	0.70±0.16	0.68±0.11	0.60±0.10	0.64±0.12
^{130}Sb(8^-)-^{130}Sb(5^+)	0.59±0.13	0.62±0.14	0.64±0.16	0.65±0.15
^{131}Sn($\frac{11}{2}^-$)-^{131}Sn($\frac{3}{2}^+$)	0.51±0.06[a] 0.70±0.05[b]	0.48±0.05[a] 0.65±0.05[b]	0.49±0.05[a] 0.67±0.07[b]	0.47±0.08[a] 0.64±0.08[b]
^{132}Sb(8^-)-^{132}Sb(4^+)	0.36±0.10	0.39±0.10	0.33±0.09	0.41±0.13
^{133}Te($\frac{11}{2}^-$)-^{133}Te($\frac{3}{2}^+$)	0.64±0.06	0.63±0.05	0.70±0.08	0.67±0.09
^{136}I(6^-)-^{136}I(2^-)	0.70±0.08	0.65±0.06	0.74±0.05	0.72±0.08

[a] Calculated with $I_{798}^{\text{abs}}=0.523$ and $I_{1226}^{\text{abs}}=1.0$ (Ref. 14).

[b] Calculated with $I_{798}^{\text{abs}}=0.680$ and $I_{1226}^{\text{abs}}=0.729$ (Ref. 14).

TABLE III. Isomeric yield ratios $\sigma_H/(\sigma_H+\sigma_L)$ for other low energy fissioning systems.

Isomeric pairs	^{233}U(n_{th},f)	^{235}U(n_{th},f)	^{239}Pu(n_{th},f)
^{130}Sb(8$^-$)-^{130}Sb(5$^+$)	0.45±0.07[a]	0.47 ±0.12[a]	0.54±0.09[a]
^{131}Sn($\frac{11}{2}^-$)-^{131}Sn($\frac{3}{2}^+$)		0.67 ±0.02[b] 0.685±0.015[c]	
^{132}Sb(8$^-$)-^{132}Sb(4$^+$)	0.26±0.07[a]	0.19 ±0.05[a] 0.31 ±0.04[d]	0.30±0.08[a]
^{133}Te($\frac{11}{2}^-$)-^{133}Te($\frac{3}{2}^+$)	0.57 ±0.05[a]	0.57±0.06[a] 0.61 ±0.08[d]	0.63±0.06[a]
^{136}I(6$^-$)-^{136}I(2$^+$)		0.55 ±0.05[e] 0.68 ±0.19[d]	

[a] Reference 17.
[b] Reference 8.
[c] Reference 16.
[d] Reference 7.
[e] Reference 18.

V. This code gives, in contrast to the Huizenga and Vandenbosch method,[19,20] a more detailed description of the deexcitation process of the fragments. In each step the competition between gamma and neutron emission is taken into account, together with the detailed level scheme of each nucleus of interest. This different treatment gives results for the ^{130}Sb isomeric pair produced in the photofission of ^{235}U of J_{rms} values which are about 3$\hbar$ lower when calculated with the MAMI code compared to the values obtained with the Huizenga and Vandenbosch method.[19,20] This means that for nuclei, as e.g., ^{130}Sb, in which some low lying high spin levels of different parities are present, the results obtained with the MAMI code are more reliable and should be preferred over those calculated with the Huizenga and Vandenbosch method. However, the MAMI code could not be used for the calculation of the J_{rms} values for the isomeric pair ^{130}Sb, in the photofission of ^{238}U, due to the very low mean excitation energy of the fragments leading to the ^{130}Sb isomers. So in this case the values listed in Table V are calculated with the Huizenga and Vandenbosch method and are about 3$\hbar$ higher than the MAMI values for ^{235}U. The values of the uncertainties given in Tables IV and V do not include a systematic contribution of about 1.5$\hbar$ (Ref. 23) due to the incomplete knowledge of the deexcitation process of the fission fragments. As no comparable photofission data are available in the literature, we have compared our results for J_{rms} with the J_{rms} values of Table VI which were deduced from the isomeric yield ratios given in Table III.

From Tables IV and V it is clear that, for the photofission of ^{235}U as well as for ^{238}U, in the excitation energy range mentioned above, there is almost no dependence of the J_{rms} values on the average excitation energy of both uranium nuclei. This is in agreement with previous results for the isomeric pairs ^{134}I and ^{131}Te in the photofission of ^{235,238}U.[13,11] Both isomeric pairs were also studied by Diksic and Yaffe[23] in the fission of ^{238}U induced by 30—85 MeV protons, and the same independency of J_{rms} on the excitation energy of the compound system was found. On the other hand, Diksic and Yaffe[23] observed an important increase of the primary angular momentum for the ^{130}I, ^{132}I, and ^{133}Te fragments. Sarantites *et al.*[22] investigated the isomeric pairs ^{131}Te($\frac{11}{2}^-$)-^{131}Te($\frac{3}{2}^+$) and ^{133}Te($\frac{11}{2}^-$)-^{133}Te($\frac{3}{2}^+$) for five different fissioning systems and found the highest fragment spin values for those systems with the highest excitation energy. However, the average initial spin of the fragments increased by only $\simeq$2$\hbar$, while the spin of the compound nucleus increased from $\simeq$3.5$\hbar$ to $\simeq$13$\hbar$ when going from ^{235}U(n_{th},f) to ^{232}Th(α_{33},f). In our photofission work this behavior could not be observed. For the isomeric pair ^{136}I(6$^-$)-^{136}I(2$^+$) Hamelin *et al.*[18] found an increase for J_{rms} of

TABLE IV. $J_{\text{rms}}(\hbar)$ deduced from isomeric yield ratios studied in the photofission of ^{235}U with 12—30-MeV bremsstrahlung.

Isomeric pairs \ E_e (MeV)	12	15	20	30
^{129}Sn($\frac{11}{2}^-$)-^{129}Sn($\frac{3}{2}^+$)	5.1±0.4	4.6±0.4	4.7±0.4	4.9±0.6
^{130}Sb(8$^-$)-^{130}Sb(5$^+$)	6.5±1.0	6.5±0.8	6.8±0.7	6.4±0.7
^{131}Sn($\frac{11}{2}^-$)-^{131}Sn($\frac{3}{2}^+$)	3.5±0.3[a] 4.5±0.4[b]	3.7±0.3[a] 4.7±0.6[b]	3.3±0.3[a] 4.1±0.5[b]	3.4±0.2[a] 4.3±0.4[b]
^{132}Sb(8$^-$)-^{132}Sb(4$^+$)	5.9±0.4	5.6±0.5	5.3±0.4	5.5±0.5
^{133}Te($\frac{11}{2}^-$)-^{133}Te($\frac{3}{2}^+$)	5.8±0.7	5.6±0.5	5.8±0.5	5.8±0.5
^{136}I(6$^-$)-^{136}I(2$^-$)	7.3±0.7	7.8±0.9	7.4±0.7	7.3±0.7

[a] Calculated with $I_{798}^{\text{abs}}=0.523$ and $I_{1226}^{\text{abs}}=1.0$ (Ref. 14).
[b] Calculated with $I_{798}^{\text{abs}}=0.680$ and $I_{1226}^{\text{abs}}=0.729$ (Ref. 14).

TABLE V. $J_{\mathrm{rms}}(\hbar)$ deduced from isomeric yields ratios studied in the photofission of ^{238}U with 12–30-MeV bremsstrahlung.

Isomeric pairs \ E_e (MeV)	12	15	20	30
$^{126}\mathrm{Sb}(8^-)$-$^{126}\mathrm{Sb}(5^+)$		10.4±1.2	10.4±1.2	11.1±1.1
$^{129}\mathrm{Sn}(\frac{11}{2}^-)$-$^{129}\mathrm{Sn}(\frac{3}{2}^+)$		5.5±0.9	4.8±0.9	5.0±0.7
$^{130}\mathrm{Sb}(8^-)$-$^{130}\mathrm{Sb}(5^+)$	9.4±1.9[a]	9.9±2.2[a]	10.3±2.4[a]	10.4±2.5[a]
$^{131}\mathrm{Sn}(\frac{11}{2}^-)$-$^{131}\mathrm{Sn}(\frac{3}{2}^+)$		3.9±0.3[b] 4.9±0.4[c]	4.0±0.3[b] 4.9±0.6[c]	4.0±0.3[b] 4.8±0.4[c]
$^{132}\mathrm{Sb}(8^-)$-$^{132}\mathrm{Sb}(4^+)$	5.5±0.6	5.9±0.7	5.4±0.6	6.1±1.0
$^{133}\mathrm{Te}(\frac{11}{2}^-)$-$^{133}\mathrm{Te}(\frac{3}{2}^+)$	5.2±0.5	5.1±0.4	5.7±0.8	5.4±0.7
$^{136}\mathrm{I}(6^-)$-$^{136}\mathrm{I}(2^-)$	7.1±1.1	6.3±0.7	7.4±0.7	7.0±0.6

[a] Calculated with the Huizenga and Vandenbosch method (Refs. 19 and 20).
[b] Calculated with $I^{\mathrm{abs}}_{798}=0.523$ and $I^{\mathrm{abs}}_{1226}=1.0$ (Ref. 14).
[c] Calculated with $I^{\mathrm{abs}}_{798}=0.680$ and $I^{\mathrm{abs}}_{1226}=0.729$ (Ref. 14).

about $1\hbar$ for the 3-MeV neutron induced fission of ^{235}U compared with the thermal-neutron-induced fission of the same nucleus. Also for this isomeric pair this trend is not confirmed in our experiments.

It is well known that, in the giant resonance region, the dominant photon absorption is of the $E1$ type. Therefore in our photofission work the spin and parity of the compound nucleus ^{235}U is most likely $J^{\pi}=\frac{5}{2}^+$, $\frac{7}{2}^+$, or $\frac{9}{2}^+$, while for ^{238}U it is predominantly $J^{\pi}=1^-$. As the J_{rms} values for the corresponding isomeric pairs in the photofission of ^{235}U and ^{238}U are nearly the same, the influence of the spin of the compound nucleus on the primary angular momenta of the fragments is negligible. This result is confirmed by the data of Table VI where, although the J^{π} values for the different fissioning systems vary between $\frac{1}{2}^+$ and $\frac{9}{2}^-$, almost the same J_{rms} values are found for the corresponding isomeric pairs.

Dietrich and Zielinska-Pfabé[24] have calculated, for several fissioning systems, the average primary fragment spin as a function of the fragment mass, for different values of the intrinsic nuclear temperature T. The results of the calculations obtained for the fissioning system ^{236}U are shown in Figs. 1 and 2, for the adiabatic case and for $T=1$, 2, and 3 MeV. In the same figures the experimentally determined J_{rms} values of Tables IV and V, together with some previously obtained results for the isomeric pairs ^{126}Sb, ^{128}Sb, ^{131}Te, and ^{134}I in the photofission of ^{235}U and the ^{131}Te, ^{132}I, and ^{134}I isomeric pairs in the photofission of ^{238}U (Refs. 11, 12, and 13), are compared with the theoretical values. The depicted points represent averaged values over the bremsstrahlung end point energy. This procedure can be performed because the J_{rms} values of the primary angular momenta, for corresponding isomeric pairs, as given in Tables IV and V, are almost independent of the bremsstrahlung end point energy. Because the J_{rms} values for the corresponding isomeric pairs obtained in the photofission of ^{235}U and ^{238}U are almost the same, it makes sense to compare our ^{238}U photofission data with the calculations of Dietrich and Zielinska-Pfabé for ^{236}U. It should be remembered that for fragments leading to the isomeric pair ^{130}Sb, in the photofission of ^{238}U, the averaged J_{rms} value of the primary angular momentum [indicated by (⧲) in Fig. 2] was calculated with the Huizenga and Vandenbosch[19,20] procedure. In view of the results obtained with the MAMI code for the same isomeric pair in the photofission of ^{235}U, this value

TABLE VI. $J_{\mathrm{rms}}(\hbar)$ values for the low energy fissioning systems mentioned in Table III.

Isomeric pairs	$^{233}\mathrm{U}(n_{\mathrm{th}},f)$	$^{235}\mathrm{U}(n_{\mathrm{th}},f)$	$^{239}\mathrm{Pu}(n_{\mathrm{th}},f)$
$^{130}\mathrm{Sb}(8^-)$-$^{130}\mathrm{Sb}(5^+)$	9.7±0.6[a]	9.7±0.6[a]	11.4±0.8[a]
$^{131}\mathrm{Sn}(\frac{11}{2}^-)$-$^{131}\mathrm{Sn}(\frac{3}{2}^+)$		6.8±0.5[b] 6.8±0.3[c]	
$^{132}\mathrm{Sb}(8^-)$-$^{132}\mathrm{Sb}(5^+)$	7.4±0.6[a]	6.6±0.6[a] 6.2±0.6[d]	7.8±0.6[a]
$^{133}\mathrm{Te}(\frac{11}{2}^-)$-$^{133}\mathrm{Te}(\frac{3}{2}^+)$	6.0±0.4[a]	6.1±0.4[a] 6.1±0.4[d]	6.5±0.4[a]
$^{136}\mathrm{I}(6^-)$-$^{136}\mathrm{I}(2^+)$		7.0±0.3[d] 5.9±0.4[e]	

[a] Reference 17.
[b] Reference 8.
[c] Reference 16.
[d] Reference 7.
[e] Reference 18.

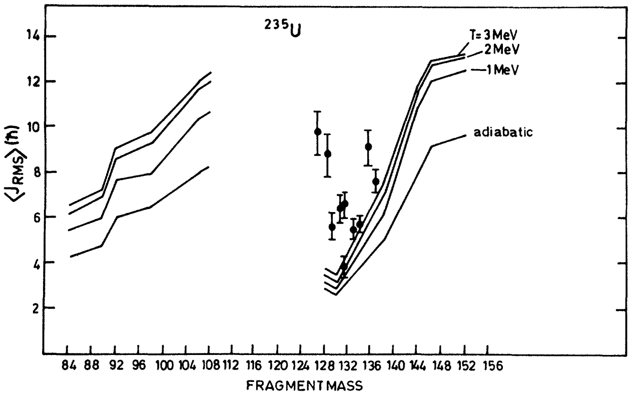

FIG. 1. The average root mean square values of the fragment spins for the photofission of ^{235}U calculated with the MAMI code are given by (⌽). The expected values following Dietrich and Zielinska-Pfabé (Ref. 24) for the fissioning system ^{236}U and for different values of the nuclear temperature T are represented by the solid lines.

is probably too high. The conversion of post-neutron masses to pre-neutron masses was performed as described in Ref. 10.

As can be seen from Figs. 1 and 2, the theoretical $J_{\rm rms}$ values show a sawtooth structure and are a function of the value of the intrinsic temperature T. This behavior is caused by the influence of shell effects on the "bending" mode. The adiabatic case apparently gives the worst description of the experimental data, but even for the unrealistic value of $T=3$ MeV the calculated $J_{\rm rms}$ values are, in general, still too small. Qualitatively there is a certain agreement between the behavior of the theoretical $J_{\rm rms}$ values and our photofission results. Indeed, for the heavy fragments, theoretically as well as in our photofission data, the lowest $J_{\rm rms}$ values are found for fragment masses with $A \simeq 132$, and the more the fragments differ from that doubly magic configuration, the higher the primary angular momenta will be. In the model of Dietrich and Zielinska-Pfabé[24] the generated angular momentum is of purely collective nature. It is explained by the excitation of the "bending" and "wriggling" modes during scission and by post-scission Coulomb excitation of the fragments. On the contrary, in the statistical model of Fong,[25] the generated angular momentum is of single particle nature. In this model much higher $J_{\rm rms}$ values are found for fragments with masses $A \simeq 132$ ($J_{\rm rms} \simeq 7\hbar$), which may be a hint that the single particle contribution in the generated angular momentum in the fragments is not so small.

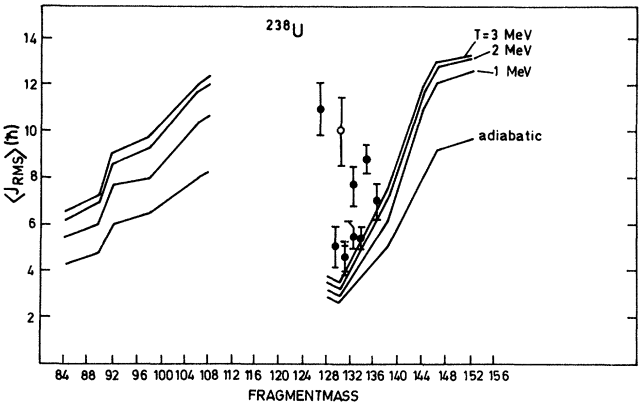

FIG. 2. The average root mean square values of the fragment spins for the photofission of ^{238}U calculated with the MAMI code (Ref. 21) are represented by (⌽). In the case of ^{130}Sb the corresponding $\langle J_{\rm rms} \rangle$ value was calculated with the Huizenga and Vandenbosch method (Refs. 19 and 20) and given by (⌽). The expected values following Dietrich and Zielinska-Pfabé (Ref. 24) for the fissioning system ^{236}U and for different values of the nuclear temperature T are represented by the solid lines.

As mentioned before, Fujiwara *et al.*[9] observed in a recent study of the primary angular momenta of fragments of iodine, xenon, and cesium isotopes produced in the thermal neutron induced fission of ^{233,235}U and ^{239}Pu a pronounced proton odd-even effect. This means that the primary angular momenta of the even-Z fragments are significantly lower than those of the neighboring odd-Z nuclei. In Figs. 3 and 4 we have plotted, as a function of the charge of the fragments, the $J_{\rm rms}$ values obtained in this study, together with some previous results[11–13] again averaged over the bremsstrahlung end point energy as was done in Figs. 1 and 2. From Figs. 3 and 4 it is clear that, for the photofission of ^{235}U as well as for ^{238}U, the $J_{\rm rms}$ values for the even-Z isotopes, tin and tellurium, are significantly lower than for the odd-Z isotopes, antimony

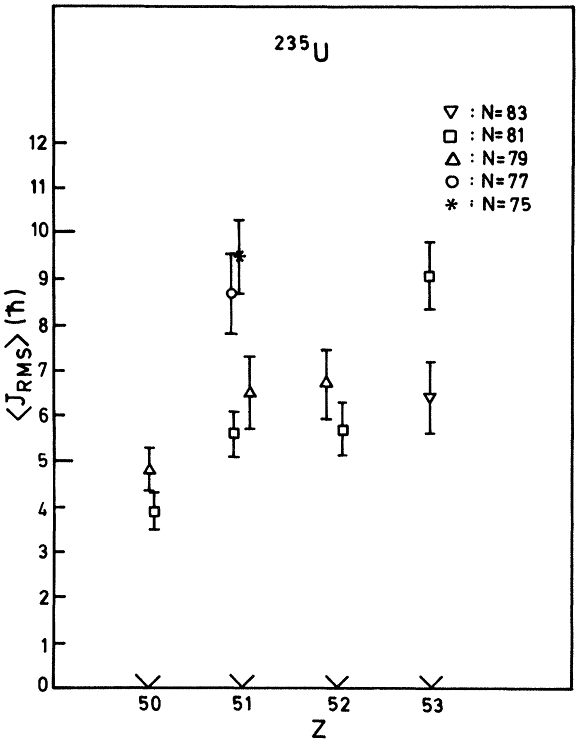

FIG. 3. The average root mean square values of the fragment spins for the photofission of ^{235}U as a function of the charge of the fragments.

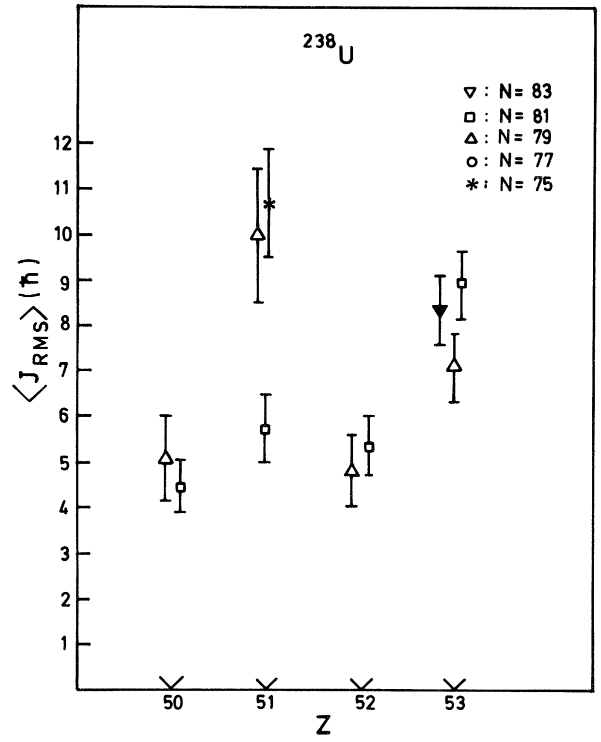

FIG. 4. The average root mean square values of the fragment spins for the photofission of ^{238}U as a function of the charge of the fragments.

and iodine. This is in agreement with the results of Fujiwara *et al.*[9] and is an indication that there exists a correlation between the population of the states with high primary angular momentum and the number of uncoupled protons. This effect cannot be explained by a mechanism which takes into account only the collective motion of the fragments. This proton odd-even effect points to the role uncoupled nucleons, created between saddle point and scission point, may play in the generation of angular momenta in the fragments.

In our photofission experiments it was not possible to obtain the $J_{\rm rms}$ values as a function of the kinetic energy of the fragments. Nevertheless, one can have an idea concerning the behavior of those $J_{\rm rms}$ values of the primary fragment spins as a function of the mean excitation energy of the fragments. Indeed, it was noted several years ago by different groups, e.g., by Denschlag *et al.*[7] for the ^{235}U(n$_{\rm th}$,*f*) fission, that the most neutron rich members of a given mass chain originate from fragments with the lowest excitation energy, while for less neutron rich nuclei it is the opposite. If we define, as was done by Fujiwara *et al.*,[9] a neutron displacement parameter δN as the difference between the number of neutrons N in the fission product and the number of neutrons N_p of the most probable fission product of a given isotopic distribution, than $\delta N = N - N_p$ is a measure of the excitation energy of a given fragment. The more negative the δN values are, the higher the excitation energy of the fragments is. The most probable neutron numbers were deduced from the isotope distributions published in a separate paper in this issue.[26] In Figs. 5 and 6 the $J_{\rm rms}$ values obtained for the same isomeric pairs as in Figs. 1—4 are given as a function of δN. The conclusion of Fujiwara *et al.*[9] that the mean angular momenta of the investigated fragments increase with increasing excitation energy of the fragments, up to a certain value of δN, is confirmed by our experimental results for ^{235}U and not contradicted by our results for the photofission of ^{238}U.

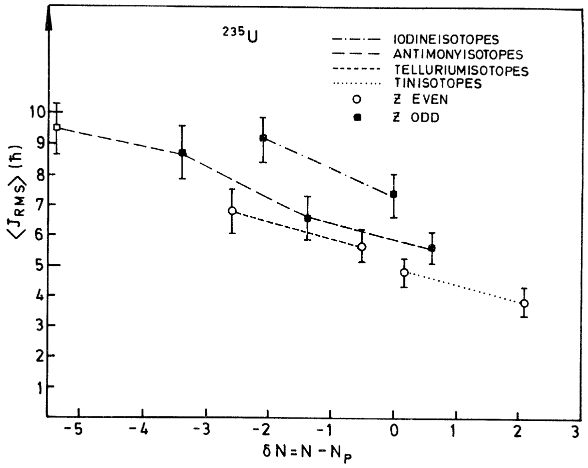

FIG. 5. The average root mean square values of the fragment spins for the photofission of ^{235}U as a function of $\delta N = N - N_p$.

As can be seen from Fig. 5 we have, for the photofission of ^{235}U, experimental results for four antimony isotopes: $A=126$, 128, 130, and 132. Based on these data we calculated a value for the change of $J_{\rm rms}$ per additional neutron, $\Delta\langle J_{\rm rms}\rangle/\Delta(\delta N)\simeq -0.9\hbar$. Taking into account that, on the average, an energy of 8.6 MeV is needed to

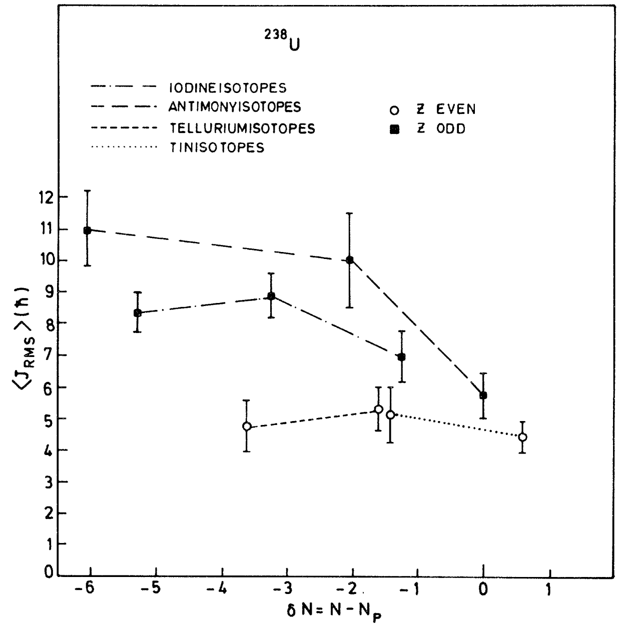

FIG. 6. The average root mean square values of the fragment spins for the photofission of ^{238}U as a function of $\delta N = N - N_p$.

release a supplementary neutron,[27] one finds for the antimony isotopes an increase of J_{rms} of $\sim 0.1\hbar/\mathrm{MeV}$. This is in good agreement with the results of Fujiwara *et al.*[9]

III. CONCLUSIONS

We have investigated the primary angular momenta for a number of fragments produced in the photofission of $^{235,238}\mathrm{U}$ with 12—30 MeV bremsstrahlung. The primary angular momenta calculated with a statistical method developed by Huizenga and Vandenbosch and with the more sophisticated treatment of Min and Martinot showed an independency of the primary angular momenta on the compound nucleus spin and excitation energy. Analogous to the results of Fujiwara *et al.*, a proton odd-even effect on the J_{rms} values of the primary angular momenta was observed. The J_{rms} values for the investigated fragments increased with the excitation energy of those fragments.

ACKNOWLEDGMENTS

We are very grateful to Prof. Dr. A. J. Deruytter for his interest in this work. Thanks are also expressed to Ing. J. Buysse and Mrs. L. Waerniers-Schepens for the chemical separations performed and to the Linac team of our laboratory for the operation of the linear electron accelerator. This work is part of the research program of the National Fund for Scientific Research—Interuniversity Institute for Nuclear Sciences.

---

[1] R. Vandenbosch and J. R. Huizenga, *Nuclear Fission* (Academic, New York, 1973).

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

[3] F. Pleasonton, R. L. Ferguson, and H. W. Schmitt, Phys. Rev. C 6, 1023 (1972).

[4] J. B. Wilhelmy, E. Cheifetz, R. Jared, S. G. Thompson, H. R. Bowman, and J. O. Rasmussen, Phys. Rev. C 5, 2041 (1972).

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

[6] J. R. Nix and W. J. Swiatecki, Nucl. Phys. 71, 1 (1965).

[7] H. O. Denschlag, H. Braun, W. Faubel, G. Fischbach, H. Meixler, G.Paffrath, W. Porsch, M. Weiss, H. Schrader, G. Siegert, J. Blachot, Z. B. Alfassi, H. N. Erten, T. Izak-Biran, T. Tamai, A. C. Wahl, and K. Wolfsberg, in *Proceedings of the International Symposium on the Physics and Chemistry of Fission, Julich, 1979* (International Atomic Energy Agency, Vienna, 1980), Vol. II, p. 53.

[8] J. P. Bocquet, F. Schussler, E. Monnand, and K. Sistemich, in *Proceedings of the International Symposium on the Physics and Chemistry of Fission, Julich, 1979* (International Atomic Energy Agency, Vienna, 1980), Vol. II, p. 179.

[9] I. Fujiwara, N. Imanishi, and T. Nishi, J. Phys. Soc. Jpn. 51, 1713 (1980).

[10] D. De Frenne, H. Thierens, B. Proot, E. Jacobs, P. De Gelder, and A. De Clercq, Phys. Rev. C 26, 1356 (1982).

[11] E. Jacobs, H. Thierens, D. De Frenne, A. De Clercq, P. D'hondt, P. De Gelder, and A. J. Deruytter, Phys. Rev. C 21, 237 (1980).

[12] E. Jacobs, H. Thierens, D. De Frenne, A. De Clercq, P. D'hondt, P. De Gelder, and A. J. Deruytter, Phys. Rev. C 19, 422 (1979).

[13] H. Thierens, B. Proot, D. De Frenne, and E. Jacobs, Phys. Rev. C 25, 1546 (1982).

[14] H. Huck, M. L. Perez, J. J. Rossi, and H. M. Sofia, Phys. Rev. C 24, 2227 (1981).

[15] F. Schussler, J. Blachot, E. Monnand, J. A. Pinston, H. Lawin, K. Sistemich, K. Kawade, K. Heyde, and J. Sau, in Proceedings of the Fourth International Conference on Nuclei far from Stability, Helsingør, 1981, CERN Report CERN-RD/504-1600, 1981, p. 532.

[16] H. O. Denschlag (private communication).

[17] N. Imanishi, I. Fujiwara, and T. Nishi, Nucl. Phys. A263, 141 (1976).

[18] C. Hamelin, J. Crançon, J. Blachot, G. Lhospice, J. P. Bocquet, and A. Moussa, J. Phys. L 41, 223 (1980).

[19] J. R. Huizenga and R. Vandenbosch, Phys. Rev. 120, 1305 (1960).

[20] R. Vandenbosch and J. R. Huizenga, Phys. Rev. 120, 1313 (1960).

[21] D. P. Min, Ph.D. thesis, Université de Paris-Sud, 1976 (unpublished).

[22] D. Sarantites, G. Gordon, and C. D. Coryell, Phys. Rev. 138, B353 (1965).

[23] M. Diksic and L. Yaffe, Can. J. Chem. 53, 3116 (1975).

[24] K. Dietrich and M. Zielinska-Pfabé, private communication.

[25] P. Fong, in *Proceedings of the International Symposium on the Physics and Chemistry of Fission, Julich, 1979* (International Atomic Energy Agency, Vienna, 1980), Vol. II, p. 373.

[26] D. De Frenne, H. Thierens, B. Proot, E. Jacobs, P. De Gelder, and A. De Clercq, Phys. Rev. C 29, 1908 (1984).

[27] H. Nifenecker, C. Signarbieux, R. Babinet, and J. Poitou, in *Proceedings of the Third Symposium on the Physics and Chemistry of Fission, Rochester, 1973* (International Atomic Energy Agency, Vienna, 1974), Vol. II, p. 117.