PHYSICAL REVIEW C VOLUME 10, NUMBER 2 AUGUST 1974

Spectrum of γ rays in the 8- to 20-MeV range from ^{252}Cf spontaneous fission*

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(Received 26 December 1973)

The spectrum of γ rays in the 8- to 20-MeV range has been measured for ^{252}Cf spontaneous fission using a 25.4 cm×25.4 cm NaI crystal and time-of-flight separation of γ rays and neutrons. These data, obtained at three solid angles, are in disagreement with the recent result of Brooks and Reines that γ-ray events above 10 MeV in their experiment were due to two correlated γ rays detected simultaneously. A statistical calculation using the Hauser-Feshbach formalism was performed for the deexcitation of the highly excited fission fragments. The computed γ-ray spectrum in the energy range 8–17 MeV has the same shape as the measured spectrum but is lower than the measurement by a factor of 3 to 4.

[RADIOACTIVITY, FISSION ^{252}Cf(sf); measured γ-ray spectrum, E_γ = 8–20 MeV; performed statistical calculation of high-energy γ-ray spectrum.]

I. INTRODUCTION

The spectrum of γ rays in the 0- to 10-MeV range has been measured for ^{252}Cf spontaneous fission several times to date.[1-3] Brooks and Reines[4] recently have presented data on the γ-ray spectrum above 10 MeV for ^{252}Cf spontaneous fission. They conclude that their observed spectrum above 10 MeV is due mostly to two correlated γ rays being absorbed in their NaI detectors simultaneously. If their result is correct, it could have interesting implications for the mechanism of the fission process in these events.

We have performed a measurement of the γ-ray spectrum for single γ rays between 8 and 20 MeV for ^{252}Cf spontaneous fission using a well calibrated NaI detector system designed particularly for γ-ray spectroscopy in this higher-energy region. It was found necessary to use time-of-flight techniques to eliminate the effects of fission neutrons. In addition to measuring the γ-ray spectrum we were able to investigate Brooks and Reines's claim that the high-energy events in their experiment were of multiplicity two by using several different solid angles in our experiment. We find that our results disagree with their claim as will be explained below. Another measurement of a high-energy γ-ray spectrum from fission has been reported by Sobel *et al.*[5] for spontaneous fission of ^{238}U. In comparison, the present results show many fewer γ rays in the high-energy region, and a less steep falloff with increasing energy.

We also present a statistical calculation for the deexcitation of the highly excited fission fragments using the Hauser-Feshbach formalism which we compare to our observed γ-ray spectrum.

II. EXPERIMENTAL TECHNIQUES AND RESULTS

The experimental arrangement is shown schematically in Fig. 1. The ^{252}Cf source was evaporated onto a 5-cm^2 nickel foil and placed in an ionization chamber filled with methane (CH_4). The output signal from a fast current-sensitive preamplifier was fed to a constant-fraction discriminator whose threshold was set just below the fission fragment pulses yet well above the α-decay pulses. The counting rate of the fission pulses was approximately 3.7×10^4 sec^{-1}. The timing output from the discriminator was delayed with a cable and sent to the stop input of a time-to-amplitude converter (TAC) for comparison with the γ timing signal. It was also scaled to record the total number of fissions during the runs.

The γ detector was a 25.4 cm diam ×25.4 cm long NaI scintillator surrounded by a 15.24 cm thick NE102 plastic anticoincidence shield on the sides and a 3.81 cm thick shield in front. The shield reduces cosmic-ray background and improves the energy resolution of the system. Fast electronic circuitry was used for the NaI plastic coincidence detection and for pileup rejection in the NaI as described in the literature.[6,7] A simplified block diagram of the electronic circuitry is shown in Fig. 2. The γ spectrometer is located in a target room of the Livermore cyclograaff facility; the tandem accelerator was used to generate monoenergetic line shapes for calibration of the spectrometer for the different geometries used in this experiment as discussed below.

Rejection of pileup from two low-energy pulses was accomplished by clipping the photomultiplier anode pulses to 25 nsec and opening a 250 nsec

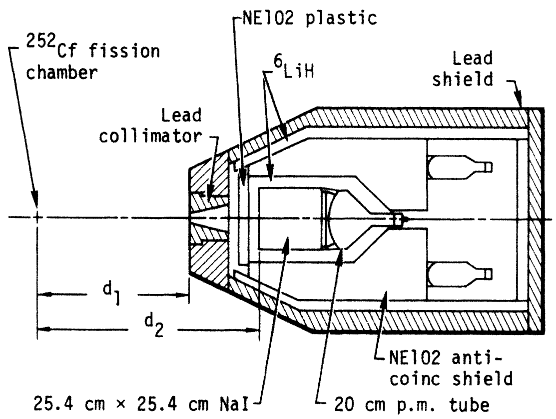

FIG. 1. Schematic diagram of the experimental setup. The distance d_1 (and hence d_2) and the lead collimator were varied to obtain the solid angles listed in the text.

linear gate for the dynode signal (previously clipped to 250 nsec) only when the anode pulse exceeded a preset discriminator level. In the present experiment this level was set at approximately 6.5 MeV. The total counting rate above 0.5 MeV (measured by the output of another fast discriminator) did not exceed 5000 counts/sec. The discriminator output was also used to check for coincidences with the plastic shields, and if a coincidence was found the analyzed linear signal was routed to a portion of the analyzer called the "rejected" spectrum.

The experiment was performed with three solid angles. At a source-to-crystal-face distance d_2 of 89 cm, two collimators were chosen to provide solid angles of 1.79×10^{-2} and 3.65×10^{-2} sr; the collimators were conical with apex at the source position. At a source distance d_2 of 43 cm and no collimator in place, the solid angle was 0.251 sr, determined by the inside edge of the front lead shield of the spectrometer.

A separate fast constant-fraction timing circuit placed on the linear signal generated start pulses for the time-to-amplitude converter. The resulting time spectrum of pulses above the 6.5-MeV threshold for the shortest distance (43 cm) is shown in Fig. 3. This spectrum contains only events *not* in coincidence with the plastic shield ("accepted" spectrum). The prompt neutrons are clearly separated from the γ events; the continuation of the spectrum to the left represents neutrons that have undergone multiple scatterings on the way to the NaI crystal. The absence of counts to the right of the γ peak indicates that cosmic-ray events and room-scattered neutrons were negligible. The full width at half-maximum (FWHM) of the γ peak is 2.4 nsec. Single-channel analyzers set on the γ and fast-neutron peaks were used to route the linear signals. The energy spectra were thus stored in four 256-channel segments of the pulse-height analyzer, corresponding to the conditions (n or γ window) × (shield coincidence yes or no).

At the largest solid angle it was necessary to introduce further discrimination against neutrons that follow a γ ray emitted from the *same* fission event, but that cannot be recognized because the γ ray has determined the position of the event in the time spectrum. The fraction of such pileup events is proportional to the solid angle. It was desired to reject neutrons following γ rays by as little as 10 nsec, which is difficult because of the 20-nsec rise time of the NaI pulses and the statistical noise on them. Figure 4 shows sche-

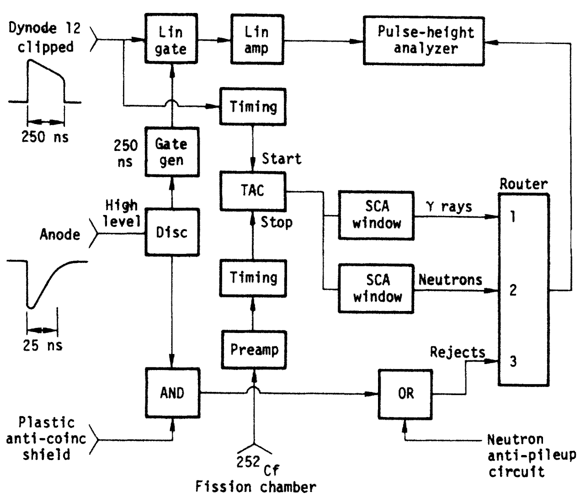

FIG. 2. Schematic diagram of the main portion of the electronic circuitry used to obtain the γ-ray pulse-height spectrum.

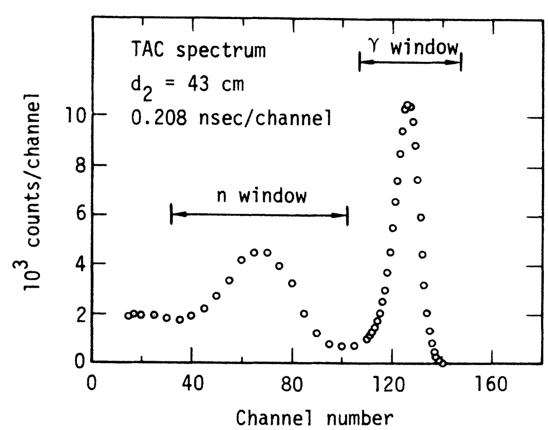

FIG. 3. TAC spectrum showing the timing relationship between γ rays and neutrons for the shortest flight path (43 cm). Each channel is shown only in the region of the γ peak.

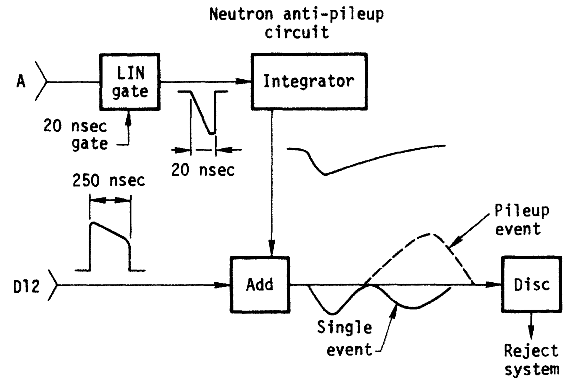

FIG. 4. Schematic diagram of the electronic circuitry used to reduce neutron pileup at the largest solid angle.

matically the pulse-shape discrimination technique that was used. The output of the constant-fraction timing discriminator opens a linear gate for 20 nsec, which passes the signal from the photomultiplier anode only until it reaches its peak. The gate cannot be reopened for about 2 μsec. The pulse from the linear gate is integrated to reduce the amplitude fluctuations, stretched, and added to the dynode signal, which has also been smoothed over a 20-nsec time interval. By adjusting the relative amplitudes and times of the added signals, the pulse from a single event can just be prevented from going positive, whereas the extra component in the dynode signal from the

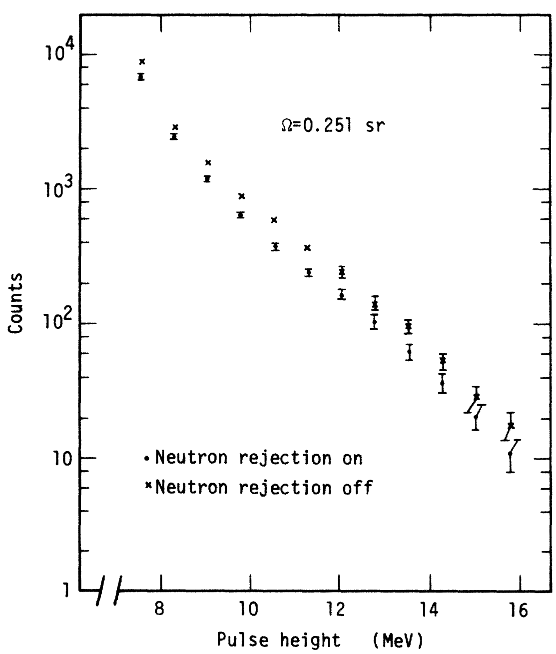

FIG. 5. The "accepted" NaI pulse-height spectra for the largest solid angle with and without the neutron antipileup circuitry shown in Fig. 4.

pileup events causes a positive overshoot in the added signal. The overshoot is detected by a fast discriminator and the event routed into the same section of the analyzer as the events rejected by the plastic shield. The circuitry was adjusted by using a PuBe source, which provides 4.43-MeV γ rays correlated with fast neutrons from the ^{9}Be$(\alpha, n)^{12}$C$^*(\gamma)$ reaction. The system was set to reject events in which a γ ray was followed by a neutron depositing an energy greater than 2.5 MeV in the NaI crystal, and in which the time separation of the two pulses was at least 10 nsec. Figure 5 shows "accepted" pulse-height spectra in the γ time window with and without the antipileup circuitry. The circuitry was used only for the largest (0.251 sr) solid angle spectra, for which the pileup causes about a 50% increase in the counting rate. The pileup effect was ignored for the other, much smaller, solid angles.

The energy calibration was accomplished by using a PuBe neutron source, which provides γ peaks of 2.23 MeV from neutron capture in the plastic shield, 4.43 MeV from ^{9}Be$(\alpha,n)^{12}$C*, and 6.797 MeV from full-energy capture of slow neutrons on ^{127}I. The calibration was linearly extrapolated to the 10- to 20-MeV region. The linearity of the system had been previously established with accelerator-produced discrete γ rays in the 10- to 30-MeV range; for this experiment the linearity of the electronic circuitry was further checked by observing the PuBe source peaks at several photomultiplier voltages. During the course of the runs the linear gate pedestals were checked at frequent intervals. The long-term gain of the system was stabilized by a GaP diode light

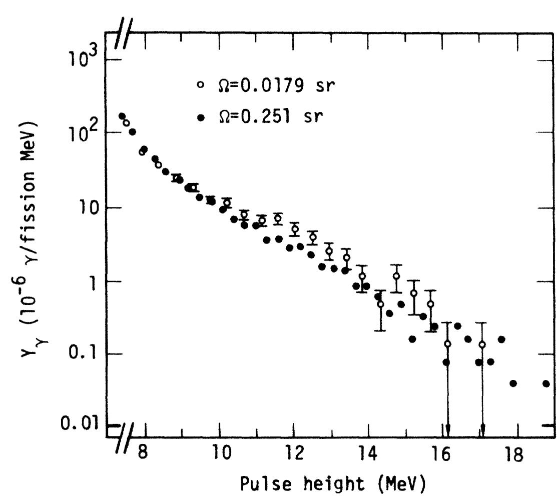

FIG. 6. The γ-ray pulse-height spectra for the smallest and largest solid angles. The difference between the spectra in the region 10-16 MeV is due to the spectrometer efficiency as discussed in the text.

pulser. It was found that the peaks from γ sources and the light pulser exhibited the same gain shifts with temperature over a 24-h period. The uncertainty in the energy calibration at 15 MeV was estimated as ±0.15 MeV.

The accepted pulse-height spectra of the γ rays for the smallest and largest solid angles are shown in Fig. 6. The errors on the black dots are about one-half those on the neighboring open circles. Only the solid angle and total number of fissions have been included in determining the absolute scale; the discrepancy between the curves above 10 MeV is due to the crystal response for different collimation conditions as shown below. The curves match in the region below 9 MeV where the 2.5-MeV threshold in the antipileup circuit is too high to prevent pileup on the copious γ pulses below 7 MeV. The yield of events in the neutron time window was always larger than the γ yield by a factor of 3 to 5 for pulse heights above 8 MeV equivalent γ energy. The counting times were 22.6 h for 0.251 sr, 23.5 h for 3.65×10^{-2} sr, and 47.3 h for 1.79×10^{-2} sr.

To determine the absolute yield, the accepted γ pulse-height spectra were unfolded by an iterative technique[8] using response functions for discrete γ lines measured with the identical geometries used in the ^{252}Cf source runs. γ rays of energy 14.0 and 16.8 MeV were produced by the $^{15}N(p,\gamma)^{16}O$ reaction at incident proton energies 2 and 5 MeV furnished by the Lawrence Livermore Laboratory (LLL) tandem accelerator; 4.43-MeV γ rays were observed from the $^{15}N(p,\alpha)^{12}C^*$ reaction in the same series of runs. An example of such a line shape is shown in Fig. 7. The line shapes were parametrized with a functional form which was also used to extrapolate them to low energies. For each geometry, line shapes at other energies were determined by linearly interpolating or extrapolating the measured line shape parameters. Uncertainty in the low-energy extrapolation of the line shapes contributes an uncertainty of ±15% to the final absolute scale. The counting statistics in the original spectra are amplified by the unfolding procedure; these variations were reduced by Gaussian smoothing with FWHM in the range 2–4%. The absolute yield was corrected for a 12% absorption of γ rays in the front ^{6}LiH shield, the front plastic, and the NaI housing materials, and for the γ rays that pass through the NaI without interaction (calculated as 3% for the two small solid angles). Otherwise, it was assumed that a γ ray entering the collimator appeared in either the accepted or rejected spectrum, and the yield was corrected by using the ratio of accepted to rejected counts observed for the monoenergetic line shapes. For the large solid angle, the correction for γ rays not interacting in the NaI was found by comparing the observed yields of the $^{15}N(p,\gamma)^{16}O$ γ rays with the different solid angles. The results are shown in Fig. 8. Figure 9 presents the same data, but with the points averaged in bins of approximately 1

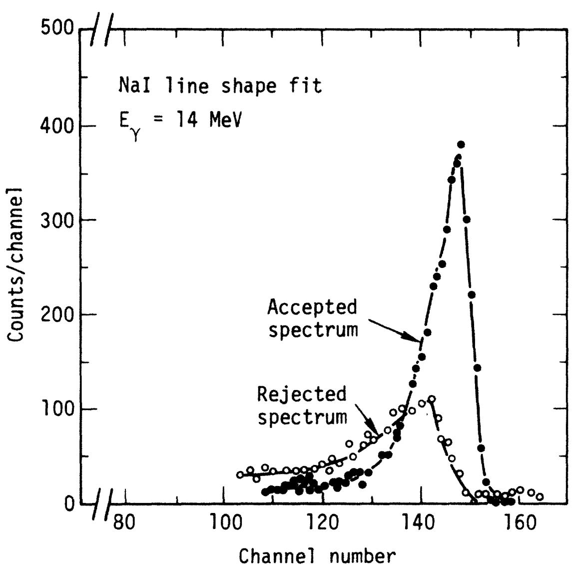

FIG. 7. Example of a NaI line shape for a 14-MeV monoenergetic γ ray obtained using the $^{15}N(p,\gamma_0)^{16}O$ reaction. The "accepted" spectrum includes only γ-ray events not in coincidence with events detected in the plastic shield. The solid curves are fits representing the parametrization of the line shapes discussed in the text.

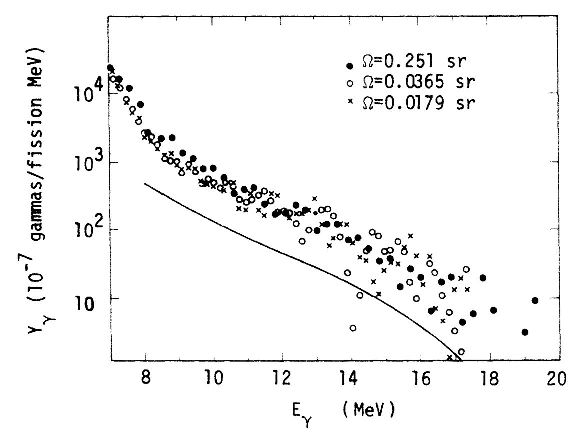

FIG. 8. γ-ray spectra for ^{252}Cf spontaneous fission for the three solid angles mentioned in the text. These spectra have been corrected using the measured NaI response functions. The spectrum at 0.251 sr below 10 MeV is distorted by pileup effects. The uncertainty in the vertical scale is ±15%. The solid line represents the statistical calculation discussed in Sec. III.

MeV to further suppress the statistical variations from point to point. The agreement in yield above 10 MeV for the three solid angles is good. Below 10 MeV, the points for the 0.251-sr run should be ignored because they include residual pileup events as discussed above. At the lowest energies, the yield matches the upper end of the spectrum measured by Verbinski, Weber, and Sund.[3] To check further the absolute scale, we took short runs at the two small solid angles with the thresholds reduced to 2 MeV, and found agreement to within 10% in the 4- to 6-MeV region with Ref. 3.

There is no evidence for an enhanced yield with the large solid angle which would indicate peak summing of two γ rays from the same decay. This result in fact disagrees with the conclusion of Brooks and Reines, even though the solid angle in their experiment was about 10 times larger than the largest in the present experiment. To show this, we consider the following. For events (single or double) depositing a fixed total energy, the absolute rates of single events A_1 and double events A_2 may be related to the yield C observed by the system as

$$C=\left(\frac{\Omega}{4\pi}\right)\epsilon A_1+\left(\frac{\Omega}{4\pi}\right)^2\epsilon^2 A_2\,,$$

in which Ω is the detector solid angle, and ϵ is the efficiency for detecting a single γ ray entering the solid angle and giving a pulse height in the full-energy region. We have approximated ϵ as independent of γ energy and have assumed isotropic angular correlation of the double events. By assuming A_1 is measured by the smallest solid angle runs in the present experiment, we can calculate A_2 from the value of C in Fig. 6 of Ref. 4. We can then predict the value of C which should be observed in the present experiment with any solid angle as follows:

$$\left(\frac{4\pi}{\Omega}\right)\frac{1}{\epsilon A_1}C=1+\left[\left(\frac{4\pi}{\Omega_B}\right)\left(\frac{\epsilon}{\epsilon_B}\right)^2\frac{C_B}{\epsilon A_1}-\frac{\epsilon}{\epsilon_B}\right]\frac{\Omega}{\Omega_B}\,.$$

The subscript B refers to the quantities taken from Ref. 4. The second term on the right contains the effects of peak summing. We have taken $\Omega_B/4\pi=0.283$ from Ref. 4, and have assumed $\epsilon=\epsilon_B=\frac{1}{3}$. The solid curve in Fig. 9 was drawn through the average of the points for the two smaller solid angles. The dashed curve represents the values of C calculated for our largest solid angle from the above expression, using the values of A_1, inferred from the solid curve and the values of C_B taken from Fig. 6 of Ref. 4. The inconsistency between the dashed curve and the points for the largest solid angle is about a factor of 5 near 12 MeV. The inconsistency would remain even if the neutron pileup rejection had not been used for the largest solid angle, since the pileup enhances the counting rate only by a factor of about 50% as shown in Fig. 5.

The largest uncertainty in the comparison is in the efficiencies assumed for the two systems. The photopeak efficiency for our collimated system is measured to be about $\frac{1}{3}$ for 4.43 MeV as well as for the higher energies near 15 MeV. The response matrix calculated for the system in Ref. 4 shows that the corresponding quantities for that system are not very different. Nevertheless, even if the efficiency were taken as 0.15 for our system, the discrepancy at 12 MeV would still be a factor of 3.

III. STATISTICAL-MODEL ANALYSIS

To investigate the origin of the spontaneous fission γ rays above 10 MeV we have made a statistical calculation assuming the γ rays originate by competition with neutron emission from highly excited fission fragments. The calculation employed the Hauser-Feshbach formalism.[9] For each excited nucleus Z, A we require the initial excitation energy and spin distribution $P(E,J)$;

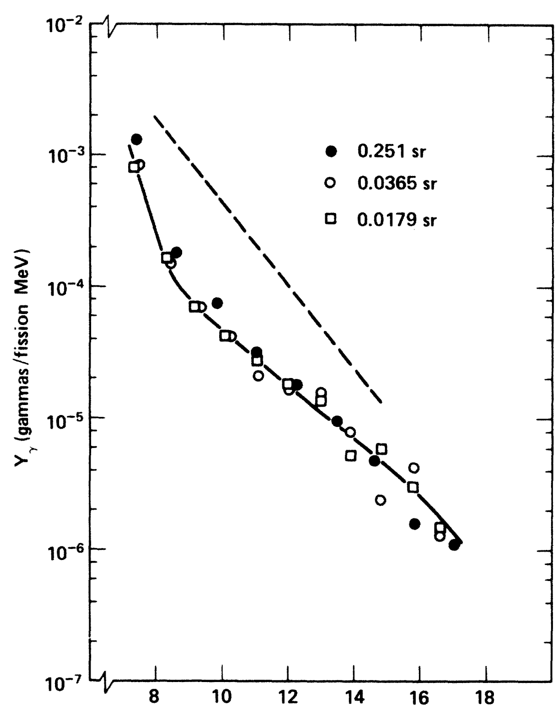

FIG. 9. The same data as in Fig. 8, but averaged in bins of approximately 1 MeV. The solid curve was sketched through the points for the two smaller solid angles. The dashed curve is discussed in the text, in the comparison with the Brooks and Reines experiment (Ref. 4).

then the partial γ spectrum is given by

$$N(E_\gamma)dE_\gamma = \sum_J \int dE\, P(E,J) \frac{\sum_{J'} T_\gamma(E_\gamma, J \to J')\rho(Z,A,E-E_\gamma,J')dE_\gamma}{\sum_{l,J'} \int dE' T_l(E', J\to J')\rho(Z,A-1,E',J')} .$$

Here the neutron transmission coefficients T_l in the denominator were calculated from the Hodgson potential[10] for $A = 110$ and $A = 140$ for the light and heavy fission fragments, respectively; the final state excitation energy is $E' = E - S_n - E_n$, where E_n is the neutron energy and S_n is the neutron separation energy from the nucleus Z,A. The results were extremely insensitive to the form of the neutron transmission coefficients; black-nucleus coefficients increase the calculated spectrum by only 20%. The γ rays were assumed to be electric dipole, and the γ transmission coefficients T_γ were taken in a form that incorporates the dipole sum rule:

$$T_\gamma(E_i - E_f, J\to J') = \frac{2}{3\pi} S\left(\frac{E_i - E_f}{\hbar c}\right)^2 L(E_i - E_f)\frac{NZ}{A} ,$$

where $L(E_i - E_f)$ must satisfy the requirement $\int_{E_f}^{\infty} dE_i L(E_i - E_f) = 1$. The quantity S is the sum-rule value $2\pi^2 e^2 \hbar / M_p c$. We have used the conventional Lorentzian form

$$L(E_\gamma) = (2/\pi\Gamma)\{[(E_0^2 - E_\gamma^2)/\Gamma E_\gamma]^2 + 1\}^{-1}$$

with the parameters $E_0 = 80A^{-1/3}$ and $\Gamma = 5$ MeV typical of the giant dipole resonance. This method, often termed the Brink hypothesis, has been used to fit γ strength functions near neutron binding energies[11]; it is used here because it conveniently concentrates the γ strength in the region of interest. The augmentation of the sum rule by exchange forces has not been included. The level densities $\rho(Z,A,E,J)$ were taken from the work of Gilbert and Cameron.[12] The consequences of using the shell-model-plus-pairing formalism[13,14] to determine the level densities will be discussed below. The form taken for the initial energy-spin distribution was

$$P(E,J) \propto (2J+1)\exp\left\{-\frac{[E - E_0(Z,A)]^2}{2(\sigma_{E(Z,A)})^2} - \frac{J(J+1)}{(B_{Z,A,E})^2}\right\} .$$

For a given pair of fission fragments, the total available energy for fission was calculated from the Garvey-Kelson mass tables.[15] The mean total excitation energy was found by subtracting the total kinetic energy of the fragment pair measured by Whetstone.[16] The division of excitation energy between the light and heavy fragment was computed from the neutron emission data reported by Nifenecker[17] in the following fashion:

$$E_{0L} = \frac{\bar{\nu}_L \bar{E}_{nL}}{\bar{\nu}_H \bar{E}_{nH} + \bar{\nu}_L \bar{E}_{nL}} E_{0T},$$

where E_{0L} is the average excitation energy of the light fragment, E_{0T} is the average total excitation energy, $\bar{\nu}_L$ is the average number of prompt neutrons emitted by the light fragment, $\bar{E}_{nL}$ is the average excitation energy carried off by a neutron emitted from the light fragment, and $\bar{\nu}_L$ and $\bar{E}_{nH}$ similarly refer to the heavy fragment. The quantities $\bar{\nu}_L$, $\bar{\nu}_H$, $\bar{E}_{nL}$, and $\bar{E}_{nH}$ were taken from Ref. 17. The variances $(\sigma_{E(Z,A)})^2$ in the excitation energy of the fragments were taken to be equal for the light and heavy fragments as in Ref. 17, and were given the value 43 MeV^2. The variance in the total excitation energy of a given fragment pair is then 86 MeV^2, assuming small correlation between the excitation energies of the two fragments, as shown by Signarbieux *et al.*[18]; this value is a reasonable average for all pairs except very close to symmetric fission.[17] The spin parameter $B_{Z,A,E}$ was taken as $B_{Z,A,E} = \bar{B} + [E - E_0(Z,A)]/(8\text{ MeV})$, with $\bar{B} = 6$ for $A < 130$ and $\bar{B} = 7.2$ for $A > 130$. These values are consistent with the analysis of Wilhelmy *et al.*[19]; in any case, the calculated γ spectra are very weakly dependent on the details of the spin distribution.

For each excited fragment Z,A considered, the γ and neutron spectra were calculated, and then the calculation repeated for $Z, A-1$ with a new mean excitation energy $E_0(Z,A-1) = E_0(Z,A) - S_n(A) - \bar{E}_n$, where $\bar{E}_n$ is the mean c.m. kinetic energy carried off by the emitted neutrons. A third calculation for $Z, A-2$ was made when necessary. All neutron separation energies S_n were taken from Ref. 15. The calculations were made for nuclei near 102, 108, and 116 for the light fragment, and for the corresponding heavy fragments. These choices are at the top of mass distribution curve[20] and halfway down the sides. An attempt was made to average over pairing effects by calculating for an even-even, odd-odd, even-odd, and odd-even nucleus near each mass. For a given A, the Z was chosen to be consistent with the most probable value according to the method of Ref. 21. The results were averaged and weighted with the probability of initially forming the fragments. The results are shown by the solid curve in Fig. 8. The shape of the curve reasonably fits the data, but the magnitude is too low by about a factor of 4. This discrepancy could be lowered somewhat (perhaps to a factor of $2\frac{1}{2}$ or 3) by including the exchange enhancement of the dipole sum rule. Examination of the partial spectra shows that the γ rays in the 10- to 15-MeV region are largely emitted by the light fragment with masses on the heavy side of the most probable mass. This is a consequence of the increasing average excitation energy and the presumed increase in the nuclear temperature associated with the approach to shell closure which lies between the mass peaks for both neutrons and protons. The nuclei on the low-mass side of the heavy-fragment distribution show a similar, but smaller, augmentation.

The greatest uncertainty in calculating the absolute γ yield appears to be associated with the level density, which is not well known over a wide energy range, particularly for nuclei far from stability. For fission fragments excited to excitation energy E which decay by emitting γ rays of energy E_γ or neutrons of average c.m. energy $\bar{E}_n$, the γ intensity is largely governed by the ratio of level densities in the two product nuclei:

$$N_\gamma(E_\gamma) \propto \rho(Z, A, E-E_\gamma)/[T\rho(Z, A-1, E-S_n-\bar{E}_n)],$$

where S_n is the neutron separation energy and T is the temperature in the region $E-S_n-\bar{E}_n$ of the product nucleus $A-1$. To show the strong dependence of this ratio on the level-density parameters, we consider a constant-temperature level density $\rho \propto e^{E/T}$ with $T=0.7$ MeV, and $S_n+\bar{E}_n = 8$ MeV. Then for 14-MeV γ rays only a 10% increase in T is required to double the γ yield. To check alternatives to the Gilbert and Cameron level densities, we calculated the level densities for two cases ($Z, A = 46, 116$ and $55, 142$) using the formalism described by Huizenga and Moretto.[14] This procedure involves choosing a set of shell-model levels, including residual interactions in the form of a pairing energy, and performing a thermodynamic calculation. With the single-particle levels of Seeger and Perisho[22] we found the temperature in the region near 7 MeV to be 650 keV for $A=116$ as opposed to 600 keV with Gilbert and Cameron. For $A=142$ the corresponding numbers are 690 keV with the thermodynamic calculation and 750 keV with Gilbert and Cameron. In addition to the strong dependence on the level-density parameters, the calculated γ intensity is also strongly dependent on the assumed neutron separation energy. Our conclusion is that the uncertainties in the calculation may be great enough to account for the observed discrepancy in absolute magnitude.

IV. DISCUSSION

In this paper we have reported a measurement of the spectrum of single γ rays from spontaneous fission of ^{252}Cf in the energy region above 10 MeV. In addition to Brooks and Reines,[4] one other measurement of γ rays in this energy range has been reported by Sobel *et al.*[5] for spontaneous fission of ^{238}U. The spectrum of γ rays observed in the present measurement is qualitatively different from that reported for ^{238}U. In the ^{238}U work the spectrum drops off with energy as $\exp(-E_\gamma/1.41$ MeV), whereas in our experiment the falloff is much less steep, and can be approximated by $\exp(-E_\gamma/2.2$ MeV) in the 10- to 14-MeV region. The yield of 14-MeV γ rays reported in the ^{238}U measurement is about 5 times the value for ^{252}Cf. Apparently there is either an experimental discrepancy between the two results or the mechanism producing the γ rays is different. If the statistical mechanism investigated in the present work is correct, one would expect the energy dependence of the two γ spectra to be similar, but the yield of ^{238}U γ rays should be smaller than for ^{252}Cf because of the lower average excitation energy of the fission fragments.

We have found that a statistical-model analysis is capable of reproducing the observed energy dependence of the spectrum, but that the calculated absolute magnitude is very sensitive to imprecisely known level-density parameters. To obtain the calculated spectral shape it was necessary to concentrate the γ strength in the high-energy region by using giant-dipole-resonance parameters to determine the energy dependence of the γ transmission coefficients. A calculation assuming an energy-independent matrix element (i.e., $T_\gamma \propto E_\gamma{}^3$) yielded a spectrum with an energy dependence near 14 MeV as $\exp(-E_\gamma/1.2$ MeV), which is much too steep. We feel that the observed spectrum is consistent with the statistical mechanism, but that it is impossible to exclude other mechanisms such as direct excitation of the giant dipole resonance. Further experiments such as correlation of the γ spectrum with fragment mass and angular distributions of the γ rays may be required to reach more definite conclusions.

ACKNOWLEDGMENTS

We are indebted to M. S. Coops for preparing the ^{252}Cf source. We are grateful to L. G. Moretto and S. M. Grimes for discussions relating to the level-density calculations, and to R. C. Jared and R. Babinet for discussions about the properties of excited fission fragments.

*Work performed under the auspices of the U. S. Atomic Energy Commission.

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