[11$\bar{1}$] symmetry. Since the resonance either of the [$\bar{1}$11] centers or of the [1$\bar{1}$1] centers may be observed by appropriate orientation of the magnetic field, if the resonance is indeed associated with the R center, the polarized bleaching must enhance the [$\bar{1}$11] resonance at the expense of the [1$\bar{1}$1] resonance. The curves of Fig. 3 confirm this prediction. Since the magnetic field cannot be applied along the [111] and [11$\bar{1}$] directions in the present resonance rig, a quantitative comparison with the optical dichroism is not possible, but the degree of polarization indicated by Fig. 3 is consistent with the optical dichroism.

We are grateful for many helpful discussion with Mr. E. Gelerinter and Mr. E. L. Wolf.

---

*Work supported in part by the U. S. Atomic Energy Commission and the Advanced Research Projects Agency.

[1]C. Z. van Doorn, Philips Res. Rept. 12, 309 (1957).
[2]H. Pick, Z. Physik 159, 69 (1960).
[3]P. R. Moran, S. H. Christensen, and R. H. Silsbee, Phys. Rev. 124, 442 (1961).
[4]W. E. Bron, Phys. Rev. 125, 509 (1962).
[5]M. Schwoerer and H. C. Wolf, Z. Physik 175, 457 (1963).
[6]D. B. Fitchen, R. H. Silsbee, T. A. Fulton, and E. L. Wolf, Phys. Rev. Letters 11, 275 (1963).
[7]R. H. Silsbee, Bull. Am. Phys. Soc. 9, 88 (1964).
[8]H. C. Longuet-Higgins, V. Öpik, M. H. L. Pryce, and R. A. Sack, Proc. Phys. Soc. (London) A244, 1 (1958).
[9]R. Orbach, Proc. Phys. Soc. (London) A77, 821 (1961).
[10]Although defects defined by [111] and [$\bar{1}\bar{1}\bar{1}$] axes are in fact different because of the lack of inversion symmetry, this difference is not relevant to any experiments discussed here. Thus reference is frequently made to four possible orientations rather than the full eight.
[11]F. Lüty and J. Mort, Phys. Rev. Letters 12, 45 (1964).
[12]C. P. Slichter (private communication).
[13]F. Okamoto, Phys. Rev. 124, 1090 (1961).
[14]C. A. van Doorn, Philips Res. Rept., Suppl. No. 4 (1962).

GAMMA-RAY SPECTRA FROM SPONTANEOUS FISSION OF ^{252}Cf†

Harry R. Bowman, Stanley G. Thompson, and John O. Rasmussen
Lawrence Radiation Laboratory, University of California, Berkeley, California
(Received 23 January 1964)

In this note we report preliminary results of experiments that show well-defined prompt γ-ray peaks ($\tau < 10^{-9}$ sec) associated with fission fragments of selected masses. The dependence of the Doppler shift of the energy of the radiation on fragment direction and mass is found to be a valuable aid in the interpretation of the spectra. These results are of special interest because it has generally been assumed on the basis of early measurements that the gamma spectra would be sufficiently complex to preclude observing distinctly resolved spectra.[1] The identification of discrete gamma spectra offers the hope of obtaining nuclear energy-level data in a neutron-excess region not accessible by other means, and may also contribute to knowledge concerning the spins and de-excitation processes of the primary fragments.

Our results have come about through measurements of the energies of both members of pairs of fragments and of coincident gamma rays from single fission events. A weightless ^{252}Cf fission source which was prepared by self-transfer onto thin nickel foil was used in the measurements. The energies of the two fragments were measured and the direction of fission was defined by means of two solid-state counters located about 1 cm from the source. The energies of the γ rays were measured with a 3-by-3-in. NaI(Tl) counter placed at the desired angle with respect to the direction of motion of the coincident fragments. The coincidence resolving times were adjusted to accept γ rays emitted within ±50 nsec of the time of fission. The data were recorded in three dimensions by using a multidimensional pulse-height analyzer, and were stored event by event in correlated form on magnetic tape. The results were sorted by using an IBM-7094 computer in such manner that the individual gamma-ray energy spectra were obtained separately for fragment energy ratios of 1.05 to 1.15, 1.15 to 1.25, 1.25 to 1.35, and 1.35 to 1.45. The fragment energy ratio, R, approximately equals the mass ratio and is referred to hereafter as the mass ratio. The sorting interval above corresponds to about four mass units.

Figure 1(a) shows the gross gamma spectrum in prompt coincidence with fission fragments of all energies (NaI detector at 0 deg with respect to fission). There is some evidence of peaks in

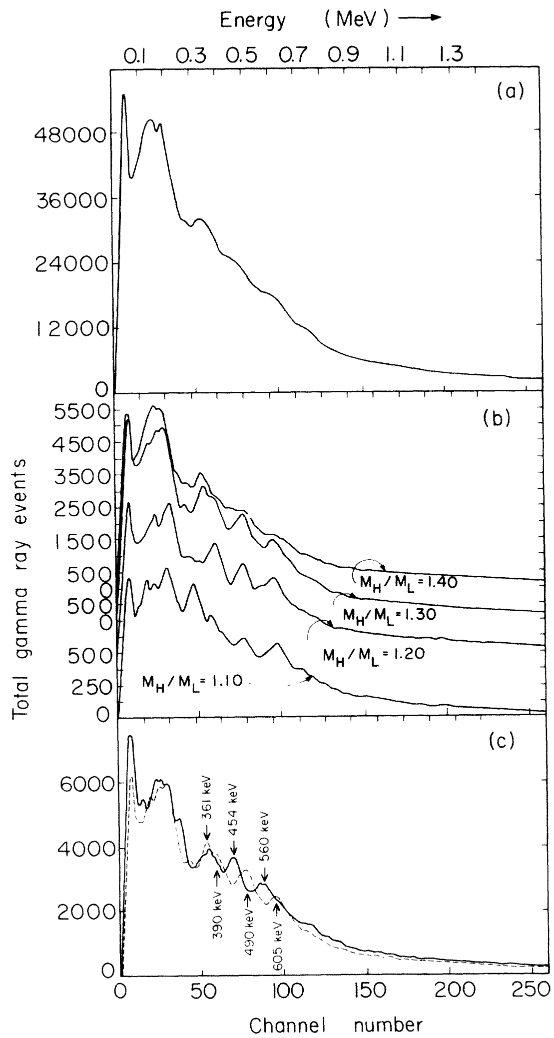

FIG. 1. (a) Total prompt γ-ray energy spectrum from spontaneous fission of ^{252}Cf measured with a 3-by-3-in. NaI(Tl) counter in coincidence (50 nsec) with two fission-fragment detectors (NaI counter at 0 deg with respect to fission direction). Events were not selected according to mass or fragment direction. (b) Spectra of prompt γ rays associated with various values of R, the mass ratio. These spectra were then measured with the NaI counter at 0 deg relative to the direction of motion of the fragments. The spectra are also associated only with the events in which the heavy-fragment members of the pairs moved toward the γ-ray counter. (c) Dependence of prompt γ-ray spectra on the direction of motion of the fragments (Doppler shift). The spectra shown were obtained with the NaI counter at 0 deg relative to the direction of motion of the fragments and are associated only with fragments of mass ratio $R = 1.30 \pm 0.05$ ($M_H = 140 \pm 2$). The solid curve is the spectrum emitted by light fragments moving toward the γ-ray counter, and the dashed curve is for heavy fragments moving in the direction of the γ-ray counter.

this complex spectrum. In order to determine the extent of the contribution of fission neutrons to the observed spectrum [i.e., (n,γ) reaction in the detector], some experiments were done using lead absorbers. It was found that the (n,γ) reaction spectrum produced by neutrons was very much smaller in magnitude, and the peaks were of different energy than those discussed here in connection with the prompt γ rays from fission. The absence of effects arising from neutrons can also be shown below in connection with the discussion of the Doppler shift in the energies of certain gamma rays that are emitted by moving fragments [i.e., such a shift in the (n,γ) spectrum would not occur].

When the events were sorted, and the gamma-ray spectra associated with a particular fission mass ratio were examined separately, a profusion of definite peaks appeared from 150 to 600 keV, most of which are probably complex. The spectra change markedly for different mass ratios, and we thus find an explanation for the fact that the discrete structure is generally obscured in a total prompt-gamma spectrum such as that given in Fig. 1(a), where no sorting according to mass ratio is done. Figure 1(b) shows spectra for several specified mass ratios taken with the NaI detector at 0 deg to the fission direction. In this case, the data are subject to a further restriction in sorting such that the spectra given are associated with the case of heavy fragments moving toward the γ-ray counter and light fragments moving in the opposite direction.

For gamma rays emitted during the time of flight to the detectors (about 1 nsec), there should be a detectable Doppler shift in the 0-deg measurements, permitting assignment of gammas to light or heavy fragments. Those gamma rays emitted after 1 nsec but within a time of 50 nsec would be observed, but without Doppler shift, since the fission-fragment detectors are seen by the gamma detector in our experimental arrangement. As a result of the Doppler effect, the γ rays emitted by the fragments are changed in energy according to the relation $E_\gamma = E_0(1 \pm v/c)$, where v is the velocity of the fragments and E_0 is the energy of the gamma rays emitted by fragments with zero velocity. The sign of v/c is positive when the gamma ray is emitted by a fragment moving in the direction of the γ-ray counter and negative when the fragment is moving away from the counter. The maximum difference in energy, ΔE, is $E_0(2v/c)$, which should be about 7% of E_0 for heavy fragments having an average velocity of 1.04×10^9 cm/sec, and 9% for average light fragments having an average velocity of 1.37 $\times10^9$ cm/sec.

An example of a fairly well-resolved peak subject to Doppler shifting is provided by the NaI-counter spectra for the mass ratio 1.3. For this mass ratio, the heavy fragment mass is 140 ± 2 when correction is made for the average emission of four neutrons. Then the masses of the heavy and light fragments total 248; the most probable charge is calculated as 54.[2] In Fig. 1(c) the solid curve represents the spectrum observed when the light fragments travel in the direction of the gamma-ray counter. The dashed curve represents the opposite case (heavy fragments traveling toward the gamma-ray counter). The peaks of the solid curve at 560, 454, and 361 keV seem to appear at approximately 605, 490, and 390 keV, respectively, in the dashed curve. The general feature of the energy shift observed for all these peaks is that expected for emission from heavy fragments of mass near 140, although changes in the peak shapes occur, suggesting unresolved components not all shifting in the same way. Further evidence for complexity is given by the observed intensity per fission of each of these three peaks summed within mass-ratio limits of 1.15 to 1.35, since each of these intensities is larger than the expected fission yield of any single nuclide in this region. The suspected complexity was confirmed in preliminary experiments using a high-resolution (full width at half-maximum = 8 keV) lithium-drifted germanium detector operated at 77°K for the gamma rays.[3] Figure 2 shows such gamma spectra for mass ratios of 1.2 and 1.3 at an angle of 0 deg (heavy fragment moving toward the gamma detector).

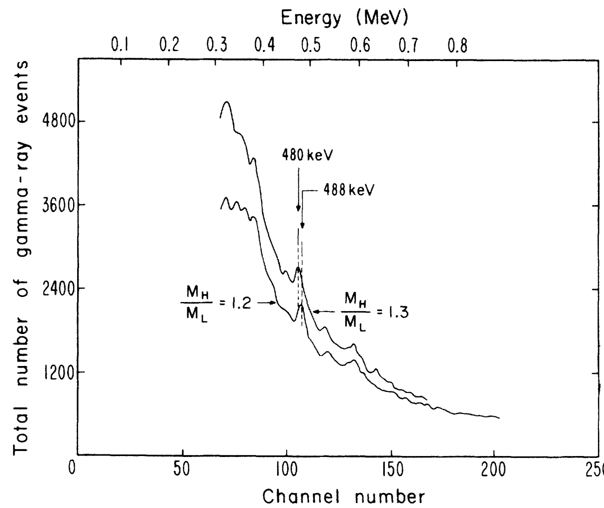

FIG. 2. Prompt γ-ray spectra obtained with a lithium-drifted germanium detector operated at 77°K. The resolution (full width at half-maximum) is 8 keV. These spectra are those associated with mass ratios 1.3 and 1.2 and for heavy fragments moving toward the Ge(Li) detector.

In all of the γ-ray measurements, a special stabilization system was continuously operated, using the annihilation radiation of ^{22}Na as a basis for eliminating drift in the electronic system. As a consequence, the energy measurements are believed to be accurate within 1 to 2 keV in the Ge(Li) measurements and ~5 keV in the case of NaI.

Although a comprehensive interpretation of these complicated results is premature, we have attempted in the following discussion to give one example of an analysis that leads to the tentative assignment of a single line. The peak at ~490 keV in the dashed curve of Fig. 1(c) lends itself to such a detailed analysis. Under the higher resolution of the germanium counter, this line is seen to consist of three principal components—the most intense at 480 keV (associated with R = 1.3, M_H = 140), a second about 5% lower in energy, and a third about 1.6% higher in energy. The third is more associated with the R = 1.2 spectrum shown in the lower curve of Fig. 2. By further analysis we have found that all three components have the correct Doppler shift (~7%) for emission from the heavy fragment in a time less than 1 nsec. The energy of the principal component at mass 140 ± 2 after subtraction of the Doppler shift is 463 keV, and its intensity per fission is roughly 3%. The lifetime ($<10^{-9}$ sec) and the sign of the anisotropy of this gamma ray (as determined from 90-deg data, not shown here) favor an $E2$ multipolarity assignment. From these results, it seems reasonable to make a tentative assignment of the 463-keV transition to the first 2^+ to ground (0^+) transition in ^{140}Xe.

As regards the significance of this above-mentioned results, one may visualize the possibility of obtaining more data and of extending the method to include detailed measurements of angular distributions and γ-ray emission times. In such case one may hope not only to obtain much new information concerning the decay characteristics of nuclides in hitherto inaccessible regions of the periodic table, but also to obtain information on the spins and the de-excitation processes of the primary fission fragments.[4]

It is a pleasure to acknowledge the contribution of Michiyuki Nakamura, Richard Mendez, John LaPierre, and Sam Nolan in connection with the multidimensional analyzer and stabilization systems. We wish to thank Claudette Rugge for help with the computer programs and Joan Phillips for help with this paper.

†Work done under the auspices of the U. S. Atomic Energy Commission.

[1]H. R. Bowman and S. G. Thompson, 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/652, p.212.

[2]H. R. Bowman, J. C. D. Milton, S. G. Thompson, and W. J. Swiatecki, Phys. Rev. 129, 2140 (1963), Table I.

[3]A. J. Tavendale and G. T. Ewan, Bull. Am. Phys. Soc. 9, 46 (1964); and (to be published).

[4]G. Bertram-Hansen, B. Elbek, K. A. Hagemann, and W. F. Hornyak, Nucl. Phys. 47, 529 (1963).

EXCITATION OF ISOBARIC ANALOG STATES IN ^{89}Y AND ^{90}Zr†

J. D. Fox, C. F. Moore, and D. Robson
Department of Physics, Florida State University, Tallahassee, Florida
(Received 16 October 1963; revised manuscript received 17 January 1964)

We wish to report the excitation of compound nucleus resonances in ^{89}Y and ^{90}Zr by proton bombardment of ^{88}Sr and ^{89}Y, respectively. These states are interpreted as isobaric analogs of the corresponding low-lying states of ^{89}Sr and ^{90}Y. Thin evaporated targets of natural strontium (83% ^{88}Sr) and yttrium (100% ^{89}Y) on evaporated carbon backings were bombarded with protons and the resulting neutrons detected with a Hanson-McKibben long counter placed at 50° to the beam direction and at 65 cm from the target. The same targets were also used for measurements of (p,p) elastic-scattering angular distributions using junction counters in a scattering chamber.

The excitation functions observed for ^{88}Sr(p,n) and ^{89}Y(p,n) are shown in Fig. 1. Proton elastic-scattering data are shown in Fig. 2(a) for ^{88}Sr $+p$ at 90° and 125.5° (laboratory angles) and in Fig. 2(b) for ^{89}Y $+p$ at the same angles. The targets were less than 10 keV thick to 5-MeV protons and the tandem Van de Graaff beam has an energy spread of approximately 3 keV. Typical bombarding times led to integrated beams of 50 to 100 microcoulombs.

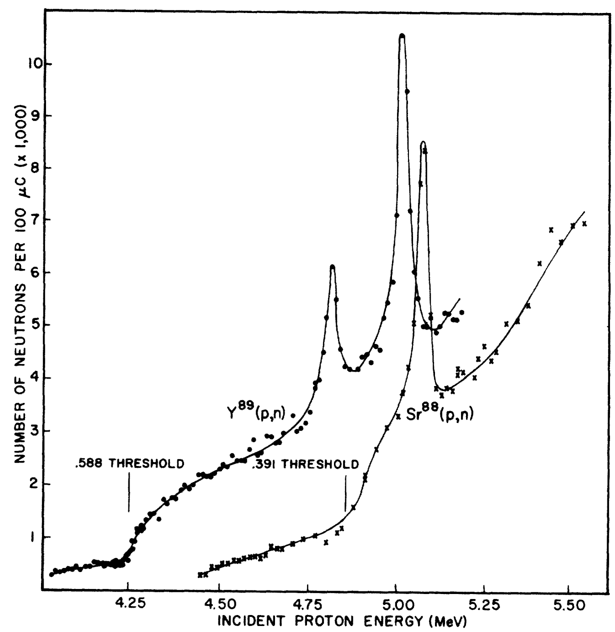

FIG. 1. Neutron yields for ^{88}Sr(p,n) and ^{89}Y(p,n) near threshold.

Analysis of the (p,p) data indicates that the strong resonances are due to d-wave proton capture and leads to spin-parity assignments of $5/2^+$ and 2^- and 3^- for the anomalies in ^{88}Sr $+p$ at 5.08 MeV and ^{89}Y $+p$ at 4.82 and 5.02 MeV, respectively. Typical theoretical fits to the data are shown for ^{89}Y(p,p) in Fig. 2(b). The theoretical curves are calculated using the conventional single-level approximation.[1] The widths used in both cases are about 10 keV and the proton partial widths are about half the total widths.

The experimental results and their interpretation on the basis of shell-model configurations are given in Table I. Also given in Table I are the known low-lying levels of the nuclei formed by (d,p) reactions[2] on the same target nuclei. Comparing the relative energies of the corresponding pairs of configurations (e. g. ^{89}Sr and ^{89}Y*), we