# Observation of $^{10}$Be Emission in the Cold Ternary Spontaneous Fission of $^{252}$Cf

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(Received 2 December 1997; revised manuscript received 7 July 1998)

The emission of $^{10}$Be in ternary cold neutronless spontaneous fission of $^{252}$Cf is observed with the Gammasphere consisting of 72 detectors. The $\gamma$ ray corresponding to the decay of the first $2^+$ state in $^{10}$Be is observed in coincidence with the $\gamma$ rays of the fission partners of $^{96}$Sr and $^{146}$Ba. The yield to the first excited state of $^{10}$Be in the $^{96}$Sr-$^{146}$Ba split is the order of $4.0 \times 10^{-4}$ per 100 fission events. [S0031-9007(98)06096-7]

PACS numbers: 25.85.Ca, 23.90.+w, 27.20.+n

The cold (neutronless) binary fission of many actinide nuclei into fragments with masses from $\approx$70 to $\approx$160 is now a well-documented phenomenon [1–3]. Since the final nuclei are generated in their ground states or some low excited states, these decays were soon related to the spontaneous emission of light nuclei (cluster radioactivity) such as alpha particles and heavier clusters ranging from $^{14}$C to $^{34}$Si [4,5]. All of these experimental findings confirmed the theoretical predictions regarding the cold rearrangement processes of large groups of nucleons from the ground state of an initial nucleus to the ground states of two final fragments. In the spontaneous and thermal neutron induced ternary fission of heavy nuclei, similar clusters have also been detected in hot fragmentations [6]. However, cold ternary fission is quite different from hot fission. Recently, the emission of an $\alpha$ particle in neutronless ternary fission [7] has been observed. However, the double magic $\alpha$ particle may be a special case because of possible preexistence in the nucleus. To definitively establish cold ternary fission or cold multifragmentation it is necessary to observe experimentally cold neutronless ternary fission (triple fission) with the third particle being a heavier cluster such as $^{10}$Be.

Contrary to $\alpha$-ternary fission whose excited state energies are very high (>20 MeV), $^{10}$Be has excited state ($2^+$) at an energy of 3.368 MeV. From a theoretical point of view it is important to see the cold fission to the ground state as well as to the first excited state of a light partner in cold ternary fission. This is not expected for $\alpha$ emission. Furthermore, $^{10}$Be and other heavier ternary fragments are more easily deformable to enhance collective effects. This could lead to hyperdeformed nuclear configurations, of a molecular type, in the exit channel. It will be very interesting to see whether modes of relative vibration and rotation of the three fragments can be seen in the future. The excitation of such modes may determine the angular distribution of the emitted fragments.

In two recent conference proceeding papers [8,9], the ternary fission modes of $^{252}$Cf were reported. The observed average number of prompt neutrons emitted in the Be-accompanied ternary fission is $\bar{\nu} \approx 2$ [8] compared to $\bar{\nu} \approx 3.8$ for binary fission of $^{252}$Cf. Also the 3.368 MeV $\gamma$ line emitted by $^{10}$Be in such ternary fission events was observed [9] in coincidence with Be recoils but not with correlated fragments. So it is not established whether it is hot or cold fission. Moreover, there is a question in that study as to why the 3.368 keV $\gamma$ line is not more Doppler spread out since the lifetime is 125 fs and the Be transit time to the detector is 2 ns. They had no explanation for this. Indeed, in both papers [8,9], they did not identify the final fragments and so could not distinguish between cold and normal ternary fission.

Cold ternary decays should produce all three fragments at very low excitation energy and, consequently, with very high kinetic energies. Their total kinetic energy will be close to the corresponding total decay energy $Q_t$ or may even be equal to it. The $^{10}$Be ternary spontaneous fission (SF) has been theoretically predicted recently [10]. In this paper we report, for the first time, the emission of $^{10}$Be and measurements of its yields with the correlated pairs $^{96}$Sr-$^{146}$Ba in the cold spontaneous ternary fission of $^{252}$Cf. In our experiment, we measured a yield to the first excited state $^{10}$Be. These results provide a significant new confirmation of the theory of cold fragmentation [10] and point the way to new detailed studies of cold SF of various heavy fragments from Li to C to further test theoretical descriptions of this process.

To study the fission of $^{252}$Cf, a 28 $\mu$Ci source was sandwiched between two Ni foils of thickness 11.3 mg/cm$^2$ and Al of 13.7 mg/cm$^2$ and was placed at the center of the Gammasphere with 72 Compton suppressed Ge detectors at Lawrence Berkeley National Laboratory. The stopping range of $^{10}$Be (average energy $\approx$17.5 MeV [8,9]) is 10.3 mg/cm$^2$ for the Ni. Since the source is covered with Ni and Al, the $^{10}$Be nuclei are completely stopped and also the fission fragments. A total of $9.8 \times 10^9$ triple- and higher-fold coincidence events were recorded. The Gammasphere was calibrated with $^{133}$Ba, $^{137}$Cs, $^{152}$Eu, $^{56}$Co, and $^{57}$Co sources. The fraction of $^{248}$Cm in our sample was estimated to give a spontaneous fission rate of 0.13 fissions/s, whereas the SF rate of $^{252}$Cf is $2.81 \times 10^4$ fissions/s. The very complex $\gamma$-ray spectra from over 100 different final fragmentations were analyzed by building a $\gamma$-$\gamma$-$\gamma$ cube and using RADWARE software [11]. The half-life of 125 fs for the $2^+$ level is fast compared to the stopping time. The stopping time in Ni for a 17.5 MeV $^{10}$Be particle is 1280 fs. Hence the 3368 keV line should be broadened. The absence of Doppler broadening in the present paper and also that of Mutterer *et al.* [8,9] can be explained as follows. The $^{10}$Be is formed and sits in the potential well of Ba and Sr while they separate. Assuming a M3Y force between Ba and Sr [10] and $^{96}$Sr to be almost spherical, $\beta_2 = 0.10$ and $^{146}$Ba with $\beta_2 = 0.22$ and $\beta_3 = -0.08$, the barrier penetration probability is $P = 0.98 \times 10^{-16}$. The frequency of collision with the barrier is calculated by assuming a beta-vibrational mode with an energy of $\hbar\omega = 1$ MeV. The half-life for penetration through the barrier is much larger than the lifetime of the level. Hence, we believe that the $2^+$ state decays, when most of the $^{10}$Be nuclei are essentially at rest.

In the ground state fission of $^{252}$Cf, the $^{252}$Cf source fissions into two primary fragments, which are formed in highly excited states ($\approx$30 MeV). These primary fragments emit neutrons forming secondary fragments until the excitation energy is below the binding energy of a neutron (7 MeV for $^{106}$Mo and 5.1 MeV for $^{146}$Ba). These secondary fragments decay to the ground states by the emission of $\gamma$ rays. For example, for $^{146}$Ba as one fission fragment, there can be several partners, different Mo isotopes depending upon the number of neutrons emitted. The $\gamma$ rays from the two secondary partner nuclei will be in coincidence because the time window of 100 ns is much larger than the fission time scale of $\approx 10^{-20}$ s. In the present paper we have chosen two complimentary partners, $^{96}$Sr and $^{146}$Ba, which are situated near the peaks of the mass distribution to study the ternary fission. For these partners the missing third particle is $^{10}$Be. Hence, by selecting two gates, for example, $2^+ \rightarrow 0^+$ transitions in both nuclei or $2^+ \rightarrow 0^+$ transition in one nucleus and $4^+ \rightarrow 2^+$ transition in its partner nucleus, in the coincidence spectrum one should observe the transitions in both of these nuclei, usually the first two or three transitions in the yrast band if they are in prompt coincidences.

In Fig. 1, we show a coincidence spectrum obtained by gating on the $2^+ \rightarrow 0^+$ transition of energy of 181.1 keV in $^{146}$Ba and on the $4^+ \rightarrow 2^+$ transition of energy 977.5 keV in $^{96}$Sr. One can clearly observe the $4^+ \rightarrow 2^+$ transition of energy 332.6 keV in $^{146}$Ba and $2^+ \rightarrow 0^+$ transition energy of 814.7 keV in $^{96}$Sr. Several cross-checks were made by shifting the gates to different energies around these peaks to make sure that these are not accidental coincidence peaks from background. Furthermore, we selected the two gates on the $2^+ \rightarrow 0^+$ transitions in both of these nuclei and observed the corresponding $4^+ \rightarrow 2^+$ transitions to be in coincidence (spectrum is not shown).

The next problem is to determine whether the missing third fragment is really $^{10}$Be or some combination of nuclei such as $^8$Be $+ 2n$ or $2\alpha + 2n$, etc. In Fig. 2(a), we show the high energy region of the coincidence spectrum obtained by gating on $2^+ \rightarrow 0^+$ transitions in $^{146}$Ba and $^{96}$Sr. In Fig. 2(a), we see a peak at an energy of $\approx$3368 keV (marked as 3362 keV) region coincident with the gate transitions. Assuming that the peak at $\approx$3368 keV is the

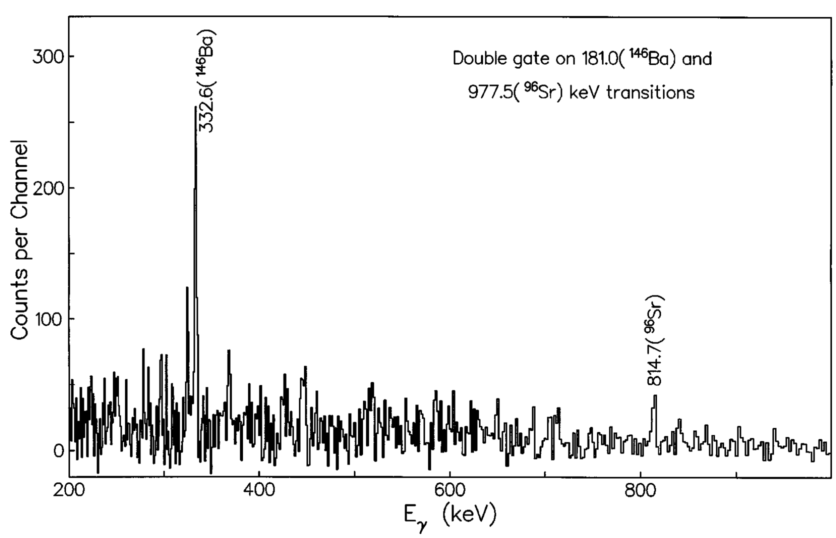


FIG. 1. Coincidence $\gamma$-ray spectrum obtained by double gating on the 977.5, $4^+ \rightarrow 2^+$ transition in $^{96}$Sr and 181.0 keV, $2^+ \rightarrow 0^+$ transition in $^{146}$Ba. About half of the 332.6 keV peak intensity comes from the background coincidence effect.

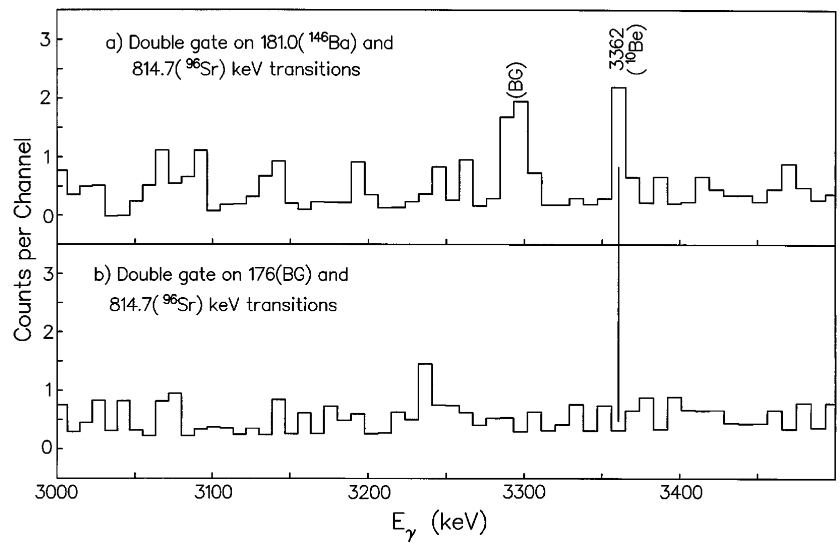


FIG. 2. (a) Coincidence $\gamma$-ray spectrum obtained by double gating on the 814.7, $2^+ \rightarrow 0^+$ transition in $^{96}$Sr and 181.0 keV, $2^+ \rightarrow 0^+$ transition in $^{146}$Ba. (b) Coincidence $\gamma$-ray spectrum obtained by double gating on the 814.7, $2^+ \rightarrow 0^+$ transition in $^{96}$Sr and on 176.0 keV background peak, which is shifted from 181.0 keV, $2^+ \rightarrow 0^+$ transition in $^{146}$Ba. BG: background.

$2^+ \rightarrow 0^+$ transition in $^{10}$Be, we set one gate on this transition and the other gate on the $2^+ \rightarrow 0^+$ transition in $^{96}$Sr. We observed in our coincidence spectra the 977.5 keV, $4^+ \rightarrow 2^+$ transition in $^{96}$Sr. Further, when we set the double gate on the $\approx$3368($^{10}$Be) and 181.0($^{146}$Ba) keV peaks, we observed the 332.6 keV ($4^+ \rightarrow 2^+$) transition in $^{146}$Ba. Our measured energy for the $\approx$3368 keV peak is 3362(4) keV. The energy values calculated from the level scheme [12] range from 3362.8 to 3367.4 keV. The value of 3362.8 keV is the difference between the transition energies of 5955.4 and 2592.6 keV [12]. Hence, we believe that our measured value is within the range of the reported values and it belongs to $^{10}$Be. Furthermore, if one moves one of the gates to a nearby energy, the 3362 keV peak disappears as shown in Fig. 2(b). The 3362(4) keV transition is not seen in Mo-$^{146}$Ba or $^{96}$Sr-Nd binary partner double gated spectra. So it is not a weak transition either in $^{96}$Sr or $^{146}$Ba. From these spectra, we have clearly observed, for the first time, the cold neutronless triple fission, with $^{10}$Be being the third partner, to definitely establish cold multifragmentation. The fact that we observed $\gamma$ rays from all three nuclei demonstrated that we have observed the triple fine structure for the first time in such ternary cold splittings.

The yield for the $^{10}$Be ternary process is obtained from the double gate on the 181.0 ($^{146}$Ba) and 814.7 keV ($^{96}$Sr) transitions. In this double gate, at the energy of 3362 keV in $^{10}$Be, the number of background subtracted events are 14 and a fitted peak half-width is less than 9 keV (27 channels at 0.3333 keV/channel). The width of the peak for a stopped recoil is reasonable based on our energy resolution. When the number of counts in the 3362 keV peak is corrected for the detector efficiency and gating conditions, the efficiency corrected count for the $^{10}$Be is normalized to the previously determined binary yields of Ba and Mo pairs. The extracted yield to the first excited state of $^{10}$Be for this split is $4(2) \times 10^{-4}$ per 100 fission events (about 2.6% of the total $^{10}$Be yield), and is the order of 4.4% of the cold $\alpha$-ternary fission yield of 0.009(4) per 100 events for $^{146}$Ba and $^{102}$Zr [7] and 1.0% of the cold binary fission yield of 0.04(1) per 100 events for $^{146}$Ba and $^{106}$Mo [7]. These new results provide significant insight into the cold rearrangement of clusters of nucleons and multifragmentation. They also point the way to exploring a variety of cold ternary spontaneous fission modes including odd and even $Z$ from $^{3}$H, $^{6,7}$Li to $^{14}$C.

The work at Vanderbilt University was supported in part by the U.S. Department of Energy under Grant No. DE-FG05-88ER40407. A complete list of authors of GANDS95 collaboration can be found in Phys. Rev. C **56**, 1344 (1997). The Joint Institute for Heavy Ion Research has as member institutions the University of Tennessee, Vanderbilt University, and Oak Ridge National Laboratory. It is supported by its members and by the U.S. Department of Energy through Contract No. DE-FG05-87ER40361 with the University of Tennessee. A. Sandulescu, A. Florescu, and W. Greiner acknowledge the hospitality of Vanderbilt University and the Joint Institute for Heavy Ion Research during the completion of this work. We also acknowledge a grant received under the Twinning Program from the National Research Council.

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