Fission probabilities for actinide nuclei excited by the (^{12}C, ^{8}Be$_{g.s.}$) reaction

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Fission probability distributions of ^{236}U and ^{240}Pu compound systems have been measured with the (^{12}C, ^{8}Be$_{g.s.}$) reaction in the excitation energy range of 7–16 MeV using 65 MeV projectiles. Identification of ^{8}Be$_{g.s.}$ as two highly correlated alpha particles showed that under the conditions of this experiment ^{8}Be$_{g.s.}$ can be separated from ^{7}Li in a simple ΔE-E system. The results are in good agreement with fission probabilities derived from neutron induced fission of ^{235}U and ^{239}Pu.

[NUCLEAR REACTIONS, FISSION Measured fission probabilities for ^{236}U and ^{240}Pu with (^{12}C, ^{8}Be$_{g.s.}$) reaction.]

Direct reactions of the type (p,p'), (d,p), (t,p), (^{3}He, d), (^{3}He, t), (^{3}He, α), (α,α'), and (^{7}Li, α) have been used extensively to study fission barriers and fission probability (P_f) distributions of actinide elements.[1-8] The attractive features of using direct reactions are that a projectile of a single energy yields a fission probability distribution over a broad excitation energy range and that the use of different reactions allows the investigation of many different fission nuclides from a single target nuclide. In general, the fission probability distribution is extracted from the ratio of a spectrum of direct particles in coincidence with fission to a spectrum of "singles" events which gives a measure of the initial probability for exciting the residual nuclei. Since both spectra are measured simultaneously and only the ratios are important, the energy dependence of P_f is determined directly. In contrast P_f determination from neutron or charged particle capture experiments requires a series of independent excitation function measurements of both the fission and compound nucleus formation cross sections.[9,10]

However, each direct reaction is applicable for P_f measurements only over a limited energy region and so it has been found useful in some cases to investigate the same nuclear system using a variety of reactions. The reactions (d,p) and (t,p) are appropriate for studying the resonance subbarrier energy region for even-even nuclei, but because of breakup effects in the singles spectra they do not give reliable information above the neutron binding energy. Because most targets are even Z these reactions are useful primarily for studying even Z residual nuclei. In contrast (^{3}He, d) and (^{3}He, t) reactions go primarily to neutron deficient odd Z nuclei and are most useful in the excitation energy region 5–11 MeV. The other case with reasonable cross section is (^{7}Li, α), which again is primarily useful for the study of odd Z nuclei and covers an effective excitation energy range of ~11–20 MeV limited by the "Q value window" for this reaction.

In this paper we present experimental results on fission probability distributions for residual nuclei excited by a (^{12}C, ^{8}Be) reaction. This reaction can reach many even Z nuclei and is useful primarily in the excitation energy range 7–16 MeV. Thus, the results can be complementary to previous (t,p) measurements and in a few cases could provide a "bridge" between the 5–11 MeV region obtained in ^{3}He reactions and the 12–20 MeV region populated in ^{7}Li reactions. In this paper we demonstrate the feasibility of using the (^{12}C, ^{8}Be) reaction by investigating two previously well-studied fissioning systems ^{236}U and ^{240}Pu.

The ^{12}C beam of 65 MeV was provided by three stage operation of the Los Alamos Tandem Van de Graaff facility. Targets of ^{232}Th and ^{236}U of approximately 200 μg/cm^2 evaporated on 50 μg/cm^2 carbon foils were used. The experimental configuration is shown in Fig. 1.

Particles of ^{8}Be which are produced in the reaction are unstable. The ground state (denoted as ^{8}Be$_{g.s}$) has a half-life of 10^{-16} s and a positive Q value of 90 keV for decay into two alpha particles. Since the ^{8}Be$_{g.s}$ produced in these reactions have kinetic energy in the vicinity of 33 MeV, the two alpha particles are highly correlated in their direction of motion with a maximum opening angle of 6° and have almost the same kinetic energy. Two equal alpha particles which simultaneously

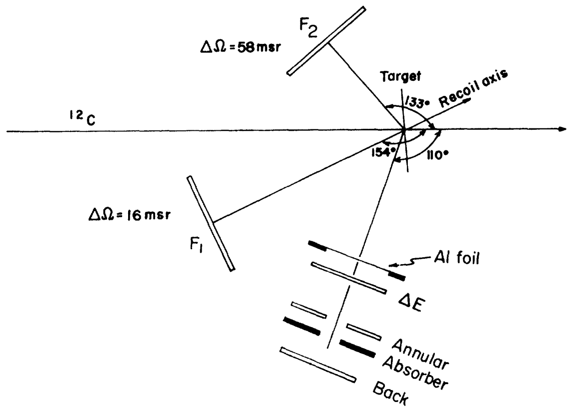

FIG. 1. Experimental arrangement. All detectors are shown to scale.

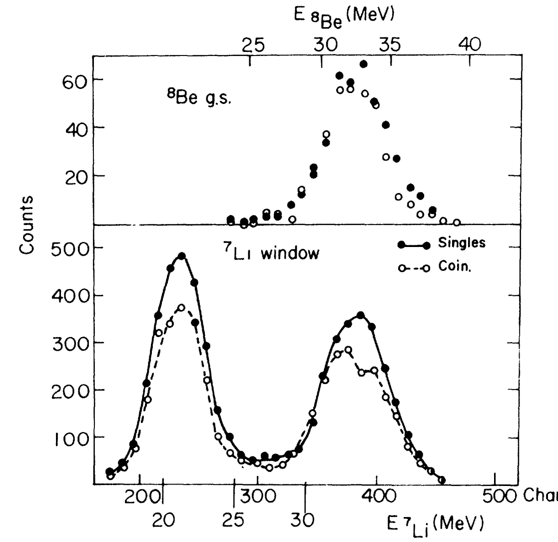

FIG. 2. Spectra of ^{7}Li and ^{8}Be$_{g.s.}$ particles with a ^{236}U target. In lower part, spectra of all particles identifying as ^{7}Li. The lower energy peak is due to ^{7}Li particles and the higher energy peak is due to two simultaneous alpha particles which register as ^{7}Li in the ΔE-E system. The upper spectra are uniquely identified ^{8}Be$_{g.s.}$ (i.e., coincidence of two particles with similar energy in the "back" and "annular" detectors).

traverse a ΔE-E system are identified as ^{7}Li, but may have a different apparent energy spectrum from "real" ^{7}Li particles. Additional identification was provided for ^{8}Be$_{g.s.}$ by a particle identification system which consisted of three detectors; a 40 μm ΔE detector, a 500 μm annular detector, and a 700 μm "back detector." The overall energy resolution of the measurements was limited to ~600 keV due to kinematic broadening. Other details of the experimental technique were very similar to that described in Ref. 2. A fast coincidence was performed using a TAC between ΔE and F_1 or F_2 with a time resolution of ~2 ns. Random contributions were directly subtracted but the corrections were in general less than 2%.

Using the three detector system, unique but low efficiency identification of ^{8}Be$_{g.s.}$ was obtained whenever one alpha particle was detected by the back detector, and one of almost equal energy was detected by the annular detector. It was also required that the ΔE signal in the transmission detector and the E signal, derived from the sum at the annular and back detectors, provided a particle identification as a ^{7}Li event. The energy spectrum of particles identified as ^{8}Be$_{g.s.}$ is shown in Fig. 2 (upper part). Also shown is the spectrum of all particles that identify as ^{7}Li in the E-ΔE system. This spectrum contains two peaks. The upper peak corresponds in shape to ^{8}Be$_{g.s.}$. The ratio of the number of counts agrees well with the calculated ratio for detecting ^{8}Be$_{g.s.}$ in the three detector system to the total number of ^{8}Be$_{g.s.}$ which pass through the ΔE detector. The calculated ratio was obtained from the solid angles of the back and annular detectors and was corrected for the probability that the two alpha particles of ^{8}Be$_{g.s.}$ were detected only by the back detector, and also for the probability that only one alpha particle is detected in the annular detector and the other one outside it. Thus, the upper peak of the ^{7}Li identification corresponds to ^{8}Be$_{g.s.}$. In this case, the energy separation of ^{7}Li and ^{8}Be$_{g.s.}$ allows the use of a relatively simple system in comparison to more complex but more precise methods[11,12] that have been developed to identify ^{8}Be$_{g.s}$. The probability of detection of the first excited state of ^{8}Be at 2.94 MeV is very small due to its low spatial correlation.

The fission probability was determined at each excitation energy from the ratio of coincidence rate to the singles rate assuming that the fission fragments had an angular distribution, $W(\theta) = A(1 + g_2 P_2 \cos\theta)$, in the center of mass of the recoiling fissioning system and relative to that axis. In previous (t, pf) studies[6] detailed in-plane angular correlations were parametrized in a series of even Legendre polynomials $P_2, \ldots, P_{12}$. In this case it was found that many terms were needed in the threshold region, but for energies greater than about 8–9 MeV only the P_2 term retained a significant coefficient. The values obtained for g_2 in this experiment are shown in Fig. 3. The results show reasonable g_2 values for $E^* > 9$ MeV. However, for lower excitation energies the g_2 coefficients obtain unphysical values greater than 1. In this region the angular distribution function $(1 + g_2 P_2)$ will tend to overestimate P_f which may

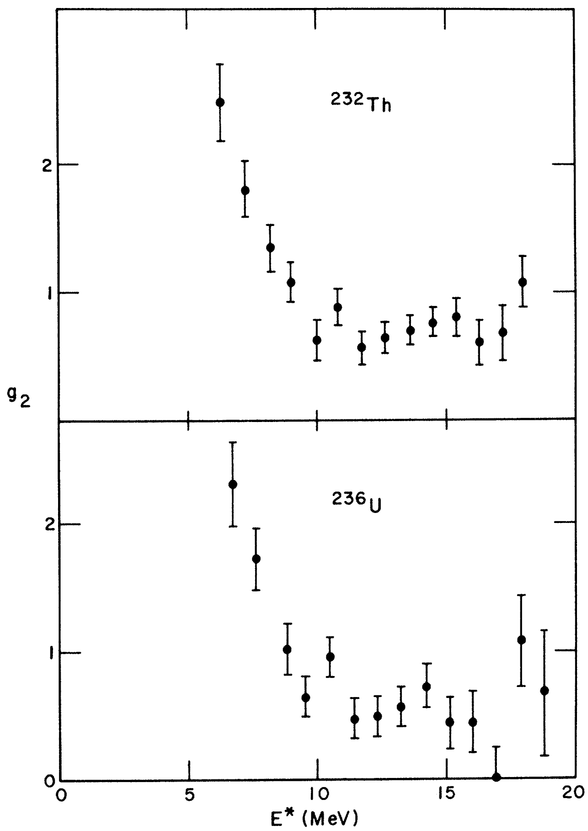

FIG. 3. Angular correlation coefficients g_2 as a function of excitation energy.

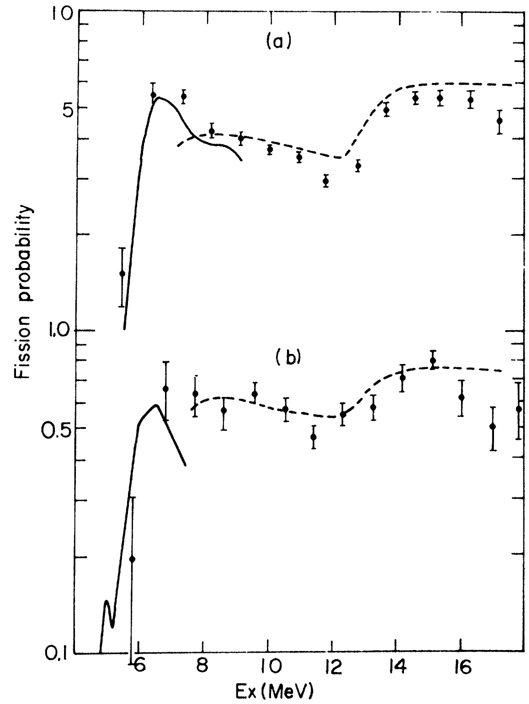

FIG. 4. Fission probability as a function of excitation energy for two compound systems: (a) ^{236}U, full circles are experimental results of ^{232}Th(^{12}C, ^{8}Be$_{g.s.}$), continuous line is experimental results of ^{234}U(t,pf) (Ref. 6), and the dashed line is $\sigma_f/3.1$ for neutron induced fission of ^{235}U; (b) ^{240}Pu, circles are experimental results of ^{236}U(^{12}C, ^{8}Be$_{g.s.}$), continuous line is results from ^{238}Pu(t,pf) (Ref. 6), and dashed line is $\sigma_f/3.1$ for ^{239}Pu(n,f).

actually be indicated in the P_f comparisons shown in Fig. 4 and discussed below. More accurate P_f values in this region would require a detailed angular correlation measurement. A more serious uncertainty in the P_f determination is the assumption of azimuthal isotropy. This so called "plane wave" assumption is appropriate for light ion stripping reactions under certain conditions as demonstrated for (d,pf) and (t,pf) reactions.[6,13] However, for higher energy reactions with heavier ions the opposite limit of grazing reactions can often be observed.[14] In this case a large out of plane anisotropy can be obtained with approximate isotropy in the reaction plane. It might be expected that the present (^{12}C, ^{8}Be) reaction would be between these two limits. However, the observation of in plane anisotropies that are similar to (t,pf) results suggests that the combination of a bombarding energy near the Coulomb barrier and a backward angle (110°) for observation of the ^{8}Be ejectiles leads to a condition closer to plane wave than "grazing." The other test is comparison to (n,f) data. If there were a large out of plane anisotropy then the current method should overestimate P_f and that does not seem to be the case as discussed below. However, to quantitatively exploit this technique the question of the out of plane angular distribution should be investigated experimentally. Corrections to P_f were also made for the instrumental dead time and for the significant laboratory to center-of-mass transformation of the recoiling nucleus in the fission fragment detection geometry.

The results of P_f for ^{236}U and ^{240}Pu compound systems are summarized in Fig. 4. In the figure are shown also fission probabilities obtained from (t,p) reactions up to 9 MeV excitation, and fission probabilities obtained from ^{235}U $+n$ and ^{239}Pu $+n$. In the latter cases the compound nuclear formation cross section was taken as 3.1 b from a recent comparison of (^{3}He,df) and (^{3}He,tf) data with (n,f) measurements in the excitation energy region up to 12 MeV.[15] There is very satisfactory agreement between the neutron induced reactions and the (^{12}C, ^{8}Be$_{g.s.}$) results, in particular in the energy region corresponding to the onset of second chance fission at ~13 MeV excitation. Above excitation energies of 16 MeV which corresponds to ^{8}Be energies below 31 MeV, the (^{12}C, ^{8}Be) results can be influenced by the contribution of ^{7}Li particles. However, even with more unique determination of ^{8}Be in this region, the Q value window limits the maximum useful excitation energy to ~19 MeV (E_{lab} = 28.0 MeV) as is evident from the shape of the uniquely identified $^{8}Be_{g.s.}$ spectrum. Altogether the reaction cross section leading to a fissioning system through emission of $^{8}Be_{g.s.}$ was about 0.3 mb/sr at the detection angle of 110°.

The reaction was carried out very near the Coulomb barrier and thus the angular momentum brought into the compound system was rather low and comparable with (^{3}He, d) or (t, p) reactions or 5–11 MeV neutron induced reactions. Since the fission probability is not very sensitive to small changes in the angular momentum distribution or its detailed shape it is reasonable that the fission probability of (^{12}C, $^{8}Be_{g.s.}$) is in good agreement with the neutron induced fission probability.

In principle, at the higher excitation energies the (^{12}C, ^{8}Be) measurement could give a more reliable estimate of P_f because of the uncertainties in the compound nucleus formation cross section and the increasing probability of preequilibrium decay in the neutron measurements. However, for the present data at high energy the contamination by ^{7}Li reactions, counting statistics, and the accuracy of the integration of the angular distributions limit the accuracy of the P_f values from the (^{12}C, ^{8}Be) reaction to the same level (~ ±10–20%) as obtained from the measured (n,f) cross sections. More quantitative results from this technique will require detailed measurements of both in and out of plane angular correlations.

The results shown here demonstrate that fission probabilities over a broad range of excitation energy from 7 to 16 MeV can be measured using a (^{12}C, ^{8}Be) reaction and yield results comparable to neutron induced fission. Further exploitation of this reaction could prove useful in expanding our knowledge of fission probabilities in the heavy actinide region. In particular, the addition of alpha particles to form a compound system might be used to study fission probabilities for a few heavy and unstable systems that were previously inaccessible using the actinide targets that are currently available.

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