Population of high-spin states in ^{234}U by an incomplete-fusion reaction

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Excited states in ^{234}U have been populated using the incomplete-fusion reaction ^{232}Th(^{9}Be,$\alpha3n$) at 52 MeV. The emitted γ rays were observed using the CAESAR array, while the α particles were detected with an array of 14 plastic scintillator detectors of phoswich type. This reaction can populate ^{234}U at higher spin than the conventional ^{232}Th(α, $2n$) reaction because the ''^{5}He'' fragment from breakup of the beam can be viewed as initiating a ^{232}Th(^{5}He,$3n$) reaction. Similar reactions could provide a valuable alternative technique for the study of relatively heavy, neutron-rich isotopes. In the present work, states in the ground-state band of ^{234}U were observed up to $J^{\pi}=18^{+}$ and previous tentative observations of (9^{-}) and (11^{-}) states in the octupole band were confirmed. A new state at 1366 keV, which is possibly the 8^{+} member of the γ band, has also been identified. [S0556-2813(99)02911-8]

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There is considerable interest in the nuclear structure of the actinide elements; however, their population at high spin is difficult, especially the more neutron-rich isotopes. Earlier studies of these nuclei used population methods such as multinucleon transfer, Coulomb excitation, and light-ion reactions such as (d,p) and (α,xn). As an example, the obvious choice of the fusion-evaporation reaction to populate high-spin states in ^{234}U is ^{232}Th(α,$2n$) [1–3]. In this Brief Report, we demonstrate the feasibility of applying incomplete-fusion reactions to populate high-spin states in neutron-rich actinide nuclei, in this case using the ^{232}Th(^{9}Be,$\alpha3n$) reaction to populate high-spin states in ^{234}U. This reaction does not proceed via the equilibration of a ^{241}Pu compound system followed by evaporation of an α particle and three neutrons, but rather by the breakup of the ^{9}Be beam into (notionally) ^{4}He+^{5}He, with the immediate emission of the α particle and fusion of the ''^{5}He'' fragment. Thus, in effect, this is a (^{5}He,$3n$) reaction, with the ''radioactive beam'' obtained from breakup of the stable beam.

Previous work in other mass regions has shown that this type of incomplete-fusion reaction has a tendency to populate slightly more neutron-rich nuclei, and at a higher spin, than the equivalent (HI,xn) reaction [4,5]. Typically, the residues for the incomplete-fusion component of the reaction are weaker than those from the complete-fusion component. However, for very heavy targets, the residues populated by incomplete fusion are expected to dominate over those from complete fusion. This can be demonstrated for the ^{9}Be + ^{232}Th system using statistical model calculations with the PACE code [6]. Values for the parameters which enter the code have been taken from Ref. [7], including the level density parameters $a_n=A/8.8$ MeV^{-1} and $a_f/a_n=0.90$ and the Kramers scaling factor of the Sierk fission barrier, $k_f=0.88$. This choice of parameters describes the decay of the nearby ^{224}Th compound system [7] and should be adequate for our illustrative purposes. Table I shows the calculated cross sections for two different reactions 52 MeV ^{9}Be and 29 MeV ^{5}He, incident on ^{232}Th. The latter beam energy was deduced by assuming an energy sharing between the two fragments of the ^{9}Be beam, i.e., $E(^{5}\mathrm{He})=5/9\times52$ MeV. (Note that fusion of the ^{5}He fragment would be expected to occur for collisions near grazing and would thus be localized at high l waves. Our illustrative calculation ignores this effect, instead assuming a standard triangular spin distribution.) For the ^{9}Be-induced reaction, less than 0.1% of the fusion cross section survives fission. This compares with the ^{5}He-induced reaction, for which 3.5% of the total cross section survives fission, eventually resulting in the population of uranium isotopes via neutron evaporation. In essence, the higher fissility of the $Z=94$ system means that very few of the compound nuclei formed by complete fusion survive fission. This means that the observation of uranium products implies that they were populated by an incomplete-fusion process.

A better estimate of uranium production can be obtained if the relative cross sections for incomplete and complete fusion are known. This quantity has been measured recently for the ^{9}Be+^{208}Pb system [8] and can be taken as a guide to the expected ratio of incomplete to complete fusion for the ^{9}Be+^{232}Th system, since the breakup will almost certainly play a more dominant role for the heavier target. In the former case, about 25% of the cross section is incomplete fusion, which would translate to ~7 mb for the production of uranium isotopes populated by the ^{232}Th(^{9}Be,αxn) incomplete-fusion reaction, approximately 20 times stronger

TABLE I. Calculated cross sections for ^{5}He- and ^{9}Be- induced fusion reactions on ^{232}Th.

52 MeV ^{9}Be+^{232}Th		29 MeV ^{5}He+^{232}Th	
Fission	437 mb	Fission	662 mb
^{236}Pu	0.4 mb	^{234}U	13 mb
		^{233}U	11 mb

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than the production of plutonium isotopes populated by the ^{232}Th(^{9}Be,xn) complete fusion-evaporation channel. A 7 mb cross section is large enough to make γ-ray spectroscopic measurements feasible, as is demonstrated below.

We performed a γ-ray spectroscopy experiment using a beam of 52 MeV ^{9}Be ions, supplied by the ANU 14UD Pelletron accelerator, incident upon a 1.0 mg/cm^2 self-supporting target of ^{232}Th. The target was chosen to be thick enough that most of the recoiling fusion products are stopped in the target, but thin enough that the majority of the fission fragments escape. The γ rays emitted in the reaction were observed using the CAESAR array of six Compton-suppressed, 25%-efficient HPGe detectors. To identify the incomplete-fusion component of the reaction, the ANU Particle Detector Ball (PDB) [9] was used to detect the emitted α particles. The PDB consists of an array of 14 fast/slow combined plastic scintillators for which the phoswich technique is used to separate the fast signals in the thin front element (ΔE) from the thicker (slow) rear element (E). The scintillator array covers 85% of 4π and has three rings of essentially equivalent detectors, i.e., four ''forward,'' six ''middle,'' and four ''backward'' detectors, subtending angles of approximately 20°–60°, 60°–120°, and 120°–165°, respectively. The forward detectors were covered with aluminum shielding foils of 45 mg/cm^2 thickness to prevent rate limitations from the scattering of beam particles. These foils were sufficient to stop ^{9}Be ions with energies up to $\sim$57 MeV, but also stopped α particles of less than $\sim$19 MeV energy, thus reducing the α-detection efficiency at forward angles.

During the experiment, pairs of γ rays within a $\pm$432 ns γ-ray time difference and up to $\sim$ 800 ns after detection of a particle were recorded. The parameters recorded included the energies and times of detection of the γ rays, the relative time between detection of a particle and a γ ray, and the time-filtered ΔE signals from the plastic scintillators concatenated into three groups corresponding to the three rings of detectors. The minimum coincidence condition was set in hardware to correspond to a particle-γ-γ event.

Singles spectra were also collected and the measured singles spectrum is shown in Fig. 1(a). The strongest lines present are the x rays and Coulomb excitation γ rays arising from the ^{232}Th target [3], together with light-ion contaminants formed from reactions on oxygen (present in the form of oxide in the target). The γ rays from the ground-state band in ^{234}U are very weak.

To enhance the ^{234}U component of the reaction, the γ-γ coincidence data were sorted offline into E_γ-E_γ matrices with various time and particle conditions. Figure 1(b) shows the projection of a γ-γ matrix created requiring two γ rays to be observed within $\pm$170 ns of each other and also in prompt coincidence with the detection of an α particle. A total of 4×10^6 α-γ-γ coincidence events were sorted into the matrix. An unresolved continuum of γ rays due to fission is the dominant feature of the matrix projection, with prominent γ rays from Coulomb excitation of the ^{232}Th target also present. The γ rays from the ground-state band in ^{234}U are strongly enhanced compared to the singles spectrum.

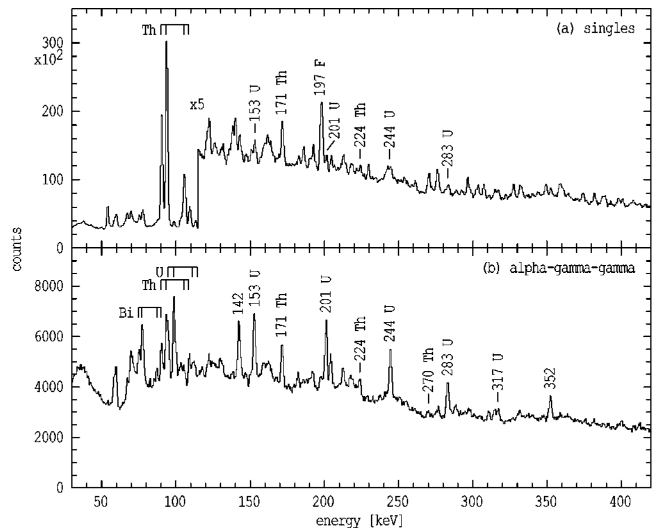

FIG. 1. (a) Singles spectra for the ^{9}Be + ^{232}Th reaction at 52 MeV. (b) Projection of the γ-γ coincidence matrix which was created requiring the detection of two γ rays within $\pm$170 ns of each other and in coincidence with an α particle. In both spectra, the characteristic patterns of the observed x rays are marked.

Figure 2 presents a sum of five background-subtracted coincidence spectra obtained from the γ-γ coincidence matrix by setting gates on the $E2$ transitions in the cascade connecting the 4^+ and 14^+ excited states in ^{234}U. The ground-state band is observed clearly up to the $18^+\rightarrow16^+$ transition [3]. Note that these highest-spin states in ^{234}U were identified previously using Coulomb excitation [10] and heavy-ion-induced transfer [11] reactions, not using the ^{232}Th(α,2n) reaction [1–3]. Because both the Coulomb excitation and transfer reactions result in the selective population of particular subsets of excited states, the incomplete-fusion reaction used here has the potential to populate new high-spin states which were not known previously. The current work was also sensitive to the identification of isomeric states, although no delayed population of the ground-state

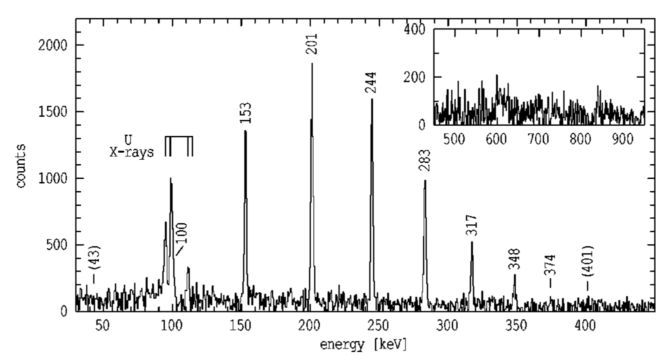

FIG. 2. Sum of coincidence spectra with gates set on the $E2$ transitions in the cascade connecting the 4^+ and 14^+ states in the ground-state band of ^{234}U. The dispersion of the main spectrum is at 0.5 keV/channel, while the inset is the higher-energy region of the spectrum, but compressed to 1.0 keV/channel. The effects of internal conversion are apparent, especially for the 43 keV, $2^+\rightarrow0^+$ transition, which proceeds almost entirely by internal conversion so that the associated γ ray is not observed.

band was observed at the level of $\sim 5\%$ of the total ^{234}U channel intensity.

With the limited statistics collected, the γ rays from known states in the octupole band in ^{234}U were only very weakly observed. The inset to Fig. 2 shows the energy region in which these γ rays are expected [3] and it is apparent that they are very weak. The coincidence spectra show that there are γ rays with energies of 838.5(5) and 848.0(5) keV feeding into the 8^+ and 10^+ levels, respectively, of the ground-state band in ^{234}U. The γ-ray intensities are approximately equal and are each only 2(1)% of the total intensity (corrected for internal conversion) of the 201 keV, $8^+ \to 6^+$ transition. This confirms the previous tentative observations of possible (9^-) and (11^-) states in the octupole band of ^{234}U [1].

In addition, a new γ ray with energy 868.8(3) keV and a total intensity 4(2)% of the 201 keV transition was found to feed the 8^+ level in the ground-state band. This suggests a new excited state at 1366 keV, which is about where the unknown 8^+ level of the γ-vibrational band is expected to lie. A dominant decay of this state via a $J \to J$ transition to the ground-state band would be consistent with this interpretation.

It should be mentioned that the current data set contains only 4×10^6 α-γ-γ coincidences, so that a significant improvement would obviously be possible using the new generations of germanium and particle detector arrays. In fact, in the current data set there are only ~ 120 coincidence counts between the 868 and 201 keV γ rays, so that there is no possibility for angular correlation or distribution information to determine the multipolarity for the new 868 keV transition.

Early [12,13] and recent [4,5] studies using incomplete-fusion reactions have shown that the angular distribution of the emitted α particles can be used to discriminate between the complete and incomplete-fusion components. However, examination of the different yields of ^{234}U when α particles were detected in the forward, middle, or backward rings of detectors did not show a strong angular dependence. This is presumably a result of the fact that the grazing angle under the present experimental conditions is $\sim 105°$.

In summary, with a modest γ-ray/particle-detector array combination, we observe excited states in ^{234}U up to a spin of $18\hbar$ using the $^{232}\mathrm{Th}(^{9}\mathrm{Be},\alpha 3n)$ incomplete-fusion reaction. Two tentative excited states in the octupole band of ^{234}U [1] are confirmed, while a new state at 1366 keV, possibly the 8^+ member of the γ band, is identified. An interesting property of the incomplete-fusion reaction used in the present work is that it is ‘‘self-selecting,’’ in the sense that only the incomplete-fusion products are likely to survive fission, and thus they will dominate over the complete-fusion channels. This type of reaction may provide a useful alternative method for the population of high-spin states in heavy, neutron-rich nuclei.

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