A precursor of β-delayed fission: ^{230}Ac

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Abstract The ^{230}Ra has been produced via multinucleon transfer and dissipative fragmentation of heavy target in the 60 MeV/u ^{18}O ion reaction with natural thorium. The radium was radiochemically separated from irradiated thorium targets. ^{230}Ac was obtained by $^{230}\mathrm{Ra} \xrightarrow{\beta^-} {}^{230}\mathrm{Ac}$. Thin Ra sources were prepared for observing fission fragments from β-delayed fission of ^{230}Ac. The sources were exposed to the mica fission track detectors and measured by a HPGe γ detector. The two fission events were obtained and could been assigned to the β-delayed fission of ^{230}Ac. The β-delayed fission probability of ^{230}Ac was determined to be $(1.19\pm0.85) \times 10^{-8}$.

Keywords β-delayed fission, Multinucleon transfer reaction, Dissipative fragmentation of heavy target, Radiochemical separation

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1 INTRODUCTION

Nuclei far from stability are characterized by a number of new phenomena. In heavy neutron-rich region, one of these is β-delayed fission (βDF), i.e., fission from an exited state in which the nucleus turns out to be after β decay. For the first time the existence of an β-delayed fission island was pointed out by Berlovich and Novikov in 1969.[1]

βDF provides the possibility of investigating nuclei far from stability, which is impossible with ordinary techniques. For example, βDF allows the study of the fission of heavy neutron-rich nuclei from excited states, which can be used as a basis for predictions of fission properties of heavier neutron-rich nuclei.[2,3]

Measurements of the probability for βDF also provide a sensitive probe of the structure of the fission barrier since the probability (and hence the half-life) of the fissioning level is exponentially dependent on the magnitude of the fission barrier.[3]

βDF also remains important in the astrophysical r–process. The production of heavy elements by successive neutron capture and β decay is of great astrophysical interest.[4-6] In r–process occurring in supernova explosions the build up of heavy elements is eventually terminated by βDF with the consequence that no superheavy elements may be produced in nature. Therefore, the βDF process is invoked to explain the observed isotopic abundances of the heavy elements and is offered as one reason why superheavy elements are not found in nature.[7] In addition, the estimates of the Universe age using

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the nuclear cosmochronology by the heavy chronometers (^{232}Th, ^{235,238}U, and ^{244}Pu) depend crucially on the βDF rates in heavy neutron-rich nuclei far from stability.

Thielemann and Klapdor *et al.* have carried out theoretical investigation of βDF probabilities of the nuclei in the island region and shown its role in the production of heavy elements and built up of heavy isotopic abundances in astrophysical r process as well as the influence of the delayed fission on the production of cosmochronometers.[4-6] Gangrskii *et al.*,[2] Bas-May *et al.*,[8] Hall *et al.*,[3] and Mezilev *et al.*[9] performed experimental searches and studies for βDF in neutron-rich actinide and the nearby region.

This paper reports the search for the βDF precursor ^{230}Ac and the determination of its β-delayed fission probability.

2 EXPERIMENTAL PROCEDURE AND RESULTS

Some experimental results reveal that in MNTR both neutron-rich projectile and target, and reasonably higher incident energy favor the production of heavy neutron-rich nuclei.[10-14] In addition, dissipative fragmentation of heavy target in the intermediate energy heavy ion collision can also produce heavy neutron-rich nuclei as target-like residues.[15] In the present work, the ^{230}Ra was produced as target-like product via MNTR, transferring two target protons to projectile, i.e. (^{232}Th-2p), and via dissipative fragmentation of the heavy target. ^{230}Ac was obtained by ^{230}Ra $\xrightarrow{\beta^-}$ ^{230}Ac. The irradiations were performed at Heavy Ion Research Facility in Lanzhou (HIRFL) of Institute of Modern Physics (IMP). The 60 MeV/u ^{18}O beam with a current intensity of ~40 enA was used to irradiate a "radium free" natural ThO_2 powder target (1.5 g/cm^2). After irradiation of 3 hours, each target was rapidly transferred to the chemical laboratory 30 meters away by a pneumatic transport system. And then the radiochemical separation was carried out. Isotopes of Ra produced in the reactions were radiochemically isolated from the mixture of thorium and reaction products. ^{230}Ac was obtained by ^{230}Ra $\xrightarrow{\beta^-}$ ^{230}Ac. Thin Ra sources were prepared for observing fission fragments from β-delayed fission of ^{230}Ac. Mica foils were sticked on the sources as fission track detectors in order to enhance counting efficiencies as high as possible. The mica foils and a HPGe having an efficiency 70% with an energy resolution of 2.0 keV(FWHM) for the 1.33 MeV line of ^{60}Co were placed face to face on both side of the sources in a lead room. The sources were exposed to the mica fission track detectors for 10 hours and measured by the HPGe γ detector for 4 hours. The γ ray time sequence spectra were recorded on magnetic disks with a PC-CAMAC Multi-Parameter Data Acquisition System. These mica foils were etched in a solution of 40% HF at 50°C for 4 hours. After processing mica foils were scanned by means of an optical microscope. A total of 20 such cycles were performed.

As a result of scanning the foils, two fission fragment tracks were observed among a lot of tracks of natural background. All tracks of natural background have the same size,

and the fission fragment tracks differ clearly in size from those of natural background (Fig. 1).

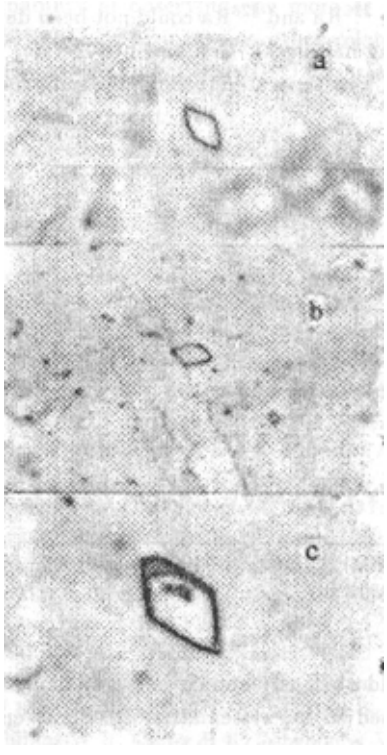

Fig.1 Two fission fragment tracks observed from β-delayed fission of ^{230}Ac (a) and (b), and a track from natural background of fission fragments (c)

A total of 1.68×10^8 ^{230}Ac β decay events registered by the fission track detectors has been determined through peak areas and branching ratios of the γ rays of ^{230}Ac[16] in the measured spectra.

3 DISCUSSION

The observation of fission fragment tracks provide the first evidence for the delayed fission of ^{230}Ac based on the following arguments:

(1) The mica foils were already etched for 10 hours before the experiments, thus the total etching time for natural fission tracks was 14 hours whereas it was only 4 hours for tracks due to fission events from the sources. So the tracks of natural background were much larger than those from sources.

As mica foils do not respond to the charged particles with the charge number smaller than 10, α particles cannot be detected. And recoil nuclei come from β-delayed neutron emissions (β-n) could not affect the experimental results for the following reasons. First, β-n events are much seldom in actinides region. Secondly, even β-n events appear, the recoil nuclei could not emit out of targets for their much lower recoil energies.

(3) The same experiments mentioned above except irradiation of the target materials were carried out, no fission event was found. Thereby, fissions induced in the fissile contaminants of our samples or our track detectors by the potential neutron field in our laboratory should be eliminated.

(4) Inspection of the samples by γ-ray spectroscopy as shown in Fig.2 indicates

that except for some impurities of Ba and Sr the radium fractions were radiochemically clean. In the spectra one can see the γ rays from ^{223}Ra, ^{224}Ra, ^{225}Ra, ^{227}Ra and the daughters of the ^{223}Ra and ^{224}Ra through their α decay, in addition to the intense γ rays from ^{230}Ra and its daughter ^{230}Ac. Moreover, those from other radioactive isotopes of radium were not detected. Because some isotopes such as ^{229}Ra, ^{231}Ra and ^{232}Ra have very short half-life, after the comparatively very long radiochemical separations of 30 minutes, almost none of them remained. While ^{226}Ra and ^{228}Ra could not been detected for their very low decay probabilities (very long half-lives). Consequently, ^{229}Ac, ^{231}Ac, ^{232}Ac, the daughters of ^{229}Ra, ^{231}Ra and ^{232}Ra, were separated through the radiochemical procedure.

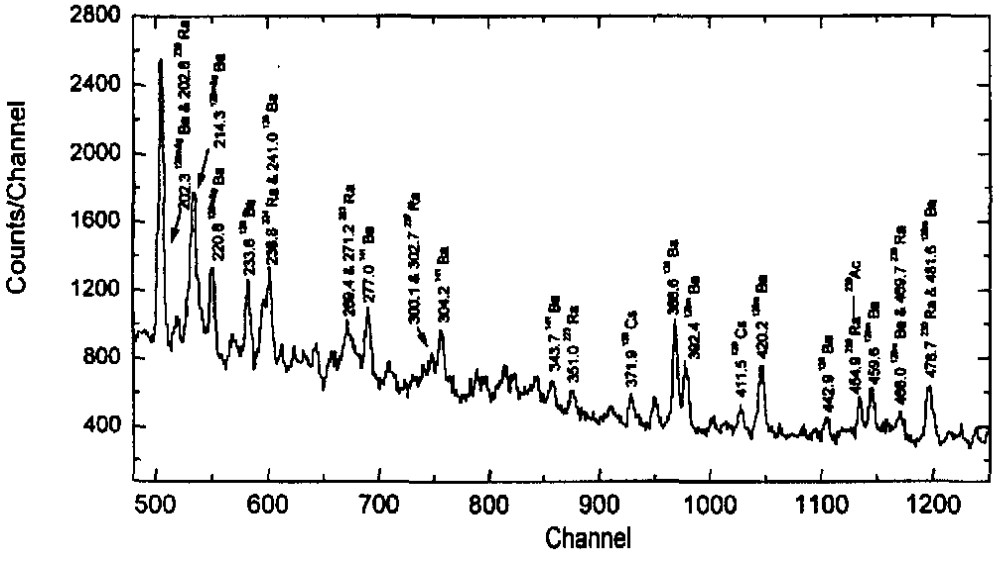

Fig.2 The measured γ-ray spectrum

(5) According to the theories, βDF should obviously appear in heavy neutron-rich nuclei far from stability.[1,4–6] In addition, based on the systematics of β-decay energies and fission-barrier heights, βDF should appear first of all in odd-odd nuclei, since they have the greatest β-decay energies and their daughter even-even nuclei are characterized by high fissility.[1–6,8,9] So it is confirmed that only the ^{230}Ac could produce βDF among all the radioactive isotopes contained in the thin Ra sources.

(6) The possibility of the spontaneous fission of ^{230}Th, the daughter of ^{230}Ac, could be excluded, because of the long half-life (7.54×10^4 a), the minor spontaneous fission probability ($< 3.8 \times 10^{-14}$),[16] and a very limited total number (1.68×10^8) of ^{230}Th in the whole experiments.

(7) On the other hand, thorium in the target was depleted by a factor $> 2 \times 10^4$ which means that during the whole series of experiments less than 2×10^{-5} fission tracks were expected from remaining ^{232}Th impurities. All the arguments mentioned above indicate that the two fission events observed in the experiments could be assigned to the βDF of ^{230}Ac.

βDF probability was defined as the number of delayed fission event divided by the number of β decay of the parent

$$P_{\beta\mathrm{DF}} = \frac{N_{\beta\mathrm{DF}}}{N_{\beta}}$$

Considering several factors such as decay probability and emission angle etc., there is probability of observing one more or one less fission event. Thus the error should be $\pm 50\%$. Considering some other related factors, the βDF probability of ^{230}Ac was obtained to be $(1.19\pm0.85)\times10^{-8}$ for assurance.

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