POPULATION OF REFLECTION-ASYMMETRIC NUCLEI BY MULTI-NUCLEON TRANSFER REACTIONS*

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(Received December 18, 1995)

The heavy-ion collisions of ^{232}Th + ^{136}Xe and ^{232}Th + ^{56}Fe with beam energies 15-20% above the Coulomb barrier have been used to populate nuclei in and around the actinide region of the nuclear chart. The product yield distributions of the binary reaction products stopped in thick targets have been obtained by measuring γ-γ coincidence intensities. A comparison of the distributions for the two reactions shows that the transfer of nucleons is dictated by the mass and charge equilibration processes. This suggests that ^{136}Xe is the better projectile for populating the region of octupole-deformed nuclei which are inaccessible by compound-nucleus reactions.

PACS numbers: 25.40.Hs

* Presented at the "High Angular Momentum Phenomena" Workshop in honour of Zdzisław Szymański, Piaski, Poland, August 23–26, 1995.

1. Introduction

Nuclei with $Z \simeq 88$ and $N \simeq 134$ have their neutron and proton Fermi levels in close proximity to the octupole-driving $\nu(j_{15/2}$ and $g_{9/2})$ and $\pi(i_{13/2}$ and $f_{7/2})$ orbitals. Thus these nuclei are susceptible to octupole deformation [1]. Nuclei in this region of the nuclear chart can be studied using fusion-evaporation reactions [2]. For example, high-spin states were simultaneously populated in the reactions ^{208}Pb(^{18}O, α2n)^{220}Ra and ^{208}Pb(^{18}O,4n)^{222}Th using the EUROGAM (phase I) gamma-ray spectrometer of 40 large germanium detectors [3] to detect de-excitation gamma-rays. Low production cross-sections (~millibarns) and large fission cross-sections (95% of the total reaction cross-section in the ^{208}Pb + ^{18}O reaction [4]) make these nuclei difficult to study by this means, even with a germanium detector array as sensitive as EUROGAM (phase I). The lack of stable targets above ^{209}Bi and suitable projectiles is another limitation in using compound-nucleus reactions to populate actinide nuclei. This is sufficient motivation to search for alternative population mechanisms.

The development of efficient Compton-suppressed germanium-detector arrays has allowed multi-nucleon transfer reactions to become a popular method of accessing many nuclei inaccessible by compound-nucleus reactions [5–10]. In these reactions many excited nuclei around the projectile and target are produced and the resulting complexity of the spectra demands high statistics and good energy resolution. This can be achieved by the use of efficient germanium-detector arrays in conjunction with the use of thick targets so that the decays from low-lying yrast states are emitted from nuclei at rest. This approach, in which γ-γ coincidence techniques are employed, can allow precise identification of the two reaction partners and measurement of their yield. In favourable cases the mutual excitation of both reaction products may be directly observed through cross-coincidence of γ-rays from both reaction partners.

The two experiments that were performed are described in Section 2 along with a comparison of their product yield distributions. A conclusion of this work is given in Section 3.

2. The reactions

2.1. ^{56}Fe + ^{232}Th

Initial studies were performed at the Accelerator Laboratory in Jyväskylä, Finland. A thick (30 mg/cm^2) ^{232}Th target was bombarded by a ^{56}Fe beam from the K-130 accelerator at an energy of 362 MeV (20% above the Coulomb barrier). The γ-γ in-beam and out-of-beam coincidence data

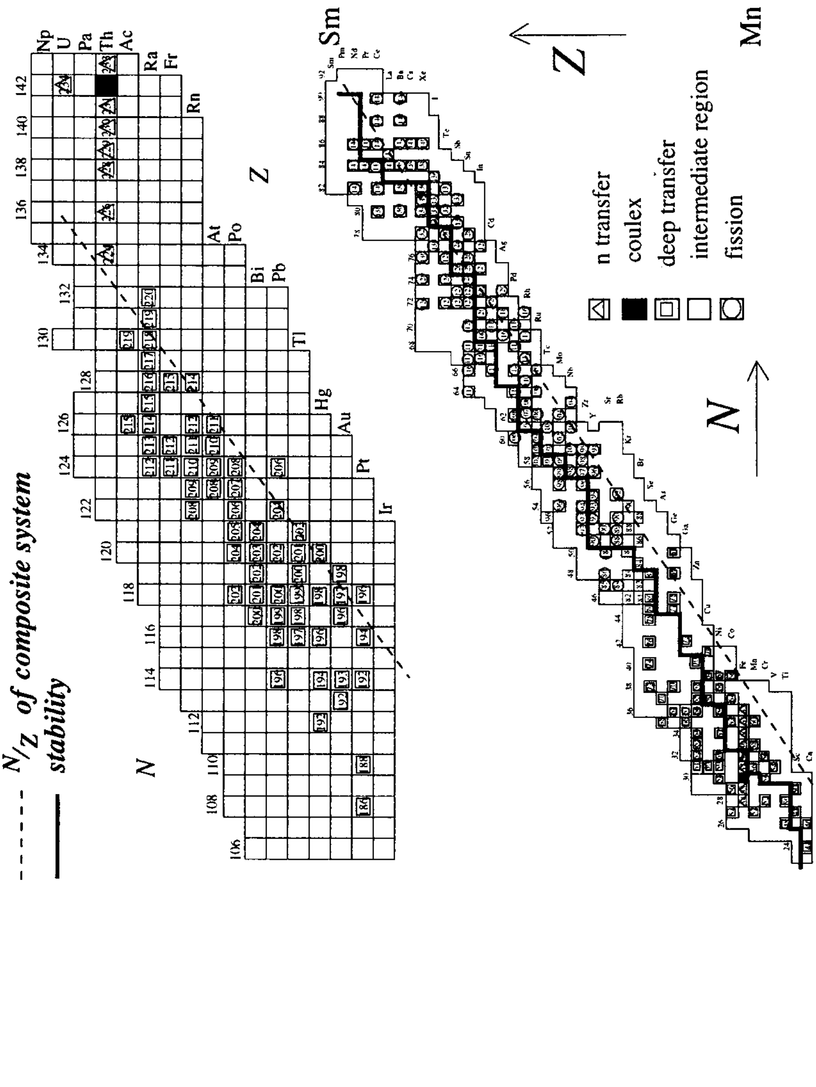

Fig. 1 Distribution of nuclei populated in the ^{56}Fe + ^{232}Th reaction. Target-like products are shown in chart (a) and projectile-like and fission products constitute chart (b).

were collected with an array of twelve Compton-suppressed TESSA-type [11] germanium detectors. As a thick target was employed, the effective bombarding energy varied from the incident beam energy down to the Coulomb barrier.

Figure 1 shows all nuclei populated and identified in this reaction. Figure 1(a) shows target-like products accessed by neutron transfer (~ quasi-elastic) and by a large transfer of both protons and neutrons (~ deep inelastic). The corresponding projectile-like transfer products can be seen on Figure 1(b). On both charts the dashed line marks the N/Z of the compound system. One can observe that population is dictated by the mass and charge equilibration processes so that the N/Z value of the populated nuclei tends to that of the composite system. The thick, black line on Figure 1(b) marks the neutron-rich edge of the β-stability which shows that many products of the transfer process are quite neutron rich. It is also evident from the figure that many nuclei are produced via fission of the target-like transfer products. In most cases we are unable to observe the mutual excitation of both transfer products: the intensity of cross-coincident γ-rays is substantially reduced because a) there is a large reduction in yield of the target-like products because of fission; b) there is large fractionation of the transfer products in this system.

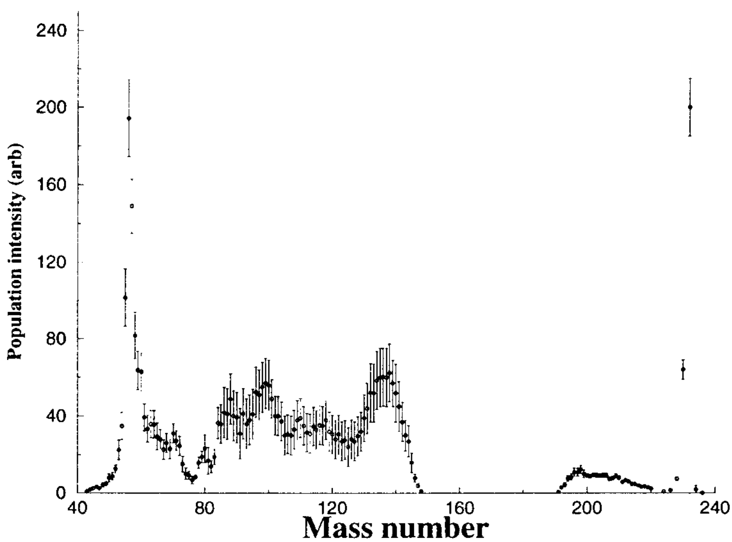

Fig. 2. Population yield plot for nuclei populated in the $^{56}Fe + ^{232}Th$ reaction.

Figure 2 shows the mass distributions of the nuclei populated in the $^{56}Fe + ^{232}Th$ reaction. The yields are from quantitative in-beam and out-of-beam γ-γ coincidence analyses, where the intensities are corrected for efficiency and internal conversion. Near the projectile and target we can see a significant yield of nuclei produced by transfer of neutrons from quasi-elastic processes. The yield of target-like nuclei corresponding to multi-nucleon (deep inelastic) transfer is substantially reduced compared to the corresponding projectile-like partner. The minimum yield appears to occur near $A \sim 224$. The two peaks evident at $A \sim 90$ and $A \sim 130$ presumably arise from asymmetric fission of near-target products of quasi-elastic processes, whereas fission of products of deep inelastic processes gives rise to symmetric fission products with $A \sim 110$.

2.2. $^{136}Xe + ^{232}Th$

In this study a thick (40 mg/cm^2) ^{232}Th target was bombarded by a ^{136}Xe beam from the ATLAS accelerator at a beam energy of 830 MeV (15% above the Coulomb barrier). In-beam and out-of-beam γ-γ coincidences were acquired with the Argonne-Notre Dame array of twelve Compton-suppressed germanium detectors. As with the ^{56}Fe + ^{232}Th reaction the mass and charge equilibration processes control the population of nuclei in this system.

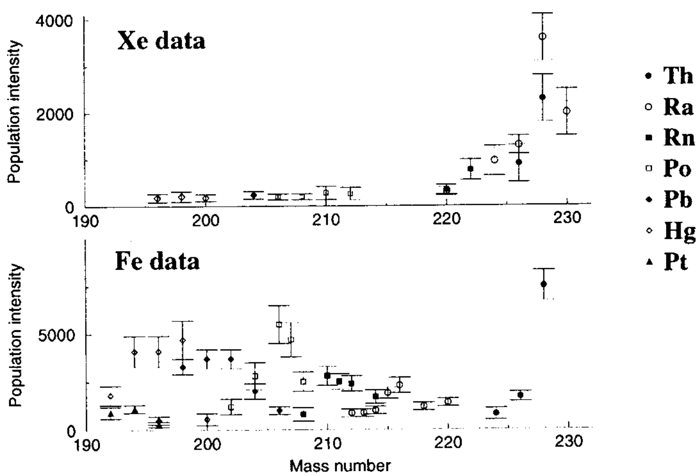

Fig. 3. Population yield of target-like nuclei populated in the ^{56}Fe + ^{232}Th and ^{136}Xe + ^{232}Th reactions.

A comparison of the target-like products produced in the two reactions indicates that ^{136}Xe is the better projectile for populating the nuclei of interest in the octupole-deformed light-actinide region. In accordance with the mass and charge equilibration processes, the less neutron-rich ^{56}Fe projectile picks up more neutrons from the target and shifts the distribution of heavy products into the region which is already accessible by compound-nucleus reactions. On the other hand, the ^{136}Xe projectile populates the region which cannot be accessed in fusion-evaporation reactions and may provide a good opportunity to study nuclei such as ^{222}Ra, ^{222}Rn and ^{220}Rn.

3. Conclusion

We have populated nuclei that presently cannot be accessed via a compound nucleus using multi-nucleon transfer reactions. The production cross-sections are rather low since there is substantial competition from fission of the target-like reaction partner. For this reason, together with large fractionation of the system, cross-coincidence measurements are difficult. Future work is planned using the GAMMASPHERE array at the Lawrence Berkeley Laboratory to obtain higher statistics.

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