Incomplete fusion reaction producing Pa nuclides in the ^{232}Th + ^{7}Li reaction[†]

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The research focuses on neptunium-237 (^{237}Np), a minor actinide present in trace amounts due to nuclear activities.[1,2] Its analysis, which is crucial for earth sciences, requires mass spectrometry (MS) with a neptunium tracer, currently unavailable.[3] The study explores using ^{236g}Np as a tracer, produced through the ^{232}Th + ^{7}Li reaction. Heavy-ion reactions, dominated by mechanisms like complete fusion (CF) and incomplete fusion (ICF), influence nuclide production. ICF, involving only partial projectile fusion, is observed in the ^{7}Li reaction. The study measures protactinium (Pa) isotopes excitation functions, comparing them with theoretical calculations, discussing the competitive relationship between ICF and CF and their impact on Np synthesis. In this study, we concentrate on nuclides that can be determined by γ-ray measurements.

The study employed thorium metal foils and electrodeposited thorium on an aluminum foil as targets for irradiation. Metal foils, stable against beam irradiation, were 9–16 mg/cm^2 thick, with sizes of 15 mm $\times$ 15 mm and purities of 99% or more. An electrodeposited target, which is less costly than Th metal foil, can be prepared to a thin thickness, enabling fine adjustment of the incident energy using a degrader. Electrodeposition was performed using thorium nitrate hydrate dissolved in 2-propanol, resulting in a 1 mg Th/cm^2 sample. The thickness of Th was determined by an α-particle spectrometry. Stacked targets were irradiated with a ^{7}Li beam at the RIKEN RI Beam Factory. For nondestructive γ-ray measurements, they were decomposed into individual targets, and Pa isotopes were analyzed. Chemical separation of Pa by using solid-phase extraction resins and γ-ray spectrometry by high-purity germanium detectors for radioactivity measurements with comparisons to standard sources were performed.

The results on nondestructive γ-ray measurements revealed peaks related to isotopes such as ^{232}Pa, ^{233}Pa, and ^{234}Np, alongside the identification of fission products (FP). Chemical separation methods effectively isolated Pa isotopes, showcasing a detailed procedure involving dissolution, evaporation, and column-based extraction. Chemical separation removed FP-derived peaks, enabling clear observation of Pa peaks, including ^{234}Pa, and confirming the decay of each nuclide.

The measured cross-sections of Pa ranged from 0.1 to approximately 100 mb and, although the cross-section of any nuclide increases with increase in incident energy, this measurement appears to be saturated in the higher-energy region. The total fission cross-sections showed deviations, particularly at certain energy points, possibly due to target material desorption during irradiation. The study compared experimental excitation functions with theoretical calculations using the EMPIRE code,[4] exploring both CF and ICF scenarios. The comparison suggests that Pa isotope production, especially the (^{7}Li, α) reaction, might be influenced by ICF.

A detailed examination of reaction mechanisms included deriving critical angular momentum for complete fusion reactions and determining orbital angular momenta for incomplete fusion using a sum rule model.[5,6] On the basis of the incomplete fusion systematics obtained by the results of this study, we proposed a novel method for producing ^{236g}Np using incomplete fusion reactions in the ^{235}U + ^{6}Li system. The selection of this system was based on theoretical calculations indicating a higher yield of ^{236}Np with a favorable ^{236}Np/^{237}Np ratio.

In conclusion, the research provided a comprehensive exploration of thorium irradiation, chemical separation techniques, reaction cross-section determination, and the comparison of experimental and theoretical results. The proposed method for ^{236g}Np production using incomplete fusion reactions holds promise for future experiments and considerations in nuclear research.

References

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