Physicists report first measured isomeric-ratio in multinucleon-transfer reactions: A doorway to access terra incognita

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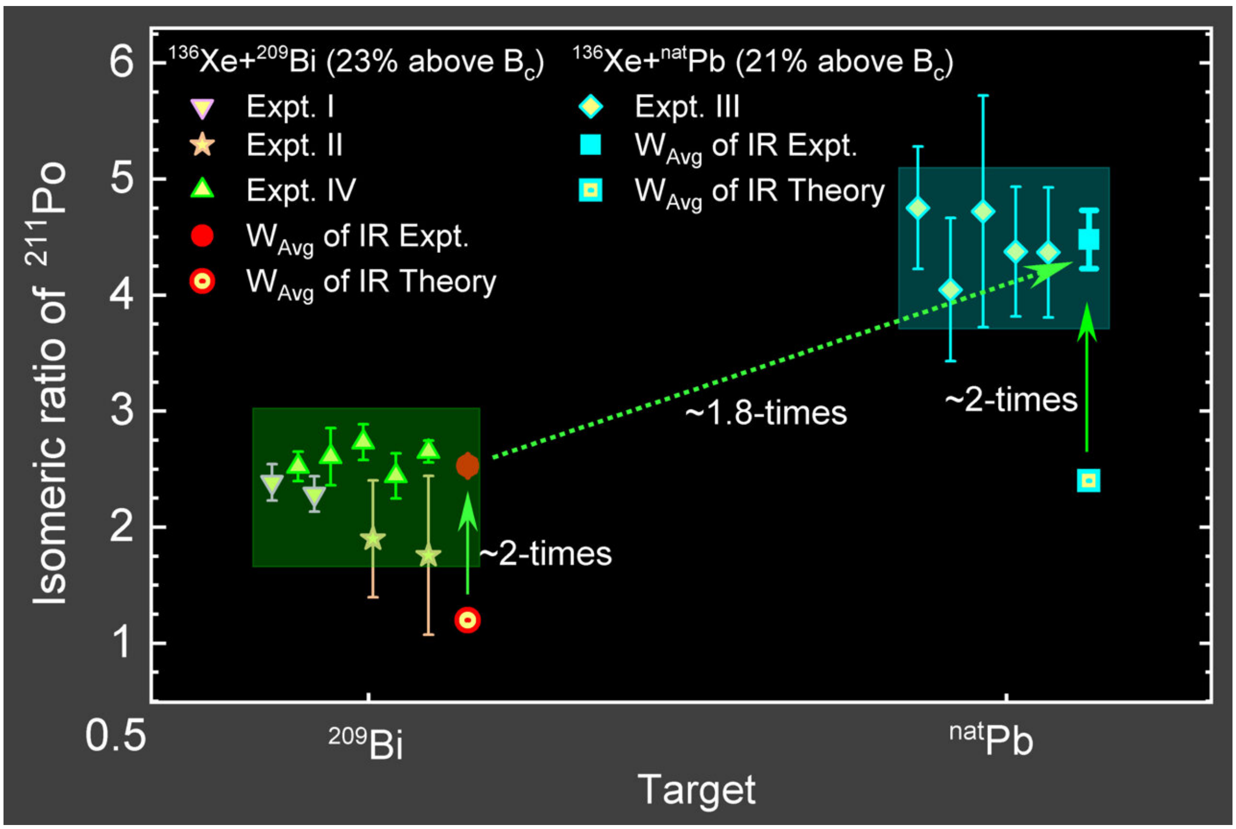

Isomeric ratio of ^{211}Po (polonium) produced in the ^{136}Xe+^{209}Bi reaction at 23% above Coulomb barrier (Bc) and ^{136}Xe+^{nat}Pb at 21% above Coulomb barrier (Bc) in different experiments (I, II, III, and IV) and subsequently deduced Weighting Average of IRs (WAvg of IR Expt.). "WAvg of IR Theory" indicates the estimation of IRs from the theoretical Langevin approach for both reactions at different projectile energy. Solid arrows show the under-prediction of the theory from the experiment. The dotted arrow represents an enhancement of ^{211}Po in ^{136}Xe+^{nat}Pb compared to ^{136}Xe+^{209}Bi. Credit: *Physics Letters B* (2024). DOI: 10.1016/j.physletb.2024.138654

Delving into the intricate properties of heavy neutron-rich nuclei is crucial since they have the potential to reshape our understanding of nuclear physics and astrophysics.

Determining the nuclear properties of these exotic nuclei is like piecing together a complex puzzle to understand the evolution or possible quenching of nuclear shell structures. These structures play a significant role in astrophysical processes like the rapid neutron capture process (r-process), which is essential for forming heavy elements in the universe.

Why multinucleon-transfer (MNT) reactions?

Production of heavy exotic nuclei, which are far from the stability line of the nuclear Segrè chart, is incredibly challenging with conventional reaction methods like fusion-evaporation, fusion-fission or fragmentation. That is why finding a way to unlock their secrets through multinucleon-transfer (MNT) reactions is essential.

The MNT reactions involve the exchange of multiple protons and neutrons between interacting systems at energies around the Coulomb barrier, allowing the population of projectile-like/target-like fragments (PLFs/TLFs). Hence, neutron-rich heavy beams, preferably intense radioactive ion beams (RIBs), targeting neutron-rich nuclei can populate neutron-rich PLF/TLF nuclei with high-spin isomeric states at low excitation energies.

Recent studies, both experimental and theoretical, have demonstrated that MNT reactions hold tremendous potential to access these exotic nuclei of the terra incognita region. Our international research team has conducted a series of MNT experiments at the Ion-Guide Isotope Separator On-Line (IGISOL), University of Jyväskylä (Finland). In addition to the general commissioning of the setup, we have collected the data to understand the reaction mechanism better.

Our work is published in the journal *Physics Letters B*.

Nuclear isomers

One of the most intriguing aspects of our study involves isomers, which are long-living excited states in nuclei. By studying the relative production of these isomers relative to their ground states, known as isomeric ratios (IRs), we gain valuable insights into nuclear structure and the underlying reaction mechanism. Our work is the first experimental and theoretical study on the IRs of nuclei created from two different proton transfer (*p*-transfer) channels via two different MNT reactions.

Through our study, we aimed to answer several questions: How does the spin of the target or nucleon transfers affect the high-spin isomer population? How accurately can state-of-the-art MNT model calculations explain our observations? What gaps remain in our understanding of these processes? These questions are essential for deciphering the spin distributions of MNT fragments, which, in turn, influence the population of isomers.

How could we determine the isomer ratios?

In our experiments, we used intense neutron-rich xenon (^{136}Xe) beams (~10^{11} particle/sec) delivered by the K-130 cyclotron at JYFL and shot them on a lead (^{nat}Pb) or bismuth (^{209}Bi) target. We conducted four distinct experiments utilizing specialized detection systems (gas-filled stopping cells).

By capturing the heavy MNT fragments within helium-filled gas cells, we could extract, accelerate, and separate these MNT ions in order to filter out a particular ion of interest— in the present case, the ions with mass number A=211. We identified these products using alpha-decay spectroscopy and observed consistent alpha-decay spectra of polonium-211 in both ground and isomeric states across various measured conditions in different experiments.

What do the isomer ratios tell us?

Our findings revealed a significantly larger production of polonium-211 isomers relative to ground states in studied MNT reactions. In addition, comparative results from different MNT reactions showed an enhanced production of polonium-211 isomer formed from 2*p*-transfer over 1*p*-transfer. Deduced results indicate a strong correlation between the isomer production and the *p*-transfer production routes.

Furthermore, meticulous comparative analysis of isomer production from different types of reaction processes over an extended projectile mass range reveals that the two entrance-channel parameters— projectile mass and *p*-transfer channels, strongly influence the population of the high-spin isomer in polonium-211. The state-of-the-art Langevin-type MNT model calculations qualitatively predict the deduced relative enhancement in the isomer population. However, more experiments are necessary in order to refine these models further.

Importance of collaborative efforts

The journey toward the unknown territory of terra incognita region via

MNT reactions is both challenging and exhilarating. The collaborative efforts of many experimentalists and theoretical physicists were important in understanding the production mechanism of isomers and comprehending the angular momentum distributions of MNT fragments.

As a next step, we plan to produce neutron-rich exotic nuclei near the neutron shell closure N=126 for precision mass measurements.

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More information: D. Kumar, T. Dickel, A. Zadvornaya, O. Beliuskina, A. Kankainen et al, First investigation on the isomeric ratio in multinucleon transfer reactions: Entrance channel effects on the spin distribution, *Physics Letters B* (2024). DOI: 10.1016/j.physletb.2024.138654

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