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New Isomers in the Neutron-Rich Region Beyond ^{208}Pb

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Abstract. The region of neutron-rich nuclei beyond ^{208}Pb has been very difficult to explore due to its high mass and exoticity. However, recent experimental improvements allowed one to perform a quite extended isomer decay spectroscopy of these nuclei.

1 Introduction

The study of exotic nuclei has shown that significant changes of the well-known shell structure along the stability valley occur, especially for very neutron-rich nuclei with mass numbers below 100. The two most accessible doubly-magic nuclei above A=100 are ^{132}Sn (Z=50, N=82) and ^{208}Pb (Z=82, N=126). Both of them are very neutron rich but the second one is nonetheless stable. The evolution of the Z=50 shell above N=82, and in general the structure of nuclei around ^{132}Sn, is nowadays an object of intense research at radioactive beams facilities accelerating fission fragments around A=140. On the other side, little is known on the evolution of Z=82 shell closure beyond N=126 and on the neutron-rich nuclei around ^{208}Pb, because of the experimental difficulties to reach such nuclei [1–3]. The study of these isotopes is relevant also for nuclear astrophysics, since the measurement of their β-decay half lives will improve the understanding of the r-process stellar nucleosynthesis in heavy nuclei [4].

2 Experimental details

The neutron-rich nuclei beyond ^{208}Pb have been populated by exploiting UNILAC-SIS accelerator facilities at GSI. A 1 GeV/A ^{238}U beam at an intensity of around 1.5×10^9 ions/spill was provided by the accelerators. The $\sim$ 1 s spills were separated by $\sim$2 s without beam. The beam impinged on a 2.5 g/cm^2 Be target (followed by a 223 mg/cm^2 Nb stripper to increase the number of fully-ionized atoms) and the isotopes resulting from the fragmentation reaction were separated and identified with the double-stage magnetic spectrometer Fragment Separator FRS [5]. The FRS allows one to discriminate the magnetic rigidities of the fragments with a resolution sufficient to distinguish the masses of adjacent isotopes even at the high masses of interest (A $\sim$ 210-220). As stated above, the experimental challenges related to this region are numerous and not limited to the difficulty in mass and atomic number resolution. In fact, a significant problem is also the fact that the magnetic rigidities of the primary beam charge states (mainly $^{238}U^{91+}$ and $^{238}U^{90+}$) and of some nearby nuclei (mainly Rn, Ra isotopes) are similar to the magnetic rigidities of the fully-stripped neutron-rich lead isotopes, in particular ^{212}Pb and ^{214}Pb. The high yield of uranium ions from the primary beam and of certain Ra and Rn fragments would lead to an unacceptably high counting rate at the intermediate focal plane, where several detectors for position and time detection are placed. In order to avoid the problem, a homogenous 2 g/cm^2 Al degrader was placed after the first dipole, to exclude from the acceptance of the FRS the uranium charge states and other heavy fragments, enabling a sustainable counting rate in the intermediate focal plane detectors. Slits after the first and the second dipoles were also partially inserted in the beam line of the spectrometer to cut the remaining contamination from the primary beam charge states. The angle of the wedge-shaped 758 mg/cm^2 Al degrader at the intermediate focal plane was set to produce a monochromatic beam, its thickness being limited by the minimum energy required to measure the atomic number at the final focal plane.
The identification in magnetic rigidity ($B\rho$) is achieved through focal-plane position measurements compared to positions of a beam with a well-known $B\rho$. The plastic scintillators at the intermediate and final focal planes allow one to extract the time of flight (TOF). The mass over charge ratio (A/q) of the fragments is calculated from the TOF and the $B\rho$, measured on an event-by-event basis. The

atomic number of the fragments is obtained from two ionization chambers placed in the final focal plane. Finally, the comparison of the $B\rho$ before and after the Al wedge-shaped degrader allows one to discriminate a possible change in the ion charge state. These measurements are sufficient to provide a complete identification of the isotopes event by event. Figure 1 shows the typical identification plot from the described setup, where only fully-stripped ions are considered. The different isotopes are clearly separated in the well-defined blobs in both Z and A/Z ratio. At the final focal plane,

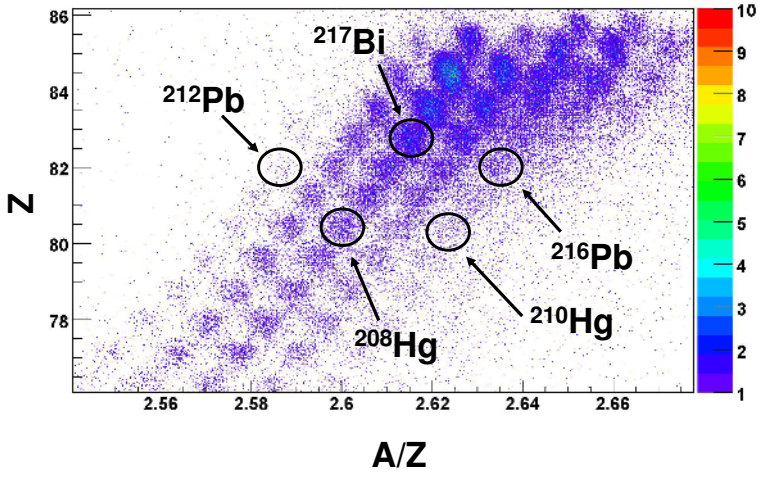

Figure 1. Ion identification plot at the final focal plane of the FRS.

the ions were slowed down in a thick Al degrader in order to reduce the energy of the fragments of interest so they could be implanted in a composite double-sided silicon-strip (DSSSD) detector system comprising 3 layers, every one with three DSSSD pads [6, 7]. Each DSSSD, 16 × 16 pixels, had dimensions 5 × 5 cm^2 and a thickness of 1 mm with an energy detection threshold of 160 keV. The DSSSD detector system was surrounded by the RISING γ spectrometer [8, 9], consisting of 105 germanium crystals arranged in 15 clusters with 7 crystals each. The full-energy gamma-ray peak detection efficiency of the array was measured to be 15% at 662 keV [8] and its time correlation with the active stopper allowed one to perform both isomer spectroscopy and β-delayed γ-ray spectroscopy.

3 Isomer-Decay spectroscopy

Many neutron-rich isotopes were identified for the first time. A significant number of new isomers were hence discovered. Seniority isomers were measured in ^{212,214,216}Pb along the Z=82 shell closure [1]. The study of their structure with state-of-the-art shell-model calculations has pointed out the importance of considering effective three-body forces when calculating the electromagnetic transition strengths with the shell model [1] in restricted valence space. Figure 2 shows a typical time-energy matrix obtained from the RISING array, gating on the ^{216}Pb nucleus. Three lines, corresponding to the γ rays emitted after the isomer decay, are clearly visible.

The ^{210}Hg nucleus was also produced and studied [10]. Its structure is somehow surprising because it deviates from the one of ^{208}Hg [3]. A 3$^-$ state has been tentatively identified below 1 MeV, at odd

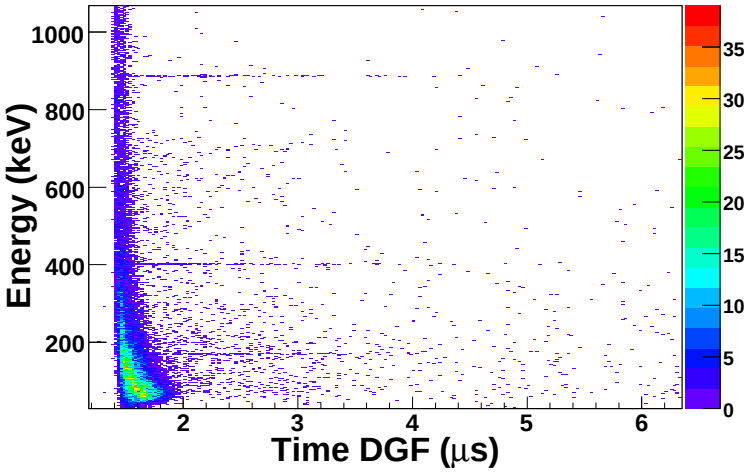

Figure 2. Time-energy matrix for the isotope ^{216}Pb.

with the present understanding of nuclear structure in this region.
Other isomers were also observed in the one proton-particle and one proton-hole bismuth and thallium isotopes, respectively. While the isomer measured in ^{217}Bi is in line with the expectations from the seniority scheme already observed for the lead isotopes, the metastable states in ^{211,213}Tl are at variance with the seniority-like structure of ^{209}Tl [3].
Finally, the use of an active stopper also enabled the measurement of the β half life of the isotopes in this region [4]. They are of crucial importance for understanding the rapid stellar nucleosynthesis process, as they act as a benchmark for calculations in more exotic nuclei.

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