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Beta-decay measurements of neutron-rich thallium, lead, and bismuth by means of resonant laser ionisation

S. Franchoo[ab], H. De Witte[c], A.N. Andreyev[d], J. Cederkäll[b], S. Dean[c], A. De Smet[c], S. Eeckhaudt[c*], D.V. Fedorov[e], V.N. Fedosseev[b], M. Górska[c†], G. Huber[a], M. Huyse[c], Z. Janas[f], U. Köster[b], W. Kurcewicz[f], J. Kurpeta[f], P. Mayet[c], A. Płochocki[f], K. Van de Vel[c], P. Van Duppen[c], L. Weissman[b‡], and the ISOLDE collaboration

[a]University of Mainz, D-55099 Mainz, Germany

[b]CERN ISOLDE, CH-1211 Genève 23, Switzerland

[c]University of Leuven, B-3001 Leuven, Belgium

[d]University of Liverpool, Liverpool L697ZE, United Kingdom

[e]Petersburg Nuclear Physics Institute, RU-188350 Gatchina, Russia

[f]University of Warsaw, PL-00681 Warsaw, Poland

Neutron-rich thallium, lead, and bismuth isotopes were investigated at the ISOLDE facility. After mass separation and resonant laser ionisation of the produced activity, new spectroscopic data were obtained for ^{215,218}Bi and ^{215}Pb. An attempt to reach heavy thallium had to be abandoned because of a strong francium component in the beam that gave rise to a neutron background through (α,n) reactions on the aluminium walls of the experimental chamber.

1. Introduction

The neutron-rich lead region is of exceptional interest to trace the evolution of single-particle levels and the residual proton-neutron interaction beyond the doubly magic nucleus ^{208}Pb. While ^{208}Pb is well understood in terms of the shell model, experimental data on the heavier isotopes is scarce and it is far from clear to what extent the shell model is upheld [1]. The β-decay half-lives and neutron branching ratios in this region also are of importance for the timescale of the r-process in stellar nucleosynthesis. The Finite Range Droplet Model, for instance, puts forward neutron branching ratios of more than 90% for $^{215-217}$Tl [2], but many of the global models may encounter difficulties when not only the allowed Gamow-Teller but also the first-forbidden decays play a role [3].

In the experiment reported here we investigated the β decay of ^{215}Pb and ^{215,218}Bi and engaged in a search for β-delayed neutron emission of ^{215}Tl. The ^{215}Bi nucleus was

*Present address: University of Jyväskyä, FIN-40351 Jyväskylä, Finland

†Present address: GSI, D-64291 Darmstadt, Germany

‡Present address: Michigan State University, MI-48824 East Lansing, United States

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seen before in the α decay of ^{219}At [4] and its β decay was studied, along with that of ^{216}Bi, in mass-separated samples that were produced in spallation of ^{232}Th by protons [5]. Since then little progress was achieved, due to the mass contaminations that on-line mass separators often suffer from. At the FRS facility at GSI, on the other hand, reaction products were identified in the fragmentation of a ^{238}U beam at 1000 MeV per nucleon up to ^{212}Tl, ^{215}Pb, and ^{218}Bi. Because of the low yields, however, spectroscopic information could only be obtained for microsecond isomers in ^{208,212}Pb and ^{210,211}Bi [6].

In a simple and elegant way, the pulsed-release technique allows to considerably reduce the contamination at on-line mass separators on the condition that the isotopes of interest are longer lived than the unwanted species [7]. In the mass region $215 < A < 219$, this indeed holds for the β-decaying lead and bismuth isotopes versus the francium α emitters. In an earlier experiment, new spectroscopic data were thus obtained in the $A = 215, 216, 217$ isobaric chains [8]. Here we have complemented the pulsed-release suppression of contaminants with the element selectivity of the RILIS laser ion source at ISOLDE [9]. By comparing spectra taken with and without laser irradiation of the ion source, the unique signature of the element under investigation becomes evident.

2. Results

The experiment was carried out at the General Purpose Separator of the ISOLDE facility at CERN, Geneva. In two sets of measurements, a 1.4-GeV pulsed proton beam was delivered by the PS Booster to a UC respectively a ThC graphite target, both of 50 g/cm^2 thickness. The intensity was on average 3×10^{13} protons per pulse. The ions diffused out of the target into a 30 mm long and 3 mm wide niobium cavity.

Resonant laser excitation of thallium, lead, and bismuth in the cavity was accomplished with tunable pulsed dye lasers, while the energy of the ionising transition was supplied directly by the copper-vapour pumping lasers. The off-line ionisation efficiency for thallium was determined at 38%, for lead at 3%, and for bismuth at 6%. During the actual experiment, however, the laser power in the last step was twice lower than off-line and the on-line efficiency can be estimated at half the off-line values.

The extracted ions were sent to the mass separator, which itself remained closed for several tens of milliseconds after the impact of the proton beam on the target. This pulsed-release way of operation enabled the efficient suppression of short-lived isobaric contaminants, in particular surface-ionised francium. The ions were implanted in an aluminised Mylar tape. After collection, the sample was transported to the detection set-up, which consisted of two high-purity germanium detectors of 70% and 75% relative efficiency, one low-energy germanium detector with a beryllium entrance window, and a thin plastic scintillator in front of the latter. All detectors were arranged in close geometry. The data were recorded as $\beta X \gamma\gamma$ coincidences.

From comparison of the β-gated γ spectra with and without laser irradiation of the ion source, spectroscopic data were obtained for the β decay of ^{215}Pb and ^{215,218}Bi. An example of spectra taken at mass 218 with the lasers resonant on bismuth is shown in Fig. 1. Contaminant lines from ^{208}Tl are visible, a product of the decay of ^{220}Fr, while also ^{84m}Br is present, most likely separated in the form of molecular BaBr after bonds with stable barium impurities in the target material. The data are currently under analysis in

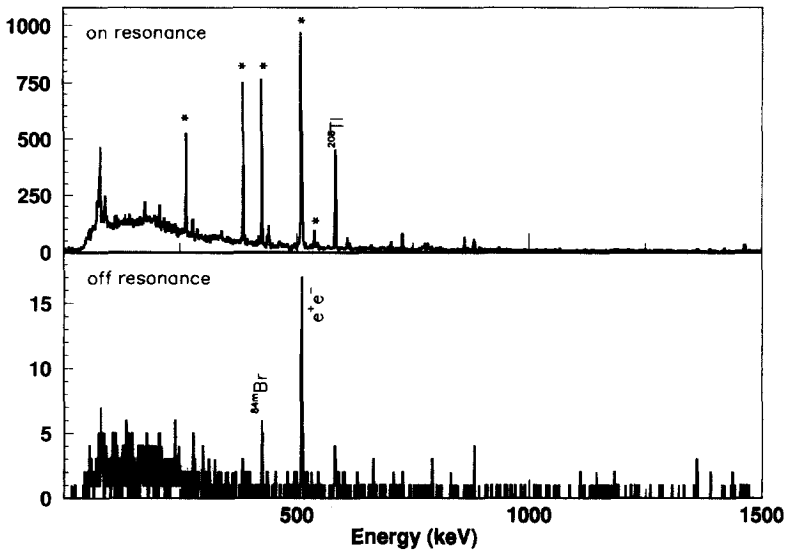

Figure 1. Beta-gated γ spectrum at mass 218 with (top) and without (bottom) lasers resonant on bismuth. The lines marked with an asterisk are attributed to the decay of ^{218}Bi

order to extract the β-decay half-lives and nuclear level schemes [10,11].

For the measurement of neutron branching ratios in thallium, a neutron detector was installed at a separate beam line. The detector consisted of a cylindrical volume of paraffin, in which 12 ^{3}He proportional counters were embedded longitudinally [12]. The detector was mounted around the experimental chamber, itself a cylindrical tube with an inner diameter of 30 mm, and positioned such that the endplate of the tube, onto which the radioactivity was deposited, corresponded to the geometrical centre of the detector. The solid angle of the neutron counter was close to 4π.

In an earlier test, it was found that in spite of the pulsed release from the separator the mass-separated thallium beam still was contaminated by surface-ionised francium. It was foreseen that the francium would give rise to a high rate of α particles in the experimental chamber. Since the cross section of the ^{27}Al(α,n) reaction runs from 30 to 120 mb in the relevant energy range from 5.5 to 7 MeV [13], the aluminium of the chamber walls would generate a neutron flux with an apparent half-life that reflects the francium activity. The tube therefore was coated with a 15 μm layer of gold, which according to SRIM calculations [14] would sufficiently slow down the α particles to an energy where they would no longer initiate reactions with the aluminium.

The experiment was focused on mass 215. While the pulsed release mode of operation satisfactorily suppressed the short-lived ^{215}Fr activity, because of the overwhelming yields it was the amount of ^{213}Fr leaking through the separator that appeared not to be neglegible. In fact, the main contaminant in the γ-ray spectra consisted of its daughter

^{209}At. While the α particles of ^{209}At have an energy below 6 MeV and also should have been stopped in the gold layer, the neutron background rate in the recorded spectra nevertheless proved to be prohibitive. A possible explanation may be that the coating was not homogenous, contained too many impurities, or that the ^{197}Au(α,n) cross sections are higher than what was extrapolated from the literature, which only is available above 10 MeV [15].

3. Outlook

Selective laser ionisation with the RILIS set-up at ISOLDE has brought lead and bismuth up to ^{215}Pb and ^{218}Bi, respectively, within reach for experimental β-decay studies. However, the small cross sections for these elements as well as for thallium are eclipsed by the huge francium yields and make it difficult to pursue further research in this region of the nuclear chart. Moreover, beyond mass 218 the half-lives of the francium isotopes become longer, rendering pulsed release of the activity ineffective. Future improvement can be expected from higher laser ionisation efficiencies, especially when new ionisation schemes will be found where the last step corresponds to a transition to a well-defined auto-ionising state in the continuum. Nevertheless, new techniques for the suppression of isobaric contaminations will remain the main focus of future experiments.

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