Physics Letters B 744 (2015) 137–141

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

First spatial separation of a heavy ion isomeric beam with a multiple-reflection time-of-flight mass spectrometer

T. Dickel [a,b], W.R. Plaß [a,b,*], S. Ayet San Andres [b], J. Ebert [a], H. Geissel [a,b], E. Haettner [a,b], C. Hornung [a], I. Miskun [a,b], S. Pietri [b], S. Purushothaman [b], M.P. Reiter [a], A.-K. Rink [a], C. Scheidenberger [a,b], H. Weick [b], P. Dendooven [c], M. Diwisch [a], F. Greiner [a], F. Heiße [b], R. Knöbel [a,b], W. Lippert [a], I.D. Moore [d], I. Pohjalainen [d], A. Prochazka [b], M. Ranjan [c], M. Takechi [b], J.S. Winfield [b], X. Xu [a,b]

[a] II. Physikalisches Institut, Justus-Liebig-Universität Gießen, 35392 Gießen, Germany
[b] GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany
[c] KVI – Center for Advanced Radiation Technology, University of Groningen, 9747 AA Groningen, The Netherlands
[d] Department of Physics, University of Jyväskylä, FI-40014 Jyväskylä, Finland

ARTICLE INFO

Article history:
Received 4 March 2015
Received in revised form 13 March 2015
Accepted 22 March 2015
Available online 24 March 2015
Editor: V. Metag

Keywords:
Isotope separation in flight
Spatial isomer separation
Multiple-reflection time-of-flight mass spectrometer
Isomer
Isomeric beam
Excitation energy
Isomeric ratio
^{211}Po ions

ABSTRACT

^{211}Po ions in the ground and isomeric states were produced via ^{238}U projectile fragmentation at 1000 MeV/u. The ^{211}Po ions were spatially separated in flight from the primary beam and other reaction products by the fragment separator FRS. The ions were energy-bunched, slowed-down and thermalized in a gas-filled cryogenic stopping cell (CSC). They were then extracted from the CSC and injected into a high-resolution multiple-reflection time-of-flight mass spectrometer (MR-TOF-MS). The excitation energy of the isomer and, for the first time, the isomeric-to-ground state ratio were determined from the measured mass spectrum. In the subsequent experimental step, the isomers were spatially separated from the ions in the ground state by an ion deflector and finally collected with a silicon detector for decay spectroscopy. This pioneering experimental result opens up unique perspectives for isomer-resolved studies. With this versatile experimental method new isomers with half-lives longer than a few milliseconds can be discovered and their decay properties can be measured with highest sensitivity and selectivity. These experiments can be extended to studies with isomeric beams in nuclear reactions.

1. Introduction

Isomers are excited metastable states of nuclei with relatively long half-lives, due to hindrance in their decay modes [1]. The interest in isomers ranges from nuclear structure [2] and nuclear astrophysics [3] to their possible use for energy storage devices [1].

So far, experiments with isomers mostly have been performed using gamma-ray spectroscopy techniques [4–7]. Isomers with half-lives in the µs range and below are especially well suited for coincidence measurements in gamma-ray spectroscopy. In complement to this, long-lived isomers can be well investigated by high-resolution mass spectrometry. Furthermore, high-accuracy mass measurements rely on the fact that ions in the ground and isomeric states are clearly identified and resolved in the mass spectrum, otherwise the results can be erratic. This requirement is a permanent strong motivation to increase the experimental mass resolving power.

The first resolution of ground and isomeric states in a mass measurement was achieved with the ISOLTRAP Penning trap [8]. At LEBIT, the first discovery of an isomer with such a device was achieved [9] and a measurement of an isomeric-to-ground state ratio was performed at JYFLTRAP [10]. By use of ions in higher charge-states in a Penning trap, the resolution of ground and isomeric states could be increased at the TITAN facility [11]. Isomers have also been observed and resolved from their ground state in mass measurements of projectile fragments stored in the Experimental Storage Ring ESR, using Schottky Mass Spectrometry (SMS) [12] and Isochronous Mass Spectrometry (IMS) [13], and

* Corresponding author at: II. Physikalisches Institut, Justus-Liebig-Universität Gießen, 35392 Gießen, Germany.
E-mail address: Wolfgang.R.Plass@exp2.physik.uni-giessen.de (W.R. Plaß).

http://dx.doi.org/10.1016/j.physletb.2015.03.047

their decay has been studied. In storage-ring experiments, the ions are mainly fully ionized or carry only a few electrons, whereas in traps the measured ions are typically singly or doubly charged. Therefore, storage ring and ion trap experiments are highly complementary, because atomic charge states can have a strong effect on the nuclear decay properties of isomers, see [14] and references therein.

Experimental methods employing pure isomeric beams can reveal new nuclear properties. Such experiments can be isomer-resolved decay spectroscopy or investigations via nuclear reactions with isomers. There are different ways to produce pure isomeric beams. The first nuclear reactions with a pure isomeric beam were performed at ISOLDE by selection of the isomer with laser resonance ionization and subsequent post-acceleration [15]. Using a novel excitation method for ion motion in a Penning trap, isomerically clean ion samples could be separated [16] and gamma-ray spectroscopy of pure nuclear states was performed at JYFLTRAP [17]. It was also shown that pure isomeric beams may be provided using storage rings [18,19]. However, these methods are limited to isomers with half-lives of one second or even longer. For the special case, where the half-life of the isomer is significantly longer than the corresponding ground state, such as in ^{212}Po, where the isomeric state has a half-life of 45 s, but the half-life of the ground state is 300 ns only, one does not need an experimental method for separation; one can simply wait until the ions in the ground state have decayed.

Multiple-reflection time-of-flight mass spectrometers (MR-TOF-MS) [20,21] have recently been developed into powerful tools for research with exotic nuclei [22–24]. They are mass spectrometers, and in combination with a Bradbury–Nielsen Gate (BNG) [25,26], a fast electrostatic ion deflector, they can also be employed as high-resolution spatial mass separators [27]. Because of their high mass resolving power, measurement speed, sensitivity and broadband characteristics, they have recently been proposed for efficient experiments with isomers [21]. In this work, such pioneering measurements have been exemplarily performed with ^{211}Po ions for the first time.

2. Experiment and data analysis

The experiment was performed with the FRS Ion Catcher setup [23] at GSI. ^{211}Po nuclei in ground and isomeric states were produced with the FRS [28] via projectile fragmentation of a ^{238}U primary beam at an energy of 1000 MeV/u in a beryllium target with an areal density of 1.629 g/cm^2, that was followed by a 0.223 g/cm^2 Nb backing. The fully ionized polonium ions were separated in flight from the primary beam and other reaction products and were energy-bunched using two-fold magnetic rigidity analysis and a 4.063 g/cm^2 Al monoenergetic degrader, located at the central focal plane of the FRS (Fig. 1, upper panel). The isotope identification of the ions was performed using the particle detectors of the FRS. After further slowing-down in a homogenous degrader at the final focal plane, the ions were injected into a gas-filled cryogenic stopping cell (CSC) [29–31]. In the CSC, they were thermalized as singly-charged ions in helium gas at a pressure of 95 mbar and a temperature of 86 K, corresponding to an areal density of 5.6 mg/cm^2. They were guided to the exit side of the CSC by electric fields, radially focussed onto an extraction nozzle by an RF carpet and extracted with the gas flow into an RFQ quadrupole beam line [23].

From there, the ions were transmitted to the MR-TOF-MS [27,32,33] (Fig. 1(a)–(c)). The MR-TOF-MS is a powerful and universal mass spectrometer with single-ion sensitivity as well as a spatial mass separator. Mass resolving powers (FWHM) as high as 600,000 and a mass accuracy of 10^{-7} have been achieved off-line [32].

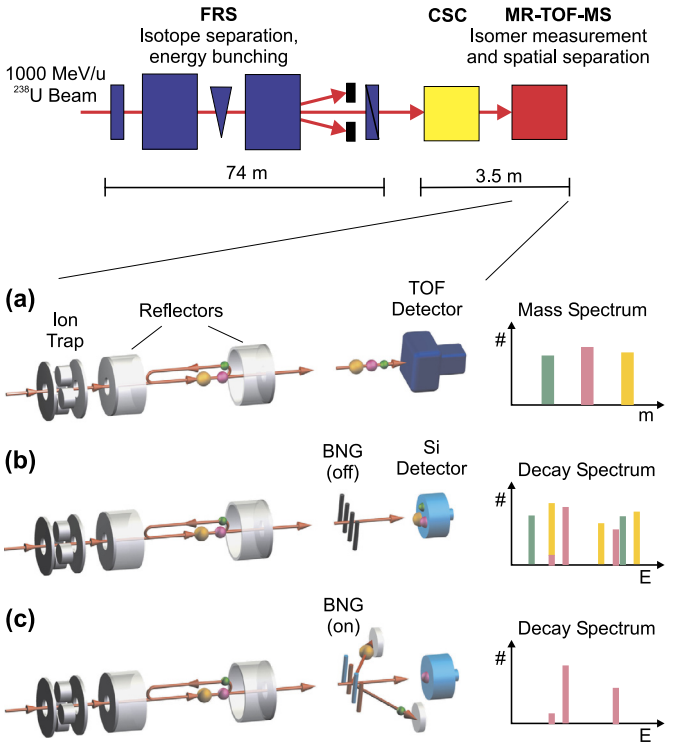

Fig. 1. Schematic drawing of the experimental setup (upper panel). The spatial isotope separation of ions and their energy bunching and slowing down were performed with the FRS before the ions were injected into the gas-filled cryogenic stopping cell (CSC). (a) Mass measurement of the extracted ions with the MR-TOF-MS. The time-of-flight is measured with a TOF detector after multiple reflections between two electrostatic reflectors. (b) Without voltages on the BNG, all ions are transmitted to the Si decay detector behind the gate. (c) With proper timing of the voltages applied on the BNG, only the selected isomer ions are transmitted and their decay is measured.

In the present experiment, a maximum mass resolving power of 370,000 has been obtained for ions with a mass of 133 u after 430 turns in the analyzer, corresponding to a time-of-flight of only 15.3 ms. In the MR-TOF-MS, the ions were accumulated, cooled by collisions with a helium buffer gas in an RF trap system and injected as bunches into the time-of-flight analyzer with a kinetic energy of 1.3 keV. The analyzer is formed by two electrostatic reflectors, between which the ions traveled for 192 turns, corresponding to a time-of-flight of 8.7 ms and a total path length of about 300 m. During their storage in the analyzer, the ions were dispersed in time according to their mass-to-charge ratios. After ejection from the analyzer, the ions alternatively (i) impinged on a TOF detector (isochronous secondary electron multiplier) for measurement of their time-of-flight and hence their mass-to-charge ratio (mass measurement mode) or (ii) passed through the BNG, in which unwanted ions can be deflected, and only the ions of interest were transmitted (mass separator mode). These latter ions were implanted into a Si detector mounted behind the BNG. In the Si detector their alpha decay pattern was measured. The TOF detector and the BNG with the Si detector are mounted on a remote-controlled platform, which can be moved such that either the TOF detector or the BNG and the Si detector are in the beam line.

A mass spectrum of ^{211g}Po and ^{211m}Po was recorded by the TOF detector for a duration of 500 s. The detector signal was digitized by a time-to-digital converter. Next, the BNG and the Si detector were moved into the ion beam. Energy spectra from the alpha decay of ^{211g}Po and ^{211m}Po ions were acquired by the Si detector with the BNG voltages turned off for transmission of all ions, as well with the BNG voltages turned on for a duration chosen such