Production of short lived radioactive beams of radium

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Abstract

Short lived $^{212,213,214}$Ra isotopes have been produced at the TRI$\mu$P facility in inverse kinematics via the fusion-evaporation reaction $^{206}$Pb$+^{12}$C at 8 MeV/u. Isotopes are separated from other reaction products online using the TRI$\mu$P magnetic separator. The energetic radium (Ra) isotopes at the exit of the separator were converted into low energy ions with a thermal ionizer. Ra isotopes have been identified by observing their $\alpha$ decay and lifetimes.

Key words: Production mechanism, Radioactive beam, Magnetic separator.

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1. Introduction

In the TRI$\mu$P program [1] radioactive beams are used to search for electric dipole moments (time reversal violation), atomic parity violation in heavy nuclei and to study the weak interaction via $\beta$ decay of light nuclei [2,3]. The aim is to study physics beyond the standard model. The heaviest alkali-earth element is radium (Ra). Ra has unique atomic and nuclear properties which make it a very promising candidate for such experimental studies [4,5]. Short life times require online production. Low-energy fusion-evaporation reactions can be used to produce Ra nuclei in the mass region A<215. These isotopes

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live long enough to be used in these studies. In particular A = 213 which has the ground state spin $\frac{1}{2}$ is of interest. For better understanding the details of the atomic spectroscopy of Ra, the study of an isotopic chain of Ra is relevant. The isotopes considered here are all $\alpha$ emitters: $^{212}$Ra ($E_{\alpha} = 6.9$ MeV), $^{213}$Ra ($E_{\alpha} = 6.623$ MeV, $6.713$ MeV), and $^{214}$Ra ($E_{\alpha} = 7.137$ MeV).

There are two fundamental approaches with which one can produce different radioactive isotopes namely ISOL [6] and in-flight separation [7]. Here we use a combination of both. In this work Ra isotopes have been produced via low-energy fusion-evaporation reactions in inverse kinematic mode, thus using in-flight separation. The secondary beam is focused into a thermal ionizer and converted to a singly charged low energy ion beam, thus exploiting also ISOL techniques. The low energy is necessary to trap the ions. The advantage of this combined technique is the negligible activation of the thermal ionizer (TI). Different alkali and alkali-earth radioactive isotopes can be produced effectively using appropriate reactions such as fusion, fragmentation or direct reactions using the same TI, i.e. decoupling the production and thermalization process.

2. Radium Production

The TRIP dual magnetic separator [8] consists of two dipole sections. The first is used to separate the products from the primary beam, whereas the second can provide further separation of reaction products and refocuses isotopes of interest at the final focal plane. Inverse kinematics helps to produce secondary beams that match the angular and momentum acceptance of the separator. Secondary beams at the exit of the separator have a wide energy distribution and their energy is too high to use directly. Therefore, thermalization is required as mentioned before.

For Ra production, a $^{206}$Pb beam of 8 MeV/u from the AGOR cyclotron bombarded a diamond-like-carbon (DLC) target [9] of 4 mg/cm$^2$ thickness. The projectile-target combination of Pb and C is chosen as it has a lower fission cross section compared to less asymmetric reactions. The isotope $^{206}$Pb has been chosen to maximize the cross section of $^{213}$Ra, while the target thickness assures that the excitation function for $^{213}$Ra production is fully used.

The charge state distribution of the $^{206}$Pb beam after passing the target was determined by measuring the beam current after the first dipole section by varying the magnetic settings. In case of a thick diamond target,
the beam charge states were not resolved. In order to better understand the charge state distribution a thin Al target of 270 µg/cm² was used. Nine beam charge states were observed as shown in Fig. 1. On the basis of these data and assuming that Ra has the same charge state distribution, we concluded that we can accept 36% of the charge state distribution with the momentum acceptance of 3% of the current configuration of the TRIμP magnetic separator [10].

Figure 1: Charge state distribution of the primary beam at intermediate focal plane after passing through a thick (dotted line) and a thin (Black bars) target. The dash line corresponds to the momentum distribution of radium products.

At the exit of separator Ra production was confirmed by stopping the products of interest and the primary beam in a 80 µm thick Al catcher foil which was mounted in front of a silicon detector. Detector and foil were at an angle of 45° allowing the α particles from the decay of Ra to be detected, while stopping the primary beam. The magnet settings were later optimized as described below.

The thermal ionizer (TI) [11] consists of a stack of thin tungsten (W) foils of 1 µm thickness placed in a W cavity. The maximal W foil thickness of the cavity was estimated with the program SRIM [12]. By heating the cavity to about T≈2500 K the isotopes diffuse out of the foils and get ionized in collisions with the cavity walls. Extraction is done by applying a negative electric potential on the extraction electrodes of 6 to 10 kV. Ra isotopes released from the TI were stopped on a thin 1.8 µm thick Al foil in front of a silicon detector. The detector was calibrated with a composite α source
(\(^{239}\text{Pu},^{241}\text{Am}\) and \(^{244}\text{Cm}\)). Only the \(\alpha\) particles from the decay of Ra and its daughter nuclei were observed. Fig. 2 shows a typical \(\alpha\)-energy spectrum. \(^{213}\text{Ra}\) has two peaks with energies of 6.623 MeV and 6.713 MeV. These two peaks are not resolved due to the straggling in the Al foil in front of the silicon detector. Also for \(^{212}\text{Ra}\) an isolated peak is not seen.

![Figure 2: Typical \(\alpha\)-energy spectrum observed after implanting Ra isotopes in a 1.8 \(\mu\)m Al foil in front of silicon detector.](image)

The separator magnet settings were optimized for Ra. The optimized setting for \(^{213}\text{Ra}\) was 8\% lower than the setting for the primary beam and therefore the Ra was not fully separated from the primary beam due to the presence of some charge state of beam at this settings (see Fig. 1). The distribution of Ra is broader because the various isotopes are produced with somewhat different average momenta. We note that the Pb beam after passing the DLC target has lost sufficient energy to minimize possible reactions in the W cavity.

In order to extract the production rate and the half life of the produced isotopes the TI output was studied in two different modes. In the first mode the extraction was continuously on and the primary beam was chopped in a cycle with 500 s beam on and 500 s beam off. In the second mode the primary beam was continuously on and the extraction voltage of the TI was cycled with the same period. The chopping time of 500 s was chosen to exceed the lifetimes of the Ra isotopes. In the extraction on/off mode the build-up and decay of the activity on the Al foil depends only on the
lifetime of the extracted isotopes. In the primary beam on/off mode the apparent lifetime of the produced isotopes at the measuring site is influenced by the time the particle spends inside the TI. Therefore, in case of the beam on/off mode the output is delayed as compared to the extraction on/off mode. Measurements with beam on/off and extraction on/off mode were carried out at temperatures 2290 K, 2400 K, 2430 K, 2480 K, and 2520 K, as measured with a pyrometer. Fig. 3a and 3b shows the output of both modes at the lowest and highest temperature, respectively. At low temperatures, the output of the TI for beam on/off mode is delayed compared to that of the extraction on/off mode, whereas the outputs were nearly identical at higher temperature. We will use this temperature dependent information to characterize the TI in more detail. This will be reported elsewhere [13]. The present result shows that the TI releases the Ra isotopes very fast at the highest temperature.

Figure 3: Activity measured after the thermal ionizer for cyclotron beam switching (solid triangle) and TI extraction switching (open circle) at $T = 2290$ K (a) and $T = 2520$ K (b). The dips in the latter are associated with sudden drops in the beam intensity.
3. Data analysis

The half life of the produced isotopes and their production rate was extracted by fitting the activity curve obtained from beam on/off and extraction on/off mode. The instantaneous dead time was measured by comparing the event rate in a scaler and the number of actual events processed by the data acquisition. The dead time was 30% to 40%. To extract the life time and the production rate of $^{214}$Ra a gate was put on the $\alpha$ energy corresponding to $^{214}$Ra (Fig. 2). Fig. 4a shows the extracted build-up and decay activity curve for this gating condition. The activity curve was fitted by assuming a single characteristic life time (Fig. 4a). Similarly the activity curves for $^{213}$Ra and $^{212}$Ra were extracted by gating on their respective $\alpha$ energies (shown in Fig. 4b and 4c). In case of $^{213}$Ra and $^{212}$Ra, the activity curve could not be fitted by a single characteristic life time because the $\alpha$-peaks of both isotopes were not resolved. Therefore the activity curve was fitted by considering two characteristic life times. The extracted characteristic lifetimes in both modes (beam on/off and extraction on/off mode) are tabulated in Table 1 and compared with the literature values. Table 1 shows that there

| Isotope | Characteristic half lifes [s] Extraction on/off mode | Characteristic half lifes [s] Beam on/off mode | Literature Value |
|---------|-----------------------------------------------------|---------------------------------------------|------------------|
| $^{214}$Ra | 2.42±0.14 | 3.48±0.12 | 2.46 ±0.03 [14] |
| $^{213}$Ra | 162±1.7 | 168±2.5 | 164.4±3.6 [15] |
| $^{212}$Ra | 12.5±1.0 | 15.8±1.0 | 13.0±0.2 [16] |
is a small difference in the characteristic life time between the two modes. This is consistent with our earlier conclusion that the TI releases the isotopes very fast, so that also the short-lived Ra isotopes can be extracted effectively. The characteristic life time from the extraction-on/off-mode activity curve (which depends exclusively on the life time of the isotopes) agrees with the literature value. In the present work the life time of $^{213}$Ra is more accurate as compared to the literature values. $^{213}$Ra and $^{214}$Ra, which are our particular interest, are produced respectively at a rate of $650 \text{ s}^{-1}$ and $200 \text{ s}^{-1}$ per particle nA of primary beam at the exit of the TI.
4. Conclusion and outlook

In conclusion, $^{212,213,214}$Ra have been produced via low-energy fusion-evaporation reactions in inverse kinematics by bombarding a diamond target with a $^{206}$Pb beam of 8 MeV/u. Identification of different Ra isotopes has been done from the observed $\alpha$ spectrum and from the characteristic life time of the isotopes. Our technique involves a hybrid of in-flight production and ISOL methods and allows a flexible approach to the production of alkali and alkali-earth elements. Most actinides have a ionization potentials not much larger than Ra. Therefore, the production method used for Ra can be exploited for other actinides as well. For completeness we also note that we transported the produced isotopes successfully through a RFQ cooler and buncher [1]. The current yields are more than sufficient to start our experimental program concerning parity violation and EDM searches. Production is limited by the maximum beam intensity that can be extracted from the AGOR cyclotron. A rotating target is currently being designed to be used with higher beam intensities.

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