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FIRST EXPERIMENT AT TASCA TOWARDS X-RAY FINGERPRINTING OF ELEMENT 115 DECAY CHAINS*

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To identify the atomic number of superheavy nuclei produced in ^{48}Ca-induced fusion-evaporation reactions, an experiment aiming at measuring characteristic X-rays is being prepared at GSI, Darmstadt, Germany. The gas-filled separator TASCA will be employed, sending the residues towards the multi-coincidence detector setup TASISpec. Two ion-optical modes relying on differing magnetic polarities of the quadrupole magnets can be used at TASCA. New simulations and experimental tests of transmission and background suppression for these two focusing modes into TASISpec are presented.

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1. Introduction

During the last decade, discoveries of several new superheavy elements (SHE) have been claimed based on ^{48}Ca-induced fusion-evaporation reactions [1,2]. These SHE decay by α emission, but the decay chains terminate in spontaneous fission before reaching the well-established part of the nuclear chart. The natural interpretation of the experiments implies the production of the new elements $Z = 113$ to $Z = 118$, but their atomic numbers have not yet been directly measured.

An appealing method to determine atomic numbers of SHE is to measure the energies of characteristic X-rays following internal conversions in the α-decay chains [3]. The likelihood of creating excited nuclei that can undergo internal conversion is generally higher for odd-A and odd–odd isotopes. However, the difficulty in making reliable nuclear structure predictions for odd–odd nuclei make odd-A nuclei a much safer choice. The isotope ^{287}115, which gives rise to long α-decay chains that are anticipated to contain several highly converted γ transitions, is considered to have production cross sections of a few pb [1]. This allows for reasonable production rates of a few atoms per week at current facilities.

The nuclei of interest are produced as evaporation residues and recoil out of a thin target. In order to separate these from nucleon transfer reaction products and from primary beam, the TASCA gas-filled separator [4] is employed. A magnetic dipole field is applied to accept only particles with a certain magnetic rigidity into the subsequent part of TASCA, which contains two magnetic quadrupoles that focus the particles to a detector setup. Depending on the polarities of the quadrupoles, two different ion-optical modes can be used. The Small Image Mode (SIM) has a transmission of $\sim$ 35–40% and a beam spot of $\sim$ 3 cm in diameter in the focal plane of TASCA for ^{48}Ca-induced reactions. The High Transmission Mode (HTM) has a transmission of $\sim$ 60% and an image size of about 12 cm×4 cm.

Various detectors, tailored for specific experimental requirements, can be used in TASCA. Here, the multi-coincidence detector setup TASISpec (TASCA in Small Image Mode Spectroscopy) [5] will be used, in which nuclei are implanted into a 5.9 cm × 5.9 cm double-sided silicon strip detector (DSSSD). Subsequent decay radiation is recorded in this, in surrounding DSSSDs, and in composite Ge detectors. The detection efficiency for K-X-rays expected in the decay chain of ^{287}115 is $\sim$ 44%, when they are emitted from residues implanted in the TASISpec DSSSD.

Previously, TASCA in SIM was considered the prime option for TASISpec. However, due to the prospect of strongly increased background suppression in HTM by inserting slits (*cf.* Fig. 1) inside TASCA, the combination TASISpec/HTM has been studied in terms of background and transmission optimization, and compared to TASISpec/SIM.

Previous experience shows that if the transmission in a certain TASCA mode to a given detector setup has been optimized for particles of a certain magnetic rigidity, optimal transmission will be maintained for particles of other magnetic rigidities if the same ratios between dipole and quadrupole strengths are used, and other TASCA parameters are unchanged. Hence, in principle, the magnet settings to use for any TASISpec/HTM experiment can be derived once the optimal ratios have been determined. Such ratios, as well as background considerations, have been investigated using the reaction ^{208}Pb(^{48}Ca,$2n$)^{254}No and a Monte Carlo based simulation code.

2. Simulations

Ion transport through TASCA for the chosen test reaction was simulated in order to facilitate the procedure of establishing the optimal TASISpec/ HTM settings. Actual values for beam energy, target thickness and composition, and TASCA gas pressure (*cf.* Sec. 3), were used in order to simulate the production and transport of ^{254}No evaporation residues.

Simulations have been performed using the code described in Ref. [6], adopted for the TASCA geometry [7]. The procedure consists of three steps. The first is the generation of fusion–evaporation residues in the target. Beam particles with a certain spread in energy and angle (*cf.* Ref. [8]) are propagated through the target backing and the target layer. An energy is randomly chosen from the interaction cross section distribution, and, if the beam particle has this energy at any point within the target, a compound nucleus is initiated in the program. The energy and angle of this nucleus is calculated using ordinary kinematics, and then modified for isotropic evaporation of a number of 2-MeV neutrons. The second part of the simulation uses SRIM 2008 [9] to propagate the ions to the end of the target layer, and the third part uses the energy and momentum vector calculated by SRIM to propagate the ions through TASCA. Here, their movement in the magnetic fields of TASCA, scattering of ions in the dilute gas, the energy loss while traversing the gas, and the electron exchange with the surrounding atoms are taken into account. The latter equilibrates the charge state of the ion to an average charge state that depends on the atomic properties of the particle and the gas, as well as on the gas density [10].

Simulated trajectories of ^{254}No in TASCA in HTM are shown in Fig. 1. The dipole is oriented such that particles with different magnetic rigidities are separated in the horizontal plane, directing most of the transfer products and primary beam to a beam dump. Via the quadrupole magnets Q_1 and Q_2 and two detector chambers, product ions reach TASISpec, which is mounted behind the last chamber to ensure a geometry where Ge detectors can be packed tightly around it. The particles enter TASISpec through a tube with

an inner diameter of 6.6 cm and a length of 13 cm. Hence, a correct focusing is crucial to maximize the transmission. The simulations suggested a span of quadrupole settings giving almost the same transmission, and one of these was chosen as a starting point for the experiment.
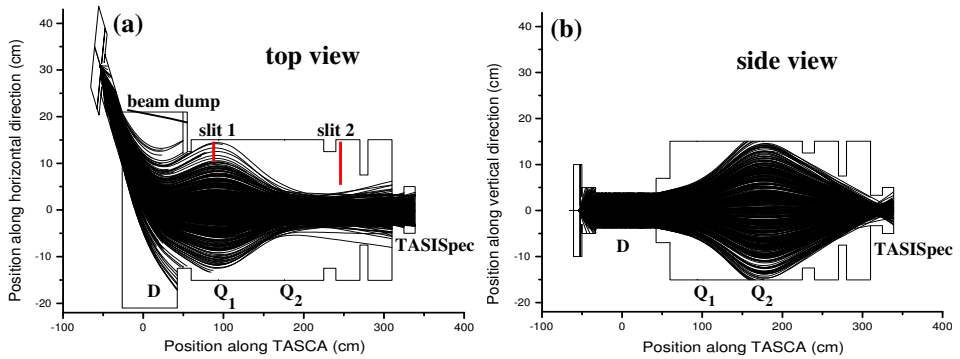

Fig. 1. Sketched top (a) and side (b) view of TASCA, and the simulated trajectories of element ^{254}No for optimized settings for TASISpec in HTM.

3. Experiment

A ^{48}Ca^{10+} beam at an energy of $4.59\,\mathrm{MeV}/u$, pulsed with a duty factor of 25% and a repetition frequency of 50 Hz, was used. The target wheel consisted of four ^{208}PbS foils with thicknesses of ~ 0.76 mg/cm^2. The PbS was deposited on $\sim 40\,\mu$g/cm^2 C backing foils. On top, thin ($\sim 10\,\mu$g/cm^2) layers of carbon were added to decrease sputtering losses during irradiation. The gas pressure in TASCA was 0.3 mbar He during measurements in SIM, and 0.8 mbar He during measurements in HTM. The dipole was set to guide ions with magnetic rigidities of ~ 2.1 Tm to the focal plane. The implantation DSSSD of TASISpec comprises 32 strips on the p-side, facing the incoming beam, and 32 n-side strips [5]. The detector was calibrated using an external 4-line α source. Signals from this detector were processed in preamplifiers, shaping amplifiers, and digitized in VME TDCs and ADCs. Data was analyzed offline using the software GO4 [11]. Note that the TASISpec setup did not include any veto detector for impinging ions like, for example, a multi-wire proportional counter.

During the first part of the experiment, the previously determined optimized settings for TASISpec/SIM were confirmed. Then, in order to study the background reduction in HTM, a series of measurements was performed with one or two slits inserted in TASCA (see Fig. 1). In the following, the HTM quadrupole field strengths were varied to determine the best settings for focusing evaporation residues into TASISpec/HTM.

4. Results

The relative transmission of fusion–evaporation products was derived from the number of events between 8.05 MeV and 8.15 MeV, recorded by p-side strips of the implantation DSSSD during the periods when no beam was impinging on the target, normalized with the beam integral. Figure 2 shows in black the summed energy spectra from a measurement done with optimized SIM settings ($D = 610$ A, *i.e.* $B\rho = 2.12$ Tm, $Q_1 = 395$ A, $Q_2 = 480$ A). The period when no beam is present yields the anticipated very clean spectrum in Fig. 2 (a). The number of events in the α peak from ^{254}No (8.10 MeV) can be accurately determined. Other peaks seen in the spectra originate from α decays of daughter nuclei of ^{254}No, *i.e.* ^{250}Fm and ^{246}Cf, and from the contaminating transfer products ^{211}Bi and ^{211}Po.
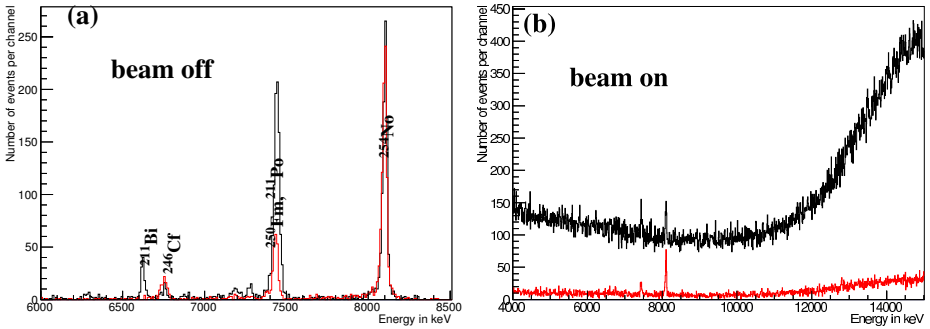

Fig. 2. Summed energy spectra from all p-side strips of the TASISpec implantation DSSSD, accumulated during the measurements at optimal settings in SIM (black) and HTM (grey/red). Panel (a) shows energy spectra recorded during beam-off periods while panel (b) shows data taken within the beam pulse. The data is normalized to the number of events in the α peak from ^{254}No during beam-off periods.

Considering shape and size of the actual beam spot emerging after the first measurements with TASISpec/HTM, the optimal setting was identified ($D = 603$ A, *i.e.* $B\rho = 2.10$ Tm, $Q_1 = 525$ A, $Q_2 = 510$ A). Several magnet strengths around these values were tested, but none of them increased the transmission further. In fact, the experimentally optimized values were within the span suggested by the simulations. An energy spectrum accumulated while using the best TASISpec/HTM setting is shown in Fig. 2 in grey (red). The transmission to TASISpec for this setting is $\sim 80\%$ of the transmission achieved using SIM, *i.e.* some 30% absolute transmission. The experimental and simulated beam spots of evaporation residues in the implantation DSSSD are shown in Fig. 3. The beam spot is elongated in the horizontal direction, and the main part of the particles that do not reach the detectors are lost on the right- and left-hand side of the TASISpec entrance tube.
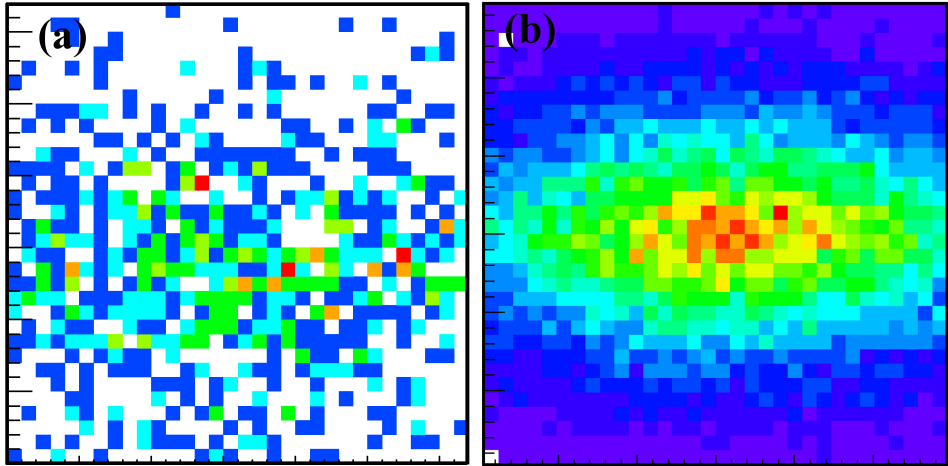
Fig. 3. Experimental (a) and simulated (b) distribution of evaporation residues in the TASISpec implantation DSSSD. The experimental beam spot relates to α decays of ^{254}No by requiring energies between 8.05 MeV and 8.15 MeV on the p-side, and energies between 1.00 MeV and 8.15 MeV on the n-side.

The background in HTM could be reduced considerably with two slits in place. The effect can be seen in Fig. 2: In the HTM beam-off spectrum, the peaks from the transfer products ^{211}Bi and ^{211}Po are not visible anymore. In the beam-on spectrum, the background from unwanted ions being implanted in the detector is strongly suppressed compared to the SIM spectrum, illustrating the effect even more dramatically.

5. Summary

The experiment has shown that the background in the focal plane of TASCA is considerably reduced in HTM by inserting two slits in TASCA, and that the transmission to TASISpec in HTM can be as high as 80% of that in SIM. In the case of TASISpec/SIM, the high background rate prevents the use of the beam-on periods for spectroscopy purposes. On the contrary, our results show an excellent background suppression in HTM and indicate that it will be possible to access data from the beam-on periods as well. As this data accounts for $\sim 25\%$ of the events, due to the duty cycle of the beam, the total amount of useful data can actually be higher in HTM than in SIM. The use of beam-on periods also allows for improved spectroscopy of short-lived isotopes and isomeric states.

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