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First direct mass measurements of stored neutron-rich ^{129,130,131}Cd isotopes with FRS-ESR

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ABSTRACT

A 410 MeV/u ^{238}U projectile beam was used to create cadmium isotopes via abrasion-fission in a beryllium target placed at the entrance of the in-flight separator FRS at GSI. The fission fragments were separated by the FRS and injected into the isochronous storage ring ESR for mass measurements. Isochronous Mass Spectrometry (IMS) was performed under two different experimental conditions, with and without Bρ-tagging at the high-resolution central focal plane of the FRS. In the experiment with Bρ-tagging the magnetic rigidity of the injected fragments was determined with an accuracy of $2 \cdot 10^{-4}$. A new method of data analysis, which uses a correlation matrix for the combined data set from both experiments, has provided experimental mass values of 25 rare isotopes for the first time. The high sensitivity and selectivity of the method have given access to nuclides detected with a rate of a few atoms per week. In this letter we present for the ^{129,130,131}Cd isotopes mass values directly measured for the first time. The experimental mass values of cadmium as well as for tellurium and tin isotopes show a pronounced shell effect towards and at $N = 82$. Shell quenching cannot be deduced from a single new mass value, nor by a better agreement with a theoretical model which explicitly takes into account a quenching feature. This is in agreement with the conclusion from γ-ray spectroscopy and confirms modern shell-model calculations.

1. Introduction

Accurate mass measurements over a range of isotopes reflect details of the evolution of nuclear structure and stability as well as the energy levels and spatial distributions of the bound nucleons [1]. A first microscopic explanation of the observed shell structure and the corresponding magic numbers [2,3] of neutrons and protons, at which the nuclei have larger binding energies, provided the basic understanding of nuclear properties. More recently, the advent and application of radioactive nuclear beam facilities [4] and novel mass spectrometers [5] have enlarged the number of known isotopes with unusual proton-to-neutron ratios and thus revealed novel nuclear properties at the outskirts of the chart of nuclides. Soon it became evident that the nuclear shell structure

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can change towards the driplines. Shell-gap quenching, complete shell disappearance, or even new magic numbers have been theoretically predicted [6,7] and observed in experiments [8–12].

The best known examples, both theoretically and experimentally, are the $N = 20$ and $N = 28$ "islands of inversion" [11–16] where the gain in correlation energy driven by quadrupole deformation is able to overcome the normal level ordering deduced from the standard spherical mean field. As a result the traditional $N = 20$ and $N = 28$ shell closures disappear. It has also been argued that such a shell quenching would occur for neutron-rich $N = 82$ nuclei. This phenomenon was originally suggested in reference [6], based on Skyrme–Hartree–Fock–Bogoliubov calculations.

Furthermore, nuclear structure properties can strongly influence the synthesis of elements in stars. In this context, it was realized that the occurrence of a discrepant abundance trough in r-process calculations [17] could be cured by using a mass model with a quenched shell gap far from stability [18–20]. The abundance trough around $A \sim 115$ is associated with a 'saddle point behavior' seen in the two-neutron separation energies for $Z \approx 40$ and $N = 75$–82 in several mass models related to a transition from deformed nuclei around $N \sim 75$ to spherical nuclei at $N = 82$ [21]. In mass models with a quenched shell-gap such as the modified extended Thomas–Fermi model (ETFSI-Q) [19] the deformation is greatly reduced and consequently the 'saddle point behavior' in the two-neutron separation energies disappears. However, it should be pointed out that the 'saddle point behavior' and the quenching of the shell gap are not necessarily related [21], because the first one could also be associated with instabilities of mean-field models in regions of shape coexistence, requiring the inclusion of additional correlations [22].

There have been many experimental attempts to provide evidence for the quenching of the shell gap at and near $N = 82$, but most of the information on the shell evolution has been indirect. The present Isochronous Mass Spectrometry (IMS) of the ^{129,130,131}Cd isotopes and the previous Penning trap mass measurements for the tin [23] and tellurium [24] isotopes yield direct information on the shell effects.

2. Experiment and data analysis

Neutron-rich fission fragments created via abrasion-fission were separated in flight for mass measurements. A 410 MeV/u ^{238}U projectile beam was extracted from the synchrotron SIS-18 [25] with an average intensity of $1 \cdot 10^9$/spill and impinged on a 1032 mg/cm^2 beryllium target at the entrance of the fragment separator FRS [26]. The fragments were spatially separated in flight with the FRS by the application of pure magnetic rigidity (Bρ) separation with the standard ion-optical operation mode. The separation mode, without degraders, was enabled by the large mean velocity difference of the projectile fragments and fission products and the restricted angular acceptance of the FRS. Practically this means a suitable $B\rho$-selection with the FRS provided fission-fragment beams without significant contributions of projectile fragments. The ions of interest were injected into the Experimental Storage Ring ESR [27] for mass measurements [28]. The mean velocity of the stored fragments corresponded to the "transition energy" of $\gamma_t = 1.41$. The magnetic fields of the FRS and ESR were set for ^{133,135,136}Sn ions in different runs, i.e., these isotopes were centred at the optical axis.

The ESR was operated in the isochronous mode [29,30] without application of any cooling. This means that the velocity spread of the fragments was determined by the Bρ acceptance of the ion-optical system. In a previous publication [31] we have demonstrated that for IMS experiments, in addition to the revolution time of the stored ions, a magnetic rigidity or velocity measurement is required, because the isochronicity is strictly realized only for a single mass-over-charge (m/q) value.

In principle, this additional measurement is not required for Schottky Mass Spectrometry (SMS) because the relative velocity spread of the different, stored and cooled, ions can be as low as 10^{-7}. Nevertheless, our refined SMS analysis has revealed that an additional influence of the cooler section on the mean velocity causes an observed correlation [32] which has to be taken into account for the final results.

The method of IMS including Bρ-tagging can be illustrated by the simple first-order formula

$$\frac{d(m/q)}{m/q} = \gamma^2 \frac{dT}{T} + \left(1 - \frac{\gamma^2}{{\gamma_t}^2}\right) \frac{d(B\rho)}{B\rho}, \tag{1}$$

where T, γ_t, and γ are the revolution time, the transition energy, and the relativistic Lorentz factor, respectively.

Additional velocity (v) and magnetic-rigidity measurements in FRS-ESR IMS experiments require special methods due to the operation with fast extracted ion bunches characterized by a width of (0.2–0.5) µs. Particle detectors inside the FRS would have severe problems to identify event-by-event the fragments and accurately measure v and $B\rho$. A Bρ-resolution of 10^{-4} or better is required to achieve a mass resolution of about 200 keV for m/q close to ideal isochronicity [33]. In this context, one has to take into account that the FRS transmission is $d(B\rho)/(B\rho) = 2\%$ and the corresponding ESR injection acceptance is more than one order of magnitude less. Therefore, mechanical slits with an opening of ± 0.5 mm placed at the central dispersive focal plane of the FRS were used in a pilot IMS experiment [31,34]. The slits defined in this way the magnetic rigidity (Bρ-tagging) of each injected ion with an accuracy of $2 \cdot 10^{-4}$. Note, that the operation of the new isochronous Rare RI-Ring at RIKEN [35] can implement additional Bρ and v measurements event-by-event, because of the effectively DC beam from the cyclotron accelerator. In the present experiments IMS measurements were performed with and without Bρ-tagging for the same settings of the magnetic fields of the FRS and ESR. The revolution time of the circulating ions in the ring was measured with a time-of-flight (ToF) detector equipped with a thin carbon foil coated with caesium-iodide and two microchannel-plate (MCP) branches [36] placed in a homogeneous magnetic dipole field of about 8.4 mT. The secondary electrons created in the foil were isochronously deflected onto the MCPs to generate timing signals at each turn. The signals were recorded with commercial digital oscilloscopes (Tektronix TDS 6154C, 40 GS/s, 15 GHz; LeCroy LC584AM, 4 GS/s, 1 GHz).

The data sets of the two different experiments, with and without Bρ-tagging, were combined and analysed with a modified correlation-matrix method [37,38]. The separate results of the run with the full Bρ acceptance of the ESR were considered to be unreliable over a large m/q range, see reference [31]. Therefore, we have published up to now only the mass values from the experiment with Bρ-tagging, e.g. [34,39]. The mass range covered in both experiments was almost the same. However, the spectra without Bρ-tagging had much better statistics but were characterized by a factor of more than two larger widths and therefore had much lower resolving power. These aspects and a first comparison of the time spectra have been presented in reference [31]. In the experiment with Bρ-tagging we achieved a mass resolving power of up to 250,000. Without Bρ-tagging the time resolution of the spectra became much worse, especially for m/q values in non-isochronous regions where even non-physical double-peak structures were observed. The much higher mass resolving power in the experiment with Bρ-tagging enabled in this case the proper identification. The combination of both experiments analysed with the modified matrix method yields reliable results even for nuclides with poor