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Isochronous Mass Measurements of Hot Exotic Nuclei

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Abstract. A novel method for mass measurements of short-lived exotic nuclides is presented. Exotic nuclides were produced and separated in flight at relativistic energies with the fragment separator (FRS) and were injected into the experimental storage ring (ESR). Operating the ESR in the isochronous mode we performed mass measurements of neutron deficient fragments of ^{84}Kr with half-lives larger than 50 ms. However, this experimental technique is applicable in a half-life range down to a few μs. A mass resolving power of 110000 (FWHM) has been achieved. Results are presented for the masses of ^{68}As, ^{70,71}Se and ^{73}Br.

Key words: mass measurements, ^{68}As, ^{70}Se, ^{71}Se, ^{73}Br, exotic nuclei, storage rings.

1. Introduction

The atomic masses are known for most of the stable and long-lived isotopes, but new experimental data are needed for nuclides far off stability. Small production cross sections and short half-lives of these exotic nuclides are the reasons why conventional techniques for mass measurements cannot access them. In this paper we present a method that has been developed for mass measurements of rare and short-lived exotic nuclear species. This technique is complementary to Schottky Mass Spectrometry of cooled exotic nuclei [1, 2], which is used at the Experimental Storage Ring (ESR) [3] for mass measurements of longer-lived exotic nuclides.

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2. Experimental method of isochronous mass measurements

The GSI fragment separator (FRS) [4] allows to produce exotic nuclides via fragmentation and fission of relativistic projectiles in thick targets of a few g/cm^2. The relativistic fragments are spatially separated in-flight and are stored in the ESR. The differential relation between the revolution time t, the mass-to-charge ratio m/q, and the velocity v of stored particles in a ring is given to first order by

$$\frac{\mathrm{d}t}{t} = \gamma_t^{-2} \cdot \frac{\mathrm{d}(m/q)}{m/q} + \left(\frac{\gamma^2}{\gamma_t^2} - 1\right)\frac{\mathrm{d}v}{v}, \tag{1}$$

where γ denotes the relativistic Lorentz factor of the circulating ions. γ_t is a parameter of the ion-optical setting of the ring. The ESR is operated in the isochronous mode [5, 6] and the velocity of the injected particles is chosen such, that the isochronicity condition $\gamma = \gamma_t$ is fulfilled. Thus, the revolution time for ions of the same species is to first order independent of the particle velocity (see Equation (1)). The distribution of the revolution times for particles of one species is narrow regardless to their momentum spread (typically $\pm 1\%$ for exotic nuclides [4]) at the exit of the FRS. The dependence of the particle revolution time on the mass-to-charge ratio m/q remains (see Equation (1)). Thus, the isochronicity results in a separation of different ion species in revolution time. This separation is achieved already one turn after injection.

In order to use this separation for mass measurements on short-lived nuclides a fast revolution-time measurement is required. A dedicated detector system allows to measure the revolution time for single stored particles within a few turns ($\approx$ 530 ns each) of the ions in the ESR. The circulating relativistic ions penetrate a thin carbon foil (coated with CsI) at each turn and release secondary electrons from both sides of the foil. Using perpendicular electrostatic and magnetic fields these electrons are guided isochronously [7] to multi-channel plates in two detector branches (MCP1 and MCP2), see Figure 1. Here, the electrons generate short signals (see Figure 2) which have time uncertainties of a few ten picoseconds. The foil is only a few tens of μg/cm^2 thick and allows the relativistic ions to circulate in the ring for several thousand turns. Thus, each stored ion generates a sequence of time signals, that can contain up to a few hundred. The particle revolution time is extracted from the time differences between the signals within such a sequence.

The revolution times of different nuclides reflect their respective mass-to-charge ratios. Since particles of different species are stored in the same ESR setting simultaneously, one can directly determine the mass-to-charge ratio of one species by comparing its revolution time to that of other nuclides with known mass values.

Either a pure magnetic rigidity analysis or a two stage magnetic separation in combination with a degrader system ($B\rho$–ΔE–$B\rho$ method) are applied at the FRS [4] in order to optimize the number of interesting stored particles without exceeding the count-rate limitation of the detector system.

The measurement requires a time of only a few tens of μs. Therefore, this method gives access in particular to the masses of short-lived nuclides.

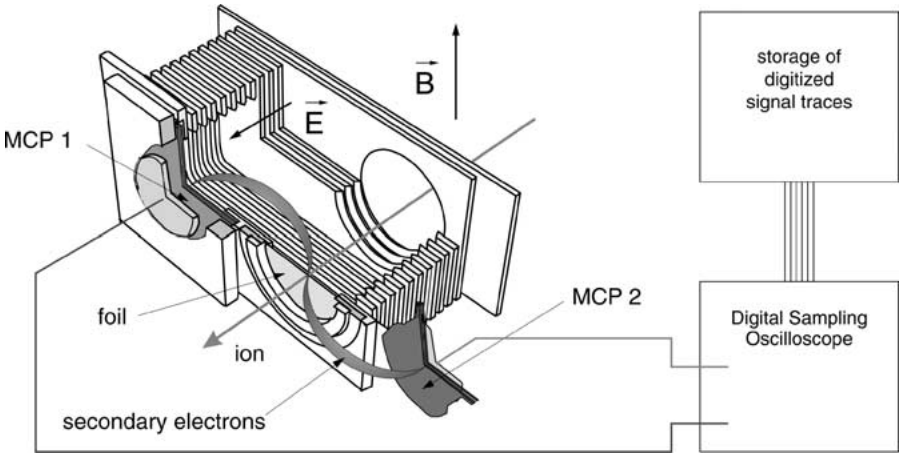

Figure 1. Schematic view of the detector used for mass measurements of hot exotic nuclei [7]. Secondary electrons are released from the foil and are guided to MCP detectors by perpendicular electric ($\vec{E}$) and magnetic ($\vec{B}$) fields. The magnetic field is generated by an external magnet. The MCP2 branch of the detector is shown only in a very schematic way. The signals of both branches are sampled by a digital sampling oscilloscope and the digital information are stored.

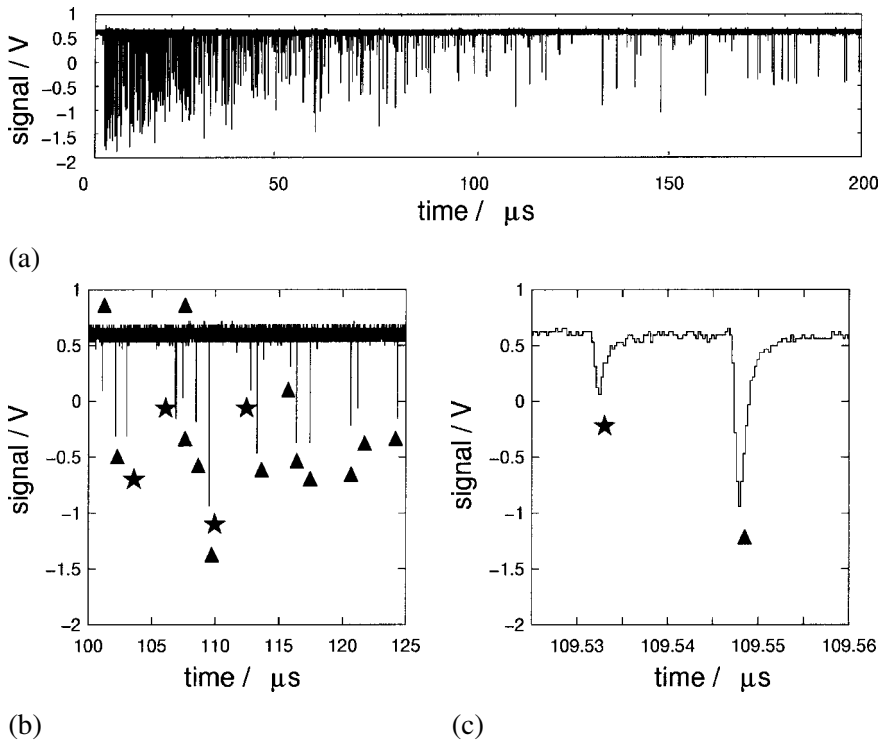

Figure 2. Trace of the signals from one detector branch. (a) Complete trace; (b) part of this trace with signals of two particles (marked as ▲ and ★). (c) Two individual signals of these two particles expanded.

3. Mass measurements of krypton fragments

In this experiment an ^{84}Kr primary beam with an incident energy of 445.3 $A \cdot$ MeV was focused on a 2.5 g/cm^2 beryllium target placed at the entrance of the FRS. The FRS and the ESR were set to the magnetic rigidity of fully ionized ^{53}Fe with an energy of 344.66 $A \cdot$ MeV, the energy required for isochronicity. All measurements were performed on fully ionized fragments in order to minimize the losses due to charge changing interactions mainly with the detector foil. Furthermore this is the dominant charge state of krypton fragments in this energy regime. A magnetic rigidity analysis was applied in the FRS and different projectile fragments with the same magnetic rigidity were injected and stored in the ESR simultaneously. Here the circulating ions generated signals which were sampled by means of a digital sampling oscilloscope at a sampling rate of typically 4 GS/s (both detector branches). Triggered at the injection time, transients of 200 μs length in time were recorded, which corresponds to about 400 turns of the particles in the ESR. An example of such a transient is shown in Figure 2. Different sampling rates and recording times were also used, and more than 3000 revolutions in the ESR have been observed.

4. Data analysis and results

Two measurements were performed, which differ slightly (by 10^{-3}) in the setting of the mean magnetic rigidity of the FRS, while the setting of the ESR remained unchanged. These different measurements were analyzed separately.

Altogether about 1500 recorded transients (from one detector branch) were analyzed. In a first step the time information of each signal was determined. Since the signals of the multi-channel plates have a large amplitude spread, the leading edge of each signal was analyzed with a routine that follows the principle of a constant fraction discriminator. The typical time uncertainties amount to a few ten picoseconds.

In a second step these times were assigned to the particles that had generated the corresponding signals. For each particle these times were investigated as a function of the number of turns since injection. To first order one finds a linear dependence with a slope that corresponds to the particle revolution time of about 500–550 ns. We found small deviations from this linearity, originating from the energy loss in the detector foil in combination with slight deviations from the isochronicity [6]. Therefore, fit-polynomials up to third order were used. Particles with second order coefficients larger than 10^{-5} (abs.) were excluded from the mass determination. In order to minimize the influence of the remaining nonlinearities the slope of the fit function at the first detection of the particle was used as particle revolution time.

In the next step the data from various individual measurements were combined to revolution time spectra. These spectra contain resolved peaks at different revolution times corresponding to the mass-to-charge ratios of the respective nuclides. For each peak the mean revolution time was calculated and the corresponding nu-

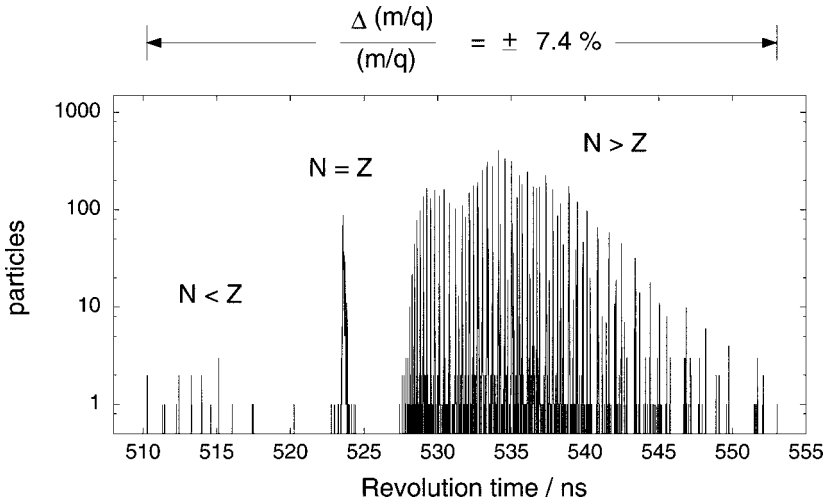

Figure 3. Revolution time spectrum of neutron deficient krypton fragments. The ESR was set to the magnetic rigidity of ^{53}Fe at an energy of 344.66 $A \cdot$ MeV. The nuclides in this spectrum cover a range of $\pm$ 7.4% in mass-to-charge ratio.

clide was assigned using a pattern recognition method. An example of a revolution time spectrum is presented in Figure 3. This spectrum illustrates the large range in mass-to-charge ratio ($\Delta(m/q)/(m/q) = \pm$ 7.4%) that was covered with one setting of the system. About 100 different nuclides were identified in this spectrum. The masses of most of these nuclides are known to high precision [8], exceptions are the nuclides ^{68}As, ^{70,71}Se and ^{73}Br. For ^{68}As and ^{73}Br compiled experimental mass values are available [8], but the uncertainties are $\geqslant$ 100 keV. In the case of the selenium isotopes extrapolations are given in [8] and only few more recent measurements exist, see Table I.

We analyzed our revolution-time spectra in two parts, one contained ^{71}Se and ^{73}Br, while the other one contained ^{68}As and ^{70}Se. For each part eleven nuclides of known mass were chosen and were used to calibrate the relation between the mass-to-charge ratio* and the measured revolution time using a second order polynomial fit. We chose lines in the spectra close to the ones corresponding to the nuclides under investigation for this purpose but excluded such lines, that were (a) too weak (below ten particles typically), or (b) closer than $5 \cdot 10^{-5}$ (relative revolution time difference) to another line, or (c) that had an unusual shape (e.g., significantly broader than all other lines), or (d) that were assigned to nuclides with a known isomeric state. In the case of ^{70}Se and ^{35}Cl an exception from exclusion criterion (b) was made, the lines were clearly separated. The masses of ^{71}Se and ^{73}Br were calibrated to the ones of ^{57}Co, ^{59}Ni, ^{40}K, ^{61}Cu, ^{67}Ge, ^{48}V, ^{25}Mg, ^{50}Cr, ^{27}Al, ^{54}Fe and ^{56}Co in the first measurement and to ^{59}Ni, ^{40}K, ^{61}Cu, ^{65}Ga, ^{67}Ge, ^{48}V, ^{50}Cr, ^{54}Fe, ^{56}Co, ^{58}Ni and ^{60}Cu in the second measurement. For the determination of the

* Obtained from [8] and corrected for the missing electrons using [9].

Table I. Atomic masses measured in this work and compared to other experimental works and the compiled tables of [8]. The mass excess is given in units of keV. Extrapolated values from [8] are marked by #

Nuclide	Mass excess and uncertainty [keV]			
	This work	Compilation [8]	GANIL [10]	Yale [11]
^{68}As	−58890(100)	−58880(100)		
^{70}Se	−62070(70)	−61940(210) #	−62310(460)	−61604(100)
^{71}Se	−63050(70)	−63090(200) #	−63490(320)	−63130(35)
^{73}Br	−63740(90)	−63530(130)		−63606(70)

masses of ^{68}As and ^{70}Se we chose ^{31}P, ^{62}Zn, ^{64}Ga, ^{33}S, ^{66}Ge, ^{35}Cl, ^{39}K, ^{41}Ca, ^{43}Sc, ^{45}Ti and ^{47}V in the first measurement, while in the second one we used ^{56}Co, ^{58}Ni, ^{60}Cu, ^{62}Zn, ^{66}Ge, ^{35}Cl, ^{39}K, ^{41}Ca, ^{43}Sc, ^{45}Ti and ^{47}V. The obtained calibration was used to calculate the mass-to-charge ratio for the nuclides under investigation. The result (mass excess) for the individual measurement was derived from this.

In order to investigate the systematic error, for each reference nuclide except the outermost ones a mass value was calculated by calibration to the other reference nuclides. From the comparison of these values to the literature [8] (by a χ^2 test) a systematic error (≈12–55 keV) was deduced for each measurement and added in quadrature to the uncertainties from the calibration. The final results were derived by averaging the results of the two measurements with different settings of the FRS, these are given in Table I. In addition, we compare our results to the compiled experimental values and extrapolations of [8] as well as to the recent experimental results from time-of-flight measurements [10]⋆ and from β end-point determinations [11]. We achieved a resolving power of $m/\Delta m = 110000$ (FWHM). This result is slightly improved compared to the value reported for this method earlier [12]. The improvement is a result of the increased number of turns observed for a single particle.

5. Outlook

Further mass measurements of shorter-lived krypton fragments have been performed. Here, the cross sections strongly favour the production of undesired contaminants, therefore the $B\rho$–ΔE–$B\rho$ method was used at the FRS [4]. Several nuclides with half-lives far below one second have been identified in the revolution time spectra of these measurements. Six of these short-lived nuclides (^{49}Fe, ^{48}Mn, ^{45}Cr, ^{43,44}V and ^{41}Ti) have unknown masses [8]. The nuclide ^{45}Cr with a half-life of 50 ms is at present the shortest-lived species identified. The nuclide ^{43}V was

⋆ The authors of [10] report separate statistical and systematic uncertainties; these have been added in quadrature in Table I.

observed in the spectra, its mass is of relevance to determine the endpoint of the astrophysical αp process. The data from these measurements are under analysis.

The duration of the individual records (200 μs) shows that the presented method is suitable for mass measurements of nuclides with half-lives down to several μs. In the future we intend to measure the masses of short-lived neutron-rich fission fragments, which are important for the understanding of the astrophysical r-process.

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