PERFORMANCE OF SCHOTTKY MASS SPETROMETRY AT THE ESR

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Abstract

The application of Schottky beam diagnosis [1] for measurements of nuclear masses and life times has been proposed more than 10 years ago as soon as storage and cooling of radioactive beams at the Experimental Storage Ring ESR came into consideration [2]. Meanwhile the novel method proved to be very successful and more than 100 mass values of predominantly proton-rich nuclear fragments of stable Bi, Au and U-projectiles have been determined experimentally, many of them with relative errors in the 10^{-7}-range. So far, the necessary time for electron cooling restricts the application of the Schottky mass spectrometry (SMS) to nuclei with life times in the order of 10 seconds. Operation of the ESR in the isochronous mode, i.e. at the transition energy, might allow to apply SMS also to "hot", uncooled beams of nuclides with life times as short as a few milliseconds.

1 INTRODUCTION

High precision spectrometry for nuclear masses of unstable nuclei had been proposed in 1985 as one of the major objectives of the SIS/ESR-project at GSI. As may be deduced from commonly used mass tables [3], there are still hundreds of nuclides – many of them not far from the valley of stability and with sufficient life times – for which experimental mass values with relative errors of better than 1×10^{-5} would be helpful to improve nuclear models.

For the production of all nuclides of interest the heavy ion accelerators UNILAC and SIS are well suited. At specific energies between 500 MeV/u and 1000 MeV/u secondary beams consisting of many hundred nuclear species are generated by passing primary beams of heavy stable nuclei up to uranium through a thick Al-target of a few g/cm^2 thickness. The nuclear fragments emerge from the target with reduced specific energy and increased momentum spread in all phase planes, but with comparable average velocities. Because of the "kinematic focusing" effect at high production energy the multi-component beam can be transported and analysed very efficiently in the large magnetic system of the fragment separator FRS [4]. Many different nuclides with same magnetic rigidity may be injected to the storage ring ESR, where all components are cooled to the same velocity with extremely small spread. In this state of the multi-component beam the frequency spectrum of the beam noise (Schottky spectrum) consists of well separated lines, and the frequency differences between lines are determined only by the mass-to-charge ratio A/Z between corresponding beam particles. The the novel method of Schottky mass spectrometry (SMS) is based thoroughly on techniques and recent achievements in accelerator and storage ring physics.

2 EXPERIMENTAL SET-UP

2.1 Relevant properties of the ESR

The maximum magnetic bending power of 10 Tm makes the ESR well suited for the injection and storage of heavy nuclei at energies between 300 and 500 MeV/u, where the charge state distribution consists mainly of fully stripped, H-like and He-like ions. At this energy and with an average residual gas pressure of approximately 1×10^{-10} mbar charge changing interactions with residual gas atoms are neglegible compared to radiative recombination in the 2 m long electron cooling section. At 50 mA electron cooler current, which is sufficient to cool low intensity ion beams, beam life times in the order of 1 hour for accordingly long-lived, heavy nuclides are attained – rather comfortable for beam analysis under stable conditions.

The ring optics for SMS is characterised by a large momentum acceptance of $\pm 1\%$, by large dispersion amplitudes of in the bending sections and small dispersion in the electron cooling section. Natural transverse chromaticities are corrected by sextupoles. The homogeneity of the main bending fields is improved by means of pole face windings. On a time scale of seconds – relevant for the SMS – the relative stability of bending field and quadrupole gradients is about $\approx \pm 4 \times 10^{-6}$.

2.2 Beam noise analysis

Probing and analysing of the beam noise (Schottky noise) delivers precise information about beam and ring parameters [1]. The noise is picked up by capacitive probes and amplified by low (thermal) noise amplifiers. The frequency spectrum of the beam noise is observed either directly by means of a spectrum analyzer or – after suitable demodulation and digitising – by a Fast Fourier Transformer (FFT) set [5]. In the spectrum of a stored beam Schottky bands appear at all harmonics n of the mean revolution frequency f_0 of beam particles. The integral power in a Schottky noise band increases $\propto NZ^2$ where N is the number of stored ions and Z their charge state. The signal-to-noise ratio and, hence, the sensivity are increased dramatically compared to a proton beam. At the ESR, even a single fully stripped tungsten ion has been observed over nearly 30 minutes.

In an one-component beam the relative frequency width $\delta f/f$ of each band is determined by the relative longitudinal

momentum spread $\delta p/p$:

$$\frac{\delta f}{f} = \frac{n\delta f}{nf} = \eta\frac{\delta p}{p} = (\frac{1}{\gamma^2} - \alpha_p)\frac{\delta p}{p} \qquad (1)$$

η indicates the mean frequency dispersion function and γ the relativistic Lorentz factor. $\alpha_p = \gamma_t^{-2}$ is the mean momentum compaction, where γ_t is the so-called transition point of the storage ring, a constant determined by ring structure and quadrupole settings. At $\gamma = \gamma_t$ the frequency dispersion vanishes and the Schottky bands degenerate to lines with zero-width. At $\gamma < \gamma_t$ the frequency bands also appear more or less as "lines", if the beam is electron cooled to an extremely small $\delta p/p$ (see below).

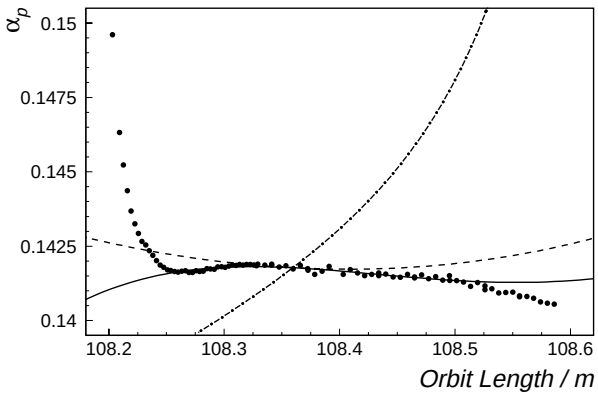

Figure 1: Experimentally determined α_p-values (dots) for the ESR magnet setting used for SMS. Calculated curves for comparison take into account: dipoles including edge effects and quadrupoles (dash-dotted), addition of sextupoles (dashed), inclusion of pseudo-octupoles from quadrupole magnets (solid).

2.3 Momentum compaction

In an electron cooled multi-component beam all components circulate with practically the same velocity. Small velocity differences may be caused by space charge effects in the electron beam, if the dispersion amplitude in the cooling section is $\neq 0$. Differences in the mass-to-charge ratio between an unknown nuclide (A/Z) and a well-known reference nuclide $(A/Z)_{ref}$ lead to different closed orbit circumferences and, therefore, to accordingly different revolution frequencies. Equation (1) is simplified to

$$\frac{\Delta f}{f_{ref}} = -\alpha_p \frac{\Delta(A/Z)}{(A/Z)_{ref}}. \qquad (2)$$

In a ring with constant focusing α_p would be constant over the full momentum acceptance. In the strong focusing lattice of the ESR linear and nonlinear variation of α_p with magnetic stiffness is caused not only by higher order fields – sextupole magnets, octupole contents of focusing quadrupole magnets, and hexapole and decapole contents in the main bending magnets – but also by azimuthal variations of dispersion function amplitudes. Thus, for the magnet settings used for SMS experiments, α_p had to be determined experimentally (see fig. 1).

2.4 Profits from electron cooling

Electron cooling compresses the stored particles N in phase space by many orders of magnitude. Due to the strongly increased power density the Schottky bands appear as "lines" with correspondingly increased amplitudes. If the total number of stored ions drops below, approximately 10^4, intra-beam scattering rates become so small that an "ultimate" $\delta p/p$ is obtained, which is determined by the longitudinal temperature of less than 0.1 meV in the electron beam [6]. The measured relative Schottky line width of $\delta f/f \approx 2.5 \times 10^{-7}$ is mainly due to fluctuations of the magnetic bending fields as mentioned above. Fortunately, at high electron cooler energy of about 200 keV and at low electron beam current below 100 mA, the measured ripple of ± 1 V of the cooler accelerating voltage does not contribute to the widths of Schottky lines.

3 EXPERIMENTAL RESULTS

At first the SMS technique was tested carefully by means of Schottky spectra containing well-known projectile-near fragments produced internally by interaction of circulating stable nuclei (^{163}Dy, ^{238}U, ^{197}Au, and ^{124}Xe) with a supersonic gas jet (nitrogen or argon). A detailed discussion of the achieved accuracy, resolution and reproducibility in Schottky mass spectrometry is given elsewhere [7]. Meanwhile, a few 1000 spectra from externally produced Au, Pb and U fragments have been evaluated [8].

The experience with SMS experiments may be summarised as follows.

- Electron cooled multi-component beams containing a large number of reference nuclides (well-known with respect to their mass) offer optimal conditions for SMS. Regardless of the non-linear variation of α_p with A/Z (at constant velocity of beam particles) the majority of A/Z-differences could be determined with high precision by linear interpolation within small intervals.

- The best results with respect to accuracy and resolution are achieved at extremely low beam intensity, when the total number of stored nuclei within a small A/Z-intervall was below 1000.

- The mass resolution $A/\Delta A$ in SMS is presently limited by the short term stability of the main magnet power supplies to about 1×10^6. Many nuclides in ground state can easily be resolved from their heavier, excited isomers. The high resolution is demostrated also in fig. 2, where a zoomed part of a 100 kHz-spectrum of Au-fragments is displayed and an example for the deter-

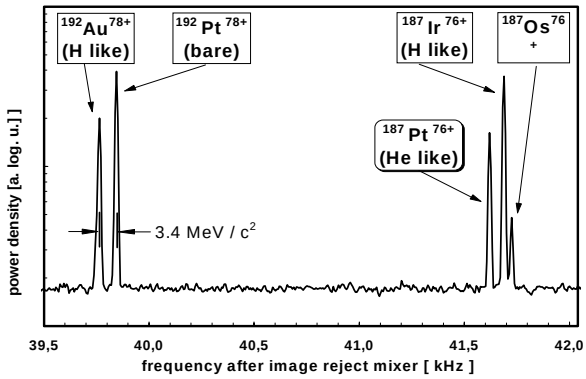

Figure 2: Zoomed part of a Schottky mass spectrum of electron cooled Au-fragments in the ESR. Additional lines are resolved from nearly 60 peaks seen in the original 100 kHz-spectrum. The published mass value for the ^{187}Pt-nucleus could be improved essentially with respect to absolute value and relative error.

mination of the poorly known mass value for ^{187}Pt is illustrated.

- Relative errors $\delta A/A$ between 1.3×10^{-6} and 5×10^{-7} have been achieved depending on special experimental conditions as, e.g., total ion beam intensity, height of spectral line, number of reference lines, and number of overlapping spectra applied for cross references.

- A series of multi-line spectra recorded at different times within a period of 9 days showed that the reproducibility of experimental mass values is in the order of 1 ppm. The long term reproducibility of a single mass line – without reference lines – would be in the order of 10 ppm.

- Mass values for nearly 300 species were determined experimentally. About 70 of them have been measured for the first time, and 40 mass values have been improved essentially.

4 CONCLUSIONS AND OUTLOOK

The present accuracy and resolution limit of the Schottky mass spectrometry at the ESR is determined mainly by the short term stability of the power supplies for the main bending and quadrupole magnets. The high resolution and accuracy in combination with the large number of radioactive nuclides, for which masses can be measured within rather short beam times, makes the SMS a very attractive and efficient method. Compared to ion trap measurements, the relative error is still larger by roughly an order of magnitude. On the other hand, all nuclides with life times in the order of milliseconds are available for SMS, independent of specific physico-chemical properties. Ring operation in the isochronous mode, i.e. at the transition point, will probably help to apply SMS to uncooled nuclides with life times of a few milliseconds. Corresponding machine developments were done recently with primising results [10]. For much shorter-lived nuclei the isochronous ring could be used as multi-turn time of flight spectrometer, though with essentially reduced mass resolution [11].

Additional stabilisation of dipole fields by NMR might improve the quality figures of SMS by a factor of up to 4. Fast recording of digitised Schottky noise signals and off-line Fourier transformation of subsequent time intervals of a few milliseconds allows to correct for frequency shifts caused by fluctuations of the bending field. The periodic influence of the SIS magnet cycle on the static ESR bending field was clearly seen in single spectra from fast records of digitised Schottky signals. Averaging of corrected spectra should lead to enhanced resolution and accuracy in coming SMS experiments.

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