Schottky detection techniques for ultra-rare short-lived ions in heavy-ion storage rings*

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Abstract: Non-destructive Schottky detectors are indispensable devices widely used in experiments at heavy-ion storage rings. In particular, they can be used to accurately determine the masses and lifetimes of short-lived exotic nuclear species. Single-ion sensitivity – which is the highest level of sensitivity – has been regularly achieved in the past by utilizing resonant cavity detectors. Recent designs and analysis methods aim to push the limits of measurement accuracy by increasing the dimensionality of the acquired data, namely, the position of the particle as well as the phase difference between several detectors. This paper describes current methods and future perspectives for Schottky detection techniques, with a focus on their application to mass and lifetime measurements of the most rare and simultaneously short-lived radio nuclides.

Keywords: heavy ion storage rings, mass spectroscopy, lifetime measurement, rare isotopes, highly charged ions, instrumentation

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I. SCHOTTKY DETECTION TECHNIQUE

Swift charged particles traversing accelerator chambers induce an opposite equivalent charge on the inner surface of the beam pipe. For rapidly moving particles, this charge is assumed to be concentrated around an infinitesimally thin ring along the particle's trajectory. On the surface of an isolated region within the beam pipe, such as detector plates (see e.g., [1]), the surface charge undergoes redistribution until equilibrium is achieved. For a particle passing repeatedly, this charge redistribution can be quantified as an equivalent induced current $i(t)$, characterised by the shape of a periodic delta function for a single particle [2].

The same phenomenon occurs on the inner walls of a cavity; however, the duration of the oscillation of the charge redistribution exceeds the time required for the particle's passage. This extended duration arises because the components of the cavity walls facing each other form a transient oscillating electric dipole. This dipole generates an alternating magnetic field, resulting in the continuous exchange of energy between the stored electric and magnetic fields. The measurement is typically conducted by extracting the field energy using either an electric pin or magnetic loop, the shape and position of which have a significant impact on the efficiency of the extracted signal.

With many particles circulating around the storage ring, the current $i(t)$ will show a macroscopic DC value referred to as *beam current* I_B. The spectrum of this current repeats its shape at integer multiples (harmonics, denoted as h) of the particle's revolution frequency, commonly referred to as *Schottky bands*. The total power, which is equal for all bands around the harmonics, is [3]

$$\langle I\rangle^2 = 2(qe)^2 f_r^2 N, \tag{1}$$

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where q and f_r are the charge state and revolution frequency of the ions, respectively, N their number, and e the elementary charge.

Particles with slightly different magnetic rigidities, $B\rho = m v \gamma / q$, where m, v, and γ represent the particle mass, velocity, and relativistic Lorentz factor, respectively, show up in the revolution frequency spectra as closely lying peaks. With increasing harmonic number, h, one can observe that the distance between these peaks, Δf, increases with $h \cdot \Delta f$. This is known as Schottky *band broadening*, which comes at the cost of losing peak power but is in fact a desirable feature for *quickly* resolving nearby peaks. This is often the case for the spectrum of short-lived low-lying nuclear isomeric states. Cavity-based Schottky detectors exploit this feature by enhancing the signal at higher frequencies. Successful examples of such cavity-based Schottky detectors can be found in [4−10].

A. Storage ring mass and lifetime spectrometry

Time-resolved frequency analysis can be used for the measurement of masses and lifetimes of unstable nuclear species. Mass measurement is performed by comparing the revolution frequencies of nuclei with unknown masses to those with known masses according to the governing equation [11, 12]

$$\frac{\Delta f}{f} = -\frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{(m/q)} + \left(1 - \frac{\gamma^2}{\gamma_t^2}\right)\frac{\Delta v}{v}, \qquad (2)$$

where γ_t is known as *transition* point which is related to storage ring's momentum compaction factor α_p.

To increase the measurement accuracy, the velocity spread of the particles (Δv in Eq. (2)) must be addressed. One approach is to reduce the velocity spread to a comparatively small value by applying beam cooling methods [13]. However, because the cooling takes some time to reach the required beam quality, efforts have been made to perform mass and lifetime measurements of shorter-lived states by tuning the lattice of the storage ring to the isochronous ion-optical (ISO) mode, where $\gamma = \gamma_t$ for the desired species [14, 15]. In the ISO mode, the magnetic lattice of the ring is tuned such that the velocity spread of particles of different momenta is compensated by the difference in their orbits lengths, such that the resulting flight times or revolution frequencies are equal [16]. This so-called Isochronous Mass Spectroscopy (IMS) method is often performed using time-of-flight (TOF) detectors [17, 18]. Recently, a combined Schottky and isochronous mass (and lifetime) spectroscopy (S+IMS) method was developed and successfully implemented, combining the advantages of isochronous mode with the benefits of non-destructive detection using resonant Schottky cavity detectors [19, 20].

For lifetime measurements, Eq. (1), together with time resolved frequency analysis, allows for monitoring of the decrease of spectral power (*i.e.*, the area under the power peak), and with that, the lifetime of unstable particles [21−24]. For individual particles that leave distinct decay patterns, the decay times can be determined individually (as in [25]). For few particles, a spectral add-up method can be used [20, 26].

B. Towards higher accuracies

A further increase in measurement accuracy puts stronger demands on the reduction of uncertainties of the term containing the velocity spread in Eq. (2). The cooling method, although very powerful for longer-lived species, is too slow for application to the short-lived nuclei of interest today. Moreoer, the isochronous setting does not allow for a complete elimination of the velocity spread. Here, the advantage of the storage ring being capable of simultaneously covering a broad range of various species brings in a complication. The bandwidth of the measured m/q ratios is several percent. Therefore, to match the given set magnetic rigidity, the ion velocities must vary by several percent as well. Hence, apart from the extreme vicinity around the particle species whose mean γ has been chosen to tune the lattice to the isochronous mode, all other particles show peak broadening due to the effect of the mismatch of their $\gamma \neq \gamma_t$ [27]. This behaviour has been observed in all storage rings employing isochronous mode for mass measurements, namely, R3 in Japan [28] and CSRe in China [29, 30]. This so-called *anisochronousity* effect must be addressed when aiming for higher accuracies.

An alternative to the elimination of the velocity mismatch would be the accurate determination of its value. To achieve this goal, the dimensionality of the data must be increased [31]. The existing three dimensions of power, frequency, and time could be augmented by considering the phase difference and position of the particles, each of which would allow for the direct or indirect determination of the velocity of the particles.

The phase difference considers the signal correlation between two or several detectors and is currently being investigated [7]. In the following, we expand on how the position determination can be used for the reduction of uncertainties.

C. Position-sensitive Schottky detectors

Position-sensitive Schottky detectors of cavity- and non-cavity-based types have been utilized throughout the history of particle accelerators [32]. Among cavity-based detectors, those that utilize the dipole mode show small sensitivity around the center of the beam pipe of storage rings with large beam pipe apertures.

A novel design with an elliptical shape was proposed to circumvent this problem by the use of the strong monopole mode. Particles passing through the offset beam pipe strongly couple to the monopole mode, albeit with different intensities depending on their offset [33, 34]. Normalised to the signal of a reference cavity with otherwise identical characteristics, the combined signal from a Schottky Cavity Doublet (SCD) can be used to extract the position information. This new dimension of data can be utilized to correct for the measured magnetic rigidity of the particles.

To test this principle, an SCD was designed for the R3 storage ring [35]. Mechanical construction and manufacturing was conducted at GSI Darmstadt. Installation in the R3 storage ring has been accomplished (see Fig. 1).

D. Correction method

The proposed correction method for mass determination is similar to the existing $B\rho$-IMS method described in [36, 37], but unlike the case of TOF detectors, it takes advantage of the non-destructive features of the SCD. This allows for the simultaneous measurement of masses and lifetimes [38].

In the isochronous mode, each particle with the same magnetic rigidity will have the same path length, C, and with that, the same lateral offset, *i.e.*, ρ at the location of the SCD, which is deliberately installed at a highly dispersive section. Simulations have confirmed that particles with slightly different momenta will occupy different orbits [39]. Using the SCD, a position value is assigned to every measured ionic peak in the revolution frequency spectrum [40, 41]. The magnetic rigidity is determined as a function of path length $B\rho(C)$ for the reference particles only. A fit over the resulting function can then be used to determine the m/q of the unknown particles. Because the measurements in the ring are repeated many times by injecting new freshly produced particles, the spectra will contain random nuclear species. To explore all possible correlations in these spectra, all information will be placed in a so-called flow-of-information correlation matrix [42–45].

Fig. 1. (color online) Photograph of a Schottky Cavity Doublet (SCD) installed at the R3 storage ring. It is on top of a green mechanical support (elliptical cavity left). A separate publication will be dedicated to the technical details and features of the new detector (Photo: S. Sanjari).

For the above method to work, a proper identification is required. The limitation of the TOF technique is the need for an extra tagging of the particles. Due to their non-destructive working principle, Schottky detectors allow for in-ring particle identification (PID) based on the simulation of peak position on the revolution frequency spectra [46, 47]. This can be performed on the spectrum of a multi-component beam or by stacking of individual spectra in case of single-ion injection. The latter is typically the case for the R3 storage ring at RIKEN; in fact this is a unique feature of the R3, allowing for the tagging and identification of individual particles.

E. Advantages of SCD for R3 storage ring

In the R3 storage ring, very high-mass measurement accuracies have already been achieved by the tagging method [28]. Here, Bρ determination and PID are performed outside of the R3. While the additional path length adds to uncertainties, the PID process limits the transmission. Particle identification is generally performed at the focal plane (F3) of the BigRIPS separator before the R3 storage ring, where energy loss is measured and plotted with repect to the TOF between sections F2 and F3. PPAC detectors are used for position measurements at the F5 section, but they are often used for PID if the resolution at section F3 is not adequate.

LISE++ simulations show that high-Z species such as ^{216}Pb could gain up to 100-fold transmission efficiency, mainly due to charge exchange reactions, if the PPACs are removed from the beam line, whereas mid-Z region particles, such as ^{78}Ge, are not significantly affected. This very feature also becomes useful during the benchmarking of the new SCD (accepted proposal NP2412-RIRING10) using mid-Z range particles; the PPAC detectors can stay in the beam line for an independent confirmation of the non-destructive in-ring PID.

Finally, the performance of the SCD will show whether the overall gain in accuracy is comparable to that of existing methods. However, as RIKEN's world's highest intensities are currently affected by limited transmission, it is hoped that the SCD will make a significant contribution to RIKEN's nuclear physics programme.

F. Future data acquisition systems

The development of novel Schottky detectors complements the development of new data acquisition systems (DAQs) [48]. Continuous and wide-band acquisition of signals from Schottky detectors places ever-increasing demands on dedicated DAQs and processing hardware, which becomes a bottleneck to the scalability of such systems due to either their high initial price or vendor lock.

Software-defined radio (SDR)-based DAQ systems have proven to be an inexpensive and scalable alternative to such DAQs. The main aim of SDRs is to digitise measurable quantities as close as possible to their source (here, the Schottky detector) and perform all signal processing and analysis in the software domain using high-level programming. Open hardware and open-source SDRs allow for collaborative development and compatibility with Open Science standards, such as F.A.I.R data principles of publicly funded research [49, 50].

SDR libraries such as GNURadio [51] can be used with PID and other related libraries (see [47, 52]) for the purpose of monitoring and analyzing Schottky spectra, with the aim of semi-automatic or automatic processing of incoming data.

II. SUMMARY AND OUTLOOK

Schottky cavity-based detectors are fast and sensitive devices that can be used for mass and lifetime measurements of exotic isotopes. The attainable high mass resolving power allows the study of known or search for new low-lying isomeric states. New position-sensitive detectors, such as the newly installed SCD for the R3 storage ring at RIKEN, allow alternative interpretations by increasing the dimensionality of the acquired data. Open-source DAQs based on SDR complement the operation of Schottky detectors and contribute to the scalability of data handling. Streams of time-stamped data samples from many Schottky detectors can be monitored and analyzed together to extract features such as the PID, mass, and lifetime of hundreds of spectral lines as well as storage ring features such as α_p curve at the same time, giving birth to the idea of *Software Defined Experiments for Nuclear Astrophysics*. It is hoped that these developments will enable an exciting future for nuclear astrophysics research at both existing and future heavy-ion storage ring facilities, such as the ESR and Collector Ring (CR) at GSI/FAIR, R3 at RIKEN, and SRing at the future HIAF facility.

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