HANDLING OF BEAM IMPURITIES IN GAMMA-SPECTROSCOPY EXPERIMENTS AT REX-ISOLDE (CERN) *

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and the REX-ISOLDE and MINIBALL collaborations

Abstract

The REX-ISOLDE facility at CERN delivers a great variety of radioactive ion beams with energies up to 3.0 MeV/u and therefore allows nuclear structure physics experiments far from the valley of stability. A crucial point for the experimentalist is the knowledge of beam contaminations, either from the bunching and charge-breeding procedure (residual gas ions) or directly from the ion-production process (isobaric contaminants), whose sources are discussed as well as possible ways of elimination during the post-acceleration. Methods to analyse the beam composition in the relevant energy range are presented on the basis of two specific experiments using the MINIBALL detector array with an emphasis on the experimental challenges in Gamma-spectroscopy experiments and data analysis.

REX-ISOLDE FACILITY

The On-Line Isotope Mass Separator ISOLDE at CERN delivers a great number of low-energy radioactive ion beams for a variety of different experiments, e.g. in the fields of atomic and nuclear physics, solid-state physics or material science. Until now, more than 600 isotopes of more than 60 elements (Z=2-88) have been produced [1]. The Radioactive beam experiment REX (proposed in 1994 and operational since 2003) was a pilot experiment to bunch, charge breed and post-accelerate singly charged radioactive ions to energies up to 3.0 MeV/u and today, together with the high resolution gamma-detector array MINIBALL, expands the spectrum of research at ISOLDE to nuclear structure physics far from the line of beta-stability.

RADIOACTIVE ION BEAM (RIB) PRODUCTION

At ISOLDE, radioactive nuclides are produced via spallation, fragmentation or fission reactions by colliding a 1.0-1.4 GeV proton beam from the PS Booster with a thick, high-temperature production target. Depending on the experimentalists requirements, it can be advantageous to utilize neutron induced reactions and therefore send the proton beam on a converter (i.e. a heavy metal rod, e.g. Ta) and hit the production target with the low-energy spallation neutrons. The produced nuclides are stopped in the target material and move towards a heated transfer line by diffusion and effusion transport processes, whose velocities depend, besides the target material and geometry, on the specific element and result in element-dependent release functions P(t). Heating both the target and the transfer line reduces the diffusion time and long adhesion times of the atoms on the surface. Inside the transfer line, the atoms can be laser ionized using the Resonant Ionization Laser Ion Source (RILIS), leading to singly-charged ions. These are extracted and subsequently mass separated using the General Purpose Separator (GPS) or the High Resolution Separator (HRS) with a mass resolving power of $(\Delta M/M)_{GPS}$=2400 and $(\Delta M/M)_{HRS}$=5000 respectively.

Post-acceleration of the RIB with REX is a multi-level process. First, the semi-continuous RIB from the mass separator is injected into a Penning Trap (REXTRAP), where it is accumulated, bunched and cooled through collisions with a buffer gas (i.e. Ar or Ne). In the adjacent electron beam ion source (REXEBIS), a higher charge state of the ions is achieved by the so called 'charge-breeding' procedure, where the ion bunches interact with a monoenergetic electron beam of 3-6 keV. The charge breeding time of 20-200 ms (depending on the ion species) in REXEBIS is identical to the trapping time in REXTRAP and allows charge states of A/q$<$4.5. The highly charged ions are accelerated to an energy of 5 keV/u, sent through an A/q-separator and finally injected into the REX linac, which consists of a RFQ and an IH structure followed by three 7-gap resonators delivering energies of 0.8-2.25 MeV/u. In 2004, an additional 9-gap structure was installed, giving rise to the present maximum beam energy of 2.8 MeV/u (design value: 3.0 MeV/u). The different stages of REX are illustrated in figure 1.

EXPERIMENTALISTS DEMANDS

The following discussion of beam-composition analysis and handling of beam impurities in gamma-spectroscopy experiments will be based on two specific experiments using the MINIBALL detector array, namely the determination of reduced transition probabilities B(E2) between low-lying levels in Coulomb-excited nuclei of ^{74,76,78}Zn [2] and ^{30,32}Mg [3]. The number of observed gamma-transitions in the investigated isotopes (see formula 1) is a function of the isotropic photopeak efficiency $\epsilon_{MB,B}$ of the MINIBALL array, the total detected de-excitation cross section $\sigma_{E2,B}$ and the total incoming beam intensity I_B.

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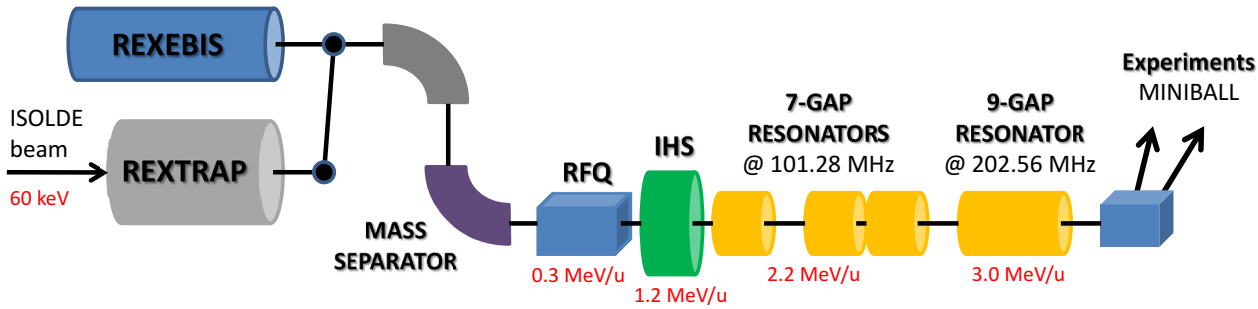

Figure 1: The individual elements of REX: Penning Trap (REXTRAP), Electron beam ion source (REXEBIS), A/q-separator and the different acceleration structures in the REX linac. (Picture adapted from [1])

$$N_\gamma^{\mathrm{B}}(2_1^+ \rightarrow 0_1^+) = \epsilon_{\mathrm{MB,B}} \cdot \sigma_{\mathrm{E2,B}} \cdot \frac{\rho d N_A}{A} \cdot I_{\mathrm{B}} \quad (1)$$

In general, the latter is not accurately known in case of RIBs, but can be treated in the data analysis by normalizing the investigated beam excitation cross section to the well-known cross section of target nuclei excitations ('B' and 'T' denote the beam and target respectively). Under the assumption of a mono-isotopic beam (i.e. exclusive excitation of target nuclei by the investigated ion species), this leads to the ratio:

$$\frac{N_\gamma^{\mathrm{B}}(2_1^+ \rightarrow 0_1^+)}{N_\gamma^{\mathrm{T}}(2_1^+ \rightarrow 0_1^+)} = \frac{\epsilon_{\mathrm{MB,B}}}{\epsilon_{\mathrm{MB,T}}} \cdot \frac{\sigma_{\mathrm{E2,B}}}{\sigma_{\mathrm{E2,T}}} \quad (2)$$

An essential point for the application of formula 2 is the knowledge of the amount of target excitations caused by beam contaminants, which has to be explicitally corrected. The applied methods to determine the beam composition are presented in the following.

A further problem caused by beam impurities are additional peaks in the de-excitation gamma-spectra from transitions in the contaminant nuclei. Particularly transition energies in the proximity (i.e. few keV) of the investigated ones may cause overlapping photopeaks, leading to indeterminable gamma yields.

SOURCES OF BEAM CONTAMINATION

The final RIBs at the MINIBALL target area exhibit two main sources of beam impurities. The first are isobaric contaminants from the ion production process, which can not be separated by the GPS/HRS mass separator. Due to the chemical selectivity of laser ionization in the RILIS, isobaric contamination directly from the ion production can be reduced in many cases to a large extent compared to the ions of interest. In the contrary case of Zn in the experiment [2], the rather high ionization potential of Zn leads to strong contamination of other elements, particularly Ga (see table 1). For short-lived elements moving towards the target area, beta-decay may in either case cause the reoccurence of isobaric impurities in the final RIB. This fraction can be deduced from the trapping and breeding time and the lifetime of the radioactive ions or the photopeak intensities of transitions in the respective daughter nuclides.

Table 1: Ionization potentials of elements near Zn

Element	Ni	Cu	Zn	Ga	Ge	As
Z	28	29	30	31	32	33
Potential [eV]	7.6	7.7	9.4	6.0	7.9	9.8

The second source of contamination are residual gas ions from the buffer gas, used in REXTRAP for cooling of the RIBs and improvement of the transverse emittance. Depending on their charge state after the charge breeding in the EBIS, the buffer gas ions may however show A/q-values similar or close to the design values for the investigated ions. In this case, they will be extracted to the acceleration structures of the REX linac by the A/q-separator. Even with the ISOLDE beam gate closed, this part of the beam contamination is present at the target area, which allows the determination of its amount relative to the investigated RIB (see figure 2).

DIAGNOSTICS OF BEAM COMPOSITION AND ELIMINATION OF IMPURITIES

There are several diagnostic tools around the MINIBALL target area to determine the amount of beam contamination. The particle detector used in the presented experiments is a Double-sided Silicon Strip Detector (DSSD). From the reaction kinematics of collisions of beam particles with the target nuclei, one expects a distinct relation between the scattering angle and energy of the projectiles. In figure 2, the energy of scattered ^{76}Zn-particles is plotted over their scattering angle, showing a clear separation from residual gas ions (^{22}Ne and ^{40}Ar).

Isobaric beam contaminants show similar reaction kinematics, thus a charge number (Z) selective mechanism has to be used for their separation. One possible mechanism is the energy loss of the beam particles in matter, whereas the differential stopping power can be written as $-\frac{\mathrm{dE}}{\mathrm{dx}} \propto \mathrm{Z}^2 \cdot \mathrm{f}(\beta)$. For the Mg-experiment in 2004 [3],

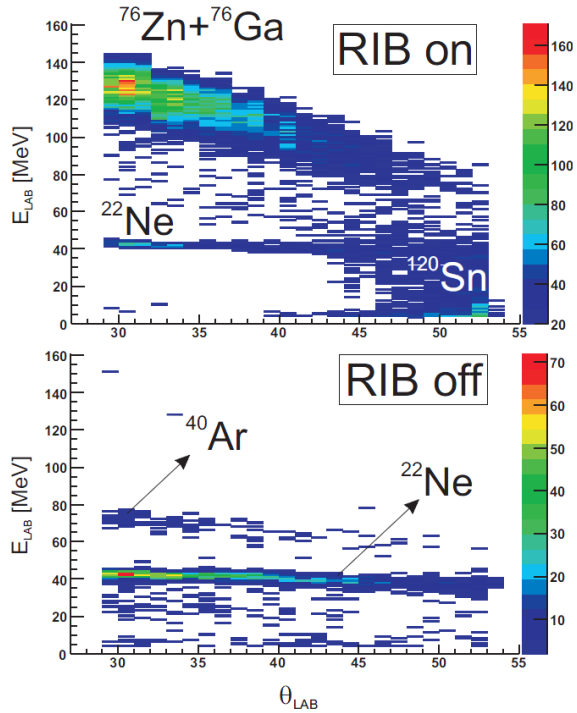

Figure 2: Energy E_{lab} of scattered particles over the scattering angle Θ_{lab}. RIB on/off denotes the open/closed ISOLDE beam gate, exhibiting the amount of residual gas ions in the final RIB. (Picture taken from [2])

two 10 μm Si-detectors (ΔE-E-telescope) were installed in the MINIBALL setup for investigating the structure of the EBIS pulses by means of the composition of the RIB. As mentioned above, particle-dependent release functions P(t) lead to a time varying ratio of designated beam ions to the isobaric contaminant particles. This behaviour can be clearly seen in figure 3, where the energy loss in the ΔE-detector is plotted against the time T_p since the last proton pulse hit the ion production target. Due to similar velocities β for all beam particles, the energy loss dependency on the charge number Z is visible. The investigated ^{32}Mg is mainly present in the early part of the EBIS pulse, whereby a gate on the early particles in each pulse improves the fraction of 'good' particles in the recorded spectra.

The same mechanism of Z-dependent energy loss is applied in the Bragg chamber at the end of the MINIBALL beamline. Here, the beam composition can be analyzed due to respective energy loss of the particles in the detector gas P10 ($ArCH_4$) and the measurement of the total energy in a subsequent silicon detector. It should be mentioned that, for both the ΔE-E-telescope and the Bragg chamber, beam energy is needed, making those tools only applicable at the medium energy experiments of ISOLDE after the REX linac. The discussed methods of beam composition analysis are summarized in table 2.

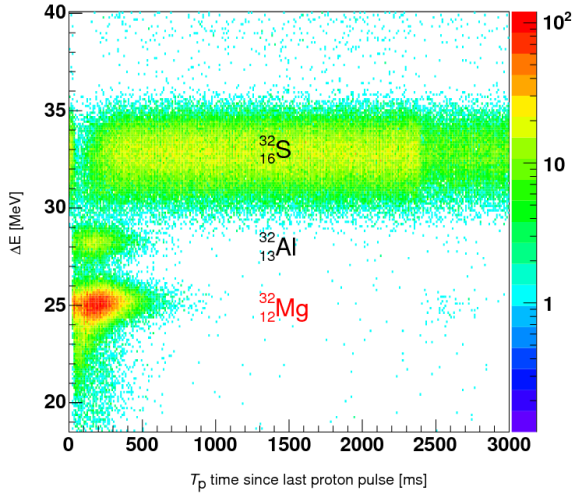

Figure 3: Energy loss of the beam particles in the ΔE-detector over the time T_p since the last proton impact on the ion production target. Different charge numbers Z of the isobaric contaminants separate the investigated ^{32}Mg. (Picture taken from [3])

Besides the reviewed methods of beam-composition analysis and offline correction in the presented experiments, another possibility of elimination of impurities is the use of stripper foils in the REX linac. In the example of a fluorine (Z=9) beam, contaminated with oxygen (Z=8), one selects a charge state of 8^+ after the EBIS, resulting in fully stripped oxygen and fluorine with one electron left. Using a stripper foil for those remaining electrons before the last bending magnet and scaling the rest of the linac to a charge state of 9^+, one obtains a pure fluorine beam.

Table 2: Sources of beam contamination and respective methods of beam-composition analysis

Source	Method
Isobaric ions	RILIS on/off measurement
Ion-production	REXEBIS pulse structure analysis
Beta-decay	ΔE-E-telescope/Bragg chamber
	Breeding time/lifetime analysis
	Photopeak intensities
Residual gas ions	RIB on/off measurement
Buffer gas	Particle detector
	(Scattering kinematics)

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