Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

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To cite this article: P. Reiter and MINIBALL collaboration 2018 *J. Phys.: Conf. Ser.* **966** 012005

IOP Conf. Series: Journal of Physics: Conf. Series **966** (2018) 012005 doi:10.1088/1742-6596/966/1/012005

Nuclear-Structure Physics with MINIBALL at HIE-ISOLDE

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Abstract. The MINIBALL spectrometer utilizes successfully a variety of post-accelerated radioactive ion beams provided by the new HIE-ISOLDE accelerator at CERN. In-beam γ-ray spectroscopy after Coulomb excitation (CE) or transfer reactions is performed with optimized setups of ancillary detectors for particle detection. The physics program covers a wide range of shell model investigations. Exotic heavy ion beams will enable unique studies of collective properties up to the actinide region. First data taking with HIE-ISOLDE beams started recently. The higher energies and intensities of the new post-accelerator provides a promising perspective for a new generation of MINIBALL experiments. Intriguing first results were obtained by employing beams of ^{74,76,78}Zn, ^{110,132}Sn, ^{144}Xe with beam energies in the range of 4.0 - 5.5 MeV/u for CE experiments at 'safe' energies. In all cases first results for various $B(E\lambda)$ values for these isotopes were obtained.

1. Introduction

Major strides were made within the on-going HIE-ISOLDE (High Intensity and Energy) project at the ISOLDE facility at CERN [1] by increasing the beam energy for post-accelerated radioactive beams. The previous REX linear accelerator with a maximum energy of 3 MeV/u was partially replaced and extended by an additional superconducting post accelerator. To study the properties of radioactive nuclei by different and specific nuclear reactions, the enlarged beam energy will provide essential advantages in the near future. For light-ion induced transfer reactions in inverse kinematics the wider energy range up to 10 MeV/u will allow for optimized conditions, e.g. via Q-value matching, over the whole chart of nuclei. The beam energies close to the Coulomb barrier will allow for improved CE measurements especially multiple CE with highest cross sections at 'safe' energies. Even higher beam energies will enable CE experiments at 'unsafe' energies above the barrier in order to extend the range of excitation energy. Moreover new reaction mechanisms like multi-nucleon transfer and deep inelastic scattering up to fusion will be feasible in the upcoming years. In this contribution the first in-beam γ-ray spectroscopy experiments will be introduced, which were performed at HIE-ISOLDE with a beam energies up to 5.5 MeV/u in 2016.

2. HIE-ISOLDE

In the past more than 90 different radioactive isotopes, ranging from the light ^{6}He up to the heavy actinide isotope ^{224}Rn have been efficiently post-accelerated and studied employing the REX-ISOLDE setup at beam energies up to 3.0 MeV/u [2]. Also the new HIE-ISOLDE

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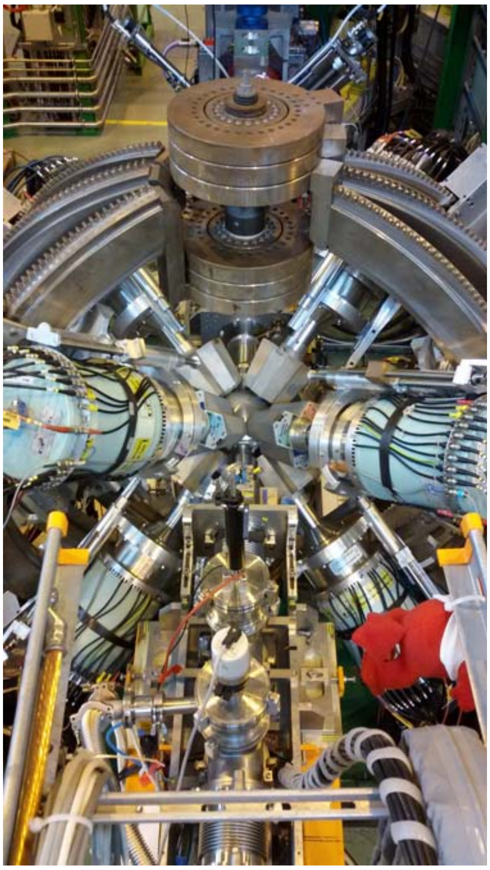

Figure 1. Picture of the MINIBALL setup in 2016. The radioactive ion beam delivered by HIE-ISOLDE is coming from the top, hitting the secondary target right in the middle of the MINIBALL spectrometer. Downstream of the scattering chamber additional detector systems are installed to monitor the position of the beam and its composition.

accelerator facility is based on the production of highly charged ions. For this purpose singly charged radioactive ions coming from ISOLDE are first cooled and bunched in a Penning trap (REXTRAP) [3] before they are charge bred to higher charge states, using an electron beam ion source (REXEBIS) [4]. The ions with a mass-to-charge ratio of $A/q < 4.5$ are injected into a compact linear accelerator via a mass separator. The normal conducting linear accelerator consists of a Radio Frequency Quadrupole (RFQ) accelerator which accelerates ions from 5 to 300 keV/u, a rebuncher section, an Interdigital H-type (IH) structure that boosts the energy to 1.2 MeV/u, three seven-gap spiral-resonators and a 9-gap IH resonator; it provides a maximum energy of 3.0 MeV/u [5].

The decisive new HIE-ISOLDE accelerator component for the higher beam energies are the superconducting Quarter Wave Resonators (QWRs) for post-acceleration. The QWR geometry comprises twenty high-β cavities cooled by a 4.5 K cryogenic facility for helium. The twenty cavities are grouped and installed in four cryo-modules. The accelerating cavities feature a very high voltage gradient of 6 MV/m and low heat dissipation. The transverse focusing is achieved by four superconducting solenoids housed inside the cryo-modules. Each cryo-module contains five cavities with its 101.28 MHz niobium-sputtered copper Quarter Wave Resonators and one solenoid. In 2016, the first two cryo-modules were operated successfully with the design energy of 5.5 MeV/u for A/q = 4.5.

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In future, the HIE-ISOLDE upgrade will improve the experimental capabilities at ISOLDE continuously. An important step will be the increase of the beam energy from currently 5.5 MeV/u to finally 10 MeV/u by adding two more cryo-modules. The third cryo-module was successfully installed before the physics campaign in 2017 and beam energies of 7.5 MeV/u were already achieved in 2017. Installation of the last module is foreseen before the start of the 2018 campaign and will allow experiments at 10 MeV/u which will enlarge the opportunities for experiments at ISOLDE. More detailed descriptions of the complete HIE-ISOLDE project can be found in Ref. [6, 7] or in the contribution by M. J. G. Borge to this volume.

3. First MINIBALL campaign at HIE-ISOLDE

3.1. Experimental setup

The high-resolution and highly efficient MINIBALL spectrometer [8] was reinstalled around the new target position of the extended HIE-ISOLDE accelerator complex (see Figure 1). The spectrometer consists of eight triple cluster detectors, mounted on movable arms around the target chamber to allow a compact configuration. Each cryostat contains three individually large volume encapsulated six-fold segmented high-purity germanium crystals. With close distances between target and Ge-detectors the array covers a solid angle of approximately 50-60% of 4π. The photopeak efficiency of MINIBALL at 1.3 MeV is $\approx 8\%$ after cluster addback. An average energy resolution of 2.3 keV at $E = 1.33$ MeV is achieved. The azimuthal electrical segmentation of the detector increases the granularity and ensures a proper Doppler correction for in-flight γ-ray emission at higher β values well above 10% even at the very close distances between target and detector.

To ensure a proper Doppler correction for in flight γ-ray emission at increased velocities, the angular information of the γ ray, provided by the position sensitive MINIBALL detectors, is combined with the direction and velocity of the scattered beam particle that was measured in coincidence. For this purpose, the scattered beam and recoiling target nuclei are detected by silicon strip detectors which are employed in two different configurations. First, a CD-shaped double-sided silicon strip detector (DSSSD) was used for CE experiments in order to detect forward scattered beam- or target like reaction products [9]. Each quadrant comprises 16 annular strips at the front side and 24 radial strips at the back side for identification and reconstruction of the trajectories of the scattered nuclei. The distance between the scattering target and the DSSSD is about 30 mm corresponding to a forward angle range between 16.8° and 53.7° in the laboratory frame. This CD detector was mounted for the HIE-ISOLDE commissioning measurements in 2015.

A second particle detector array was employed for the experiments performed in 2016. The so-called C-REX array consists of a suit of DSSSDs: one in forward and one in backward direction, and a barrel of four position-sensitive planar detectors under backward direction [10]. The forward and backward DSSSD is cicular shaped with 16 annular strips at the front side and 24 radial strips at the back side. The distance between target and detector front side and therefore the scattering angle range was adjusted to the requirements of the kinematics of the individual experiments performed during the campaign in 2016. The angular resolution is typically better than 5°. The backward barrel detectors consist of planar Si detectors which are segmented in 16 strips perpendicular to the beam axis. The energy resolution for the protons ranges typically from 250 keV to 2 MeV, depending on their scattering angle, energy and thickness of the target.

3.2. ^{74,76,78}Zn

The first RIBs delivered by the newly installed HIE-ISOLDE accelerator to the MINIBALL spectrometer were ^{74,76}Zn ions with energies of 4.0 MeV/u as part of the last in-beam commissioning phase in 2015. CE of both isotopes on platinum and lead targets yielded straightaway the γ-decay lines from the $4^+_1 \rightarrow 2^+_1$ and $2^+_1 \rightarrow 0^+_{\mathrm{g.s.}}$ transitions demonstrating

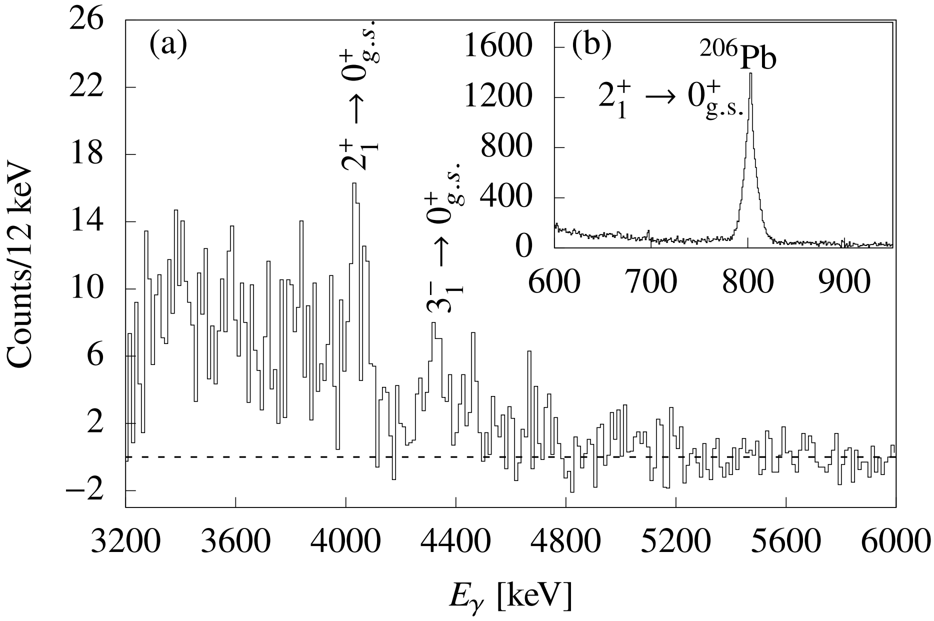

Figure 2. (a) High-energy part of the γ-ray spectrum after Doppler correction for $A = 132$ beam particles with peaks from $2_1^+ \rightarrow 0_{\text{g.s.}}^+$ and $3_1^- \rightarrow 0_{\text{g.s.}}^+$ transitions in ^{132}Sn. (b) A γ-ray spectrum, Doppler-corrected for the ^{206}Pb target excitation is shown in the inset.

the increased cross section for multiple CE. In contrast to this result a measurement at lower beam energies of 2.85 MeV/u did not show any signal from the higher lying 4_1^+ state. Another CE experiment along the chain of Zn isotopes at even higher energies of 4.3 MeV/u was performed in 2016 observing the $4_1^+ \rightarrow 2_1^+$ and $2_1^+ \rightarrow 0_{\text{g.s.}}^+$ in ^{78}Zn. Here intriguing evidence was found for excitation of even higher lying states.

These experiments explore the nature of the N=40 shell closure and the shell gap around the doubly-magic ^{78}Ni (Z=28, N=50). The nuclei around ^{78}Ni are benchmarks for latest shell-model calculations. Especially, the impact of excitations across the N=50 and Z=28 shell closures are important. A substantial set of experimental data has been obtained in this region of the nuclear chart. However, the conclusions drawn from them seem to be contradictory. The possibility of the weakening of the N=50 closure has been anticipated by [11, 12] while the contrary has been deduced by [13, 14].

Moreover, conflicting results exist between the life time of the 4_1^+ state in ^{74}Zn as deduced from Coulex measurements [14] or from direct life-time measurements using the Recoil-Distance Doppler shift method [15]. The preliminary independent results of the first HIE-ISOLDE experiment strongly support the previous findings of the Coulex measurements. In future CE studies in the neutron-rich Zn isotopes up to the N=50 shell closure are approved in order to reveal the energy of unknown excited states beside the 2_1^+ state and transition matrix element in the ^{80}Zn nucleus. These investigations are lead by E. Rapisarda (CERN), P. Van Duppen (K.U. Leuven) and M. Zielinska (CEA Saclay).

3.3. ^{110}Sn

In 2016 the in-beam campaign with MINIBALL and post-accelerated beams started in September, accelerating a beam of the semi-magic (Z=50) ^{110}Sn to 4.5 MeV/u. This first experiment addressed the determination of the transition probabilities $2_1^+ \rightarrow 0_{\text{g.s.}}^+$ that seems to differ strongly from the theoretical expectation in the light tin isotopes [16]. It is a continuation of the previous REX-ISOLDE program in the ^{100}Sn region at HIE-ISOLDE [17, 18], using the new energy $\approx$ 5 MeV/u. In a first step the γ transitions from the 2_1^+ and 4_1^+ states in ^{110}Sn were successfully detected. In future electromagnetic properties of ^{110,108,106}Sn will be addressed using CE. Even the isotope ^{104}Sn may be in reach for an in-beam study in case sufficient yield of the new RILIS will be available. These measurements are under the guidance of J. Cederkall, University of Lund.

3.4. ^{142}Xe

The second experiment in 2016 addressed the evolution of the quadrupole and octupole collectivity in ^{142}Xe. The results will shed light on the interplay between collective excitations and single particle structure when going away from the doubly-magic ^{132}Sn. The Doppler corrected γ spectrum of the ^{142}Xe beam at 4.5 MeV/u on a lead target showed a clear improvement by populating higher spin states in comparison with the equivalent spectrum obtained with the REX accelerator energies of 2.85 MeV/u. With the new energies, states up to 8^+ spin-parity are populated in multi-step CE. The experiment will aim to determine the B(E2) and B(E3) values to trace the evolution of quadrupole and octupole collectivity.

The B(E2) values connecting the ground state and the first 2_1^+ state in the even isotopes $^{138-144}$Xe have been measured at REX-ISOLDE and towards neutron-rich nuclei the trend is well described even by an empirical Grodzins-type formula. An increased dipole strength extracted from the decay of the negative parity states in ^{140,142}Xe is interpreted as indirect signature of increasing octupole correlation. However, B(E3) values are missing and subject of the new ^{144}Xe analysis. Spokesperson of this experiment is Th. Kroell, T.U. Darmstadt.

3.5. ^{132}Sn

Another important step during the 2016 campaign was to take the superconducting cavities to maximum accelerating gradient and a beam energy of 5.5 MeV/u. The vibrational first 2^+ and 3^- states of doubly-magic nucleus ^{132}Sn (Z=50, N=82) were excited via 'safe' CE after bombardment of a thin ^{206}Pb target. The optimized beam energy, the high-energy resolution and the good efficiency of the gamma spectrometer provide a favorable combination to master the demanding measurement characterized by small CE cross sections of the high-lying states with excitation energies above 4 MeV (see Figure 2). A first preliminary result for the $B(E2; 0^+ \rightarrow 2^+)$ value was obtained and also a value for the excitation strength of the 3^- state is in reach.

In the past first preliminary results for the $B(E2; 0^+ \rightarrow 2^+)$ value were obtained with an efficient scintillator array at ORNL [19, 20]. The results on excited collective states in ^{132}Sn provide crucial information on cross shell configurations that are expected to be dominated by a strong proton contribution. The results will be compared to large-scale shell model calculations, which are on its ways and new mean field calculations.

4. Summary and Outlook

The high-resolution γ-ray spectroscopy program at ISOLDE for nuclear-structure studies with reaccelerated radioactive ion beams commenced after commissioning of the first part of the HIE-ISOLDE facility. To achieve higher beam energy, better beam quality and higher secondary-beam intensity the superconducting HIE-ISOLDE linac will be in installed in stages. Two out of four superconducting cavities were put successfully into operation until spring 2016. Several CE experiments with an increased beam energy of up to 5.5 MeV/A were performed in 2016. The new facility enlarges the scope of the ongoing investigations by multi-step CE for all radioactive beams available at ISOLDE. Moreover, future transfer experiments will benefit from the higher energies and will allow an extended range for optimizing the Q-value matching condition. The final HIE-ISOLDE linac will reach an energy of 10 MeV/A. This will enable transfer reaction studies employing heavy mass beams up to masses around $A = 200$. Finally, the MINIBALL spectrometer will be augmented with new instrumentation such as the SPEDE conversion electron spectrometer [21], an upgraded version of Si detectors for the T-REX array, Anti-Compton BGO suppression shields for the HPGe triple-cluster detectors and a new digital electronics and data acquisition system in order to enlarge the detection capabilities.

Acknowledgments
The author would like to thank my colleagues P. Van Duppen (K.U. Leuven), M. Zielinska (CEA-Saclay), Th. Kroell (T.U. Darmstadt), J. Cederkall (U. Lund) for sharing preliminary and unpublished first results. The author acknowledge financial support from the German BMBF under contracts 05P12PKFNE, 05P15PKCIA, the European Unions Horizon 2020 Framework research and innovation programme under grant agreement no. 654002 (ENSAR2).

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