Low-energy beam preparation, manipulation and spectroscopy - Summarizing the activities of PREMAS in ENSAR

I.D. Moore, for the PREMAS collaboration

PREMAS is a Joint Research Activity (JRA) within the ENSAR Programme of the EU. The collaboration combines a range of expertise within the low-energy nuclear physics community to improve the beam preparation and manipulation of Radioactive Ion Beams (RIBs). Three key areas have been identified, each with a set of goals to be achieved over a period of 4 years: Novel RIB production techniques; advanced ion-beam manipulation, spectroscopic techniques and instrumentation; sources of pure and intense RIBs. These three areas provide much needed research and development, directly benefitting a number of EU Transnational Access facilities providing new opportunities to an ever-increasing user community.

The activities within PREMAS are divided into three main tasks, each coordinated by a specific institute. These tasks are further sub-divided into several sub-tasks overseen by additional institutes. Milestones must be attained throughout the 4 year period, and three final task reports serve as deliverables. The main tasks are summarized as follows:

Task 1: Novel radioactive ion-beam production techniques (KU Leuven)

The production of new RIBs, for example trans-lead nuclei, requires the development of selective and efficient laser ionization schemes, in some cases on-line when no stable isotopes exist. State-of-the-art target-ion source systems are now used at all large-scale facilities following a decade of detailed studies on atoms, molecules, photo-ions and surface ions at high temperature and in gas cells. New developments include tailored plasma conditions and gas-jet expansions. For example, by physically separating the thermalization and ionization zones in on-line gas cells the use of DC electrical fields can be applied to improve the ion beam purity. One of the most challenging obstacles at low-energy facilities is the contamination from isobaric reaction products and molecular contaminant ions, increasing as primary beam intensities are ramped up. A combination of laser selectivity and novel high-precision ion trap purification methods (for example for isomeric purification) is proposed as part of Task 1, resulting in ultra-pure RIBs for a variety of experiments.

Task 2: Advanced ion manipulation, spectroscopic techniques and instrumentation (JYFL)

The use of mass spectrometric techniques at low-energy RIB facilities enables a wide range of methods for the manipulation and preparation of short-lived nuclei prior to delivery to an experiment. Thus far, RF structures have been used for ion-beam cooling and preparation of well-defined ion bunches. Task 2 extends these applications to include novel methods of optical

manipulation on stored ions in a RF cooler-buncher, to populate or deplete selective ionic states, to polarize the nucleus or even to ionize to a higher charge state. Penning-trap technology has been widely used for precision studies. Within PREMAS, techniques are developed to optimize the coupling of ion traps to auxiliary instruments, diagnostics and novel detection setups to expand the applications of trap technology for nuclear structure studies.

Advanced spectroscopic techniques primarily focusses on applications of Resonance Ionization Spectroscopy (RIS) and its many variants, for example, in-source spectroscopy in hot cavities and gas cells, and exploratory studies of RIS within supersonic gas jets. The latter environment is highly attractive for spectroscopy due to the reduced atomic line-broadening mechanisms. In general, RIS has demonstrated impressive sensitivity for optical isotope shift studies, providing a wealth of ground state nuclear structure information (size, shape, spins and moments) of exotic nuclei. New developments in collinear resonance ionization spectroscopy (CRIS) are now pursued within PREMAS through the synchronous bunching of ion beams using an rf cooler-buncher, with low repetition rate pulsed tunable lasers.

Task 3: Sources of pure and intense radioactive ion beams (GANIL)

Ion beam purity is a major concern for nuclear physics experiments and thus a number of sub-tasks have been formulated to develop innovative techniques for the production of high purity radioactive ion beams by ionization in ECR sources and charge breeders. Although ECR sources have been successfully used for the production of pure beams of gaseous elements, the use of such sources as universal charge breeders have shown purity limitations due to background from the residual gas and support structures. Additionally, advanced methods are proposed for extending the number of possible beams, for example via the ionization of volatile molecules containing non-gaseous elements to produce pure beams of condensable elements such as carbon.

The coupling of ECR sources to targets is usually complicated by limitations in space, available power and connectivity of the target-ion source units. Activities within PREMAS are studying how to overcome these problems. In parallel, challenges exist in maintaining a high performance level after long irradiation times, an issue deemed critical for next-generation facilities such as SPIRAL-2 or HIE-ISOLDE for which the neutron flux will be significantly higher. Radiation-hard sources are thus being studied and novel magnetic field structures which do not require permanent magnets (which degrade after long term exposure to neutrons) are proposed, for example the ARC-ECRIS design from JYFL.

PREMAS – a selection of highlights

The development of laser ionization schemes using dye and/or Ti:sapphire laser technology is critical to the selective and efficient production of RIBs. Such work is often distributed among a number of laboratories and the data is then accumulated and shared within the laser community. In particular, the known excited atomic states of heavy elements are often limited to the first state in a possible 2- or 3-step ionization scheme. Indeed, even basic chemical information such

as the ionization potential (IP) may be missing completely. In a recent highlight, four PREMAS institutes were involved in a measurement of the first ionization potential of astatine, determined via laser ionization spectroscopy on a series of Rydberg states [1]. Astatine is the rarest naturally occurring element on earth. The new value serves as a benchmark for quantum chemistry calculations of the properties of astatine as well as for the theoretical prediction of the ionization potential of the heaviest homologue, super-heavy element 117.

Continuing with the theme of heavy elements, the reduced amount of experimental data in the upper part of the chart of nuclides is due to a lack of stable isotopes and low production cross sections. A search for an efficient ionization scheme has been performed for Ac (Z=89) at the University of Mainz, using the long-lived ^{227}Ac isotope ($t_{1/2}$=22 y). In addition a more precise value for the IP has been obtained [2]. One of the new schemes was subsequently utilized at LISOL, Louvain-la-Neuve, to ionize ^{212,213}Ac isotopes produced in fusion-evaporation reactions and preliminary in-gas cell broadband laser spectroscopy was performed on ^{212}Ac [3].

In order to perform high-resolution spectroscopy of high-Z elements, efforts are underway to address the limitation due to the laser bandwidth, which for solid state systems may be several GHz. Such intrinsic resolution severely hampers the ability to resolve hyperfine structure and thus to gain access to fundamental nuclear structure information. Similarly, the ability to produce pure isomeric beams is hindered. A relatively simple way to reduce the laser linewidth is by the addition of a second etalon into the cavity. At LISOL this has been demonstrated on the dye laser system and utilized on stable copper isotopes. Similarly, a dual-etalon system is now in operation for Ti:sapphire lasers at both JYFL (tested on copper) [4] and ISOLDE (in-source spectroscopy on Po, At and Au, and collinear RIS on Fr) [5]. Dramatic reductions in laser linewidth require more complicated laser developments, and members of PREMAS are constructing injection-locked laser resonators which have very recently demonstrated a linewidth reduction from ~5 GHz to ~10 MHz. This method was used in a successful study of the hyperfine structure of the atomic ground state of ^{229}Th [6] and during 2013 in the determination of the hyperfine structure in ^{227}Ac.

With the purpose of suppressing surface-ionized isobaric contaminations in RIBs produced with the hot cavity Resonance Ionization Laser Ion Source (RILIS), a Laser Ion Source Trap (LIST) has been developed by the University of Mainz. The LIST separates the regions of the laser ionization and the surface ionization through the use of a positively-charged repeller electrode. The first successful on-line test was performed in 2011 whereby Mg was laser ionized inside the LIST RFQ while surface-ionized Na and Al isotopes were suppressed by more than 3 to 4 orders of magnitude. In 2012, the first on-line physics experiment took place and laser ionization of Mg and Po was demonstrated [7]. In fact, the hyperfine structure and isotope shifts of ^{217}Po and ^{219}Po were measured for the first time using in-source laser spectroscopy due to the suppression of surface-ionized Fr by the LIST.

The main experimental conditions that prevent higher spectral resolution studies with a gas cell-based laser ion source could be overcome by performing the photo-ionization in the cold jet expanding out of the gas cell. Such a technique may be viewed as an extension of the aforementioned LIST method, in which neutral atoms are selectively ionized upon exit from the gas cell, within the gas jet, and are captured by the rf field of an rf multipole before transport to the mass separator. A key requirement is the need for a good geometrical overlap between the atoms and laser beams, and at JYFL initial work has been carried out to study the gas jet formation as a function of nozzle type [8]. On-going work at JYFL and LISOL has resulted in the first demonstration of spectroscopy on stable copper [9, 10] however a full implementation of in-gas jet laser spectroscopy for its use in the study of rare isotopes has not yet been accomplished.

The Collinear Resonance Ionization Spectroscopy (CRIS) beam line at CERN-ISOLDE is an experiment which combines the Doppler-free resolution of collinear laser spectroscopy with the high detection efficiency of resonant ionization. In an experimental campaign during 2012, the hyperfine structure of the isotopes $^{202\text{-}207,211,219\text{-}221,229,231}$Fr and of isomers in ^{202,204,206,218}Fr was studied [11]. An experimental efficiency of 1% has currently been demonstrated and a non-resonant equivalent efficiency was determined to be <0.001%. For additional selectivity, RIBs containing several isomeric states may be sent to a decay spectroscopy station. In the latest developments, laser-assisted decay spectroscopy was performed on ^{204g,m1,m2}Fr.

At GANIL, the use of an ECR charge breeder of the Phoenix type, together with a surface ionization or FEBIAD source, was found to be the most universal method for producing beams of condensable elements. The breeder is being installed at SPIRAL during 2013.

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