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LaSpec at FAIR'S low energy beamline: A new perspective for laser spectroscopy of radioactive nuclei

Wilfried Nörtershäuser · Paul Campbell · The LaSpec Collaboration

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Abstract We describe a laser spectroscopy station that has been proposed to exploit the high yields of radioactive beams at the future FAIR facility at GSI, Darmstadt. Exotic nuclei produced in the Super-Fragment-Recoil-Separator (S-FRS) are stopped in a gas cell, extracted, reaccelerated and transported to the LaSpec setup. Here, collinear spectroscopy on ions and atoms, β-NMR experiments or laser-desorbed resonance ionization can be applied to these rare isotopes.

Key words laser spectroscopy · nuclear charge radius · isotope shift · hyperfine structure

1 Introduction

New generations of radioactive beam facilities have always opened new opportunities and new challenges for laser spectroscopy experiments. A multitude of techniques have been developed over the last few decades since the invention of the laser. While the first experiments were performed off-line having collected radioactive products at the facility, true on-line experiments soon followed. Specialized methods have been developed specifically for these on-line applications, such as collinear fast beam spectroscopy, β-NMR, and resonance ionization in gas cells and these techniques have been applied to a large number of long isotopic chains. An overview

W. Nörtershäuser (✉)
Institut für Kernchemie, Universität Mainz, D-55099 Mainz and Gesellschaft für Schwerionenforschung, Darmstadt 64291, Germany
e-mail: w.noertershaeuser@gsi.de

P. Campbell
University of Manchester, Schuster Building, Brunswick Street, Manchester M13 9PL, UK

The LaSpec Collaboration
http://www.gsi.de/LaSpec

over such experiments can be found, e.g., in [1–3]. More recently, laser cooling techniques and trapping of neutral atoms in magneto optical traps have found their way into on-line experiments, e.g., to test the standard model of particle physics with short-lived isotopes [4, 5] or to determine nuclear charge radii [6]. But conventional techniques still provide very interesting and important results if they are linked to beam facilities that produce sufficient yields far from the valley of stability, or in regions that were previously not accessible. Such a case is given at in-flight facilities where gas-cells are used to stop high-energy radioactive ion beams. They provide a rapid extraction of the radioactive ions, combining the intrinsic advantages of in-flight fragmentation, short delay times and universality, with those of the ISOL concept, namely the high-quality, low-energy beams. Such set-ups are currently used or in preparation at MSU [7, 8], Riken [9], and at Argonne [10, 11]. Laser spectroscopy at these facilities is complimentary to similar experiments at ISOL facilities where many elements, like refractory or very short-lived isotopes, cannot be extracted with sufficient yields. The Super Fragment Recoil Separator (S-FRS) at the future Facility for Antiproton and Ion Research (FAIR) [12] at GSI will provide a rich spectrum of isotopes that will not be available at any other facility. A laser spectroscopy station at the low-energy beamline behind this separator is planned and will be realized by the LaSpec collaboration. From the view of optical spectroscopic research the proposed facility will afford unique access to regions of particular nuclear interest that would otherwise remain inaccessible. The accuracy of laser-spectroscopic-determined nuclear properties is very high. Requirements concerning production rates are moderate; collinear spectroscopy has been performed with production rates as few as 100 ions per second [13] and resonance ionization mass spectroscopy (combined with β-delayed neutron detection) has been achieved with rates of only a few atoms per second [14]. At FAIR it will be, for example, possible for our collaboration to greatly extend our knowledge of nuclear sizes, deformation and electromagnetic moments far into the neutron-rich side of the upper part of the nuclear chart. Here we will give a short overview of the proposed laser spectroscopy station.

2 Isotope production and the low-energy beamline at FAIR

The FAIR facility will greatly extend the current GSI facility. The heavy ion synchrotron SIS-18 will be upgraded for higher intensities. The SIS-18 beam will be used directly for in-flight fragmentation in a first phase and later as a driver beam for a larger synchrotron (SIS-100/300) that will produce intense ion beams with energies up to 1.5 GeV/u and up to 10^{12} ions/spill. With these beams, the S-FRS will be the most powerful in-flight separator for exotic nuclei up to relativistic energies. It will be possible to produce and separate rare isotopes of all elements up to uranium and the separated beams will serve three branches of different experimental areas: the ring branch, where they can be stored and cooled in a number of storage rings for different applications, the high-energy branch that is used for reaction studies, and the low-energy branch (LEB) that is primarily dedicated to precision experiments with energy-bunched beams stopped in a gas cell. Figure 1 shows the preliminary layout of the low-energy beam area. The incoming beam from the S-FRS will be used by the HISPEC (High-resolution in-flight spectroscopy) and DESPEC (Decay

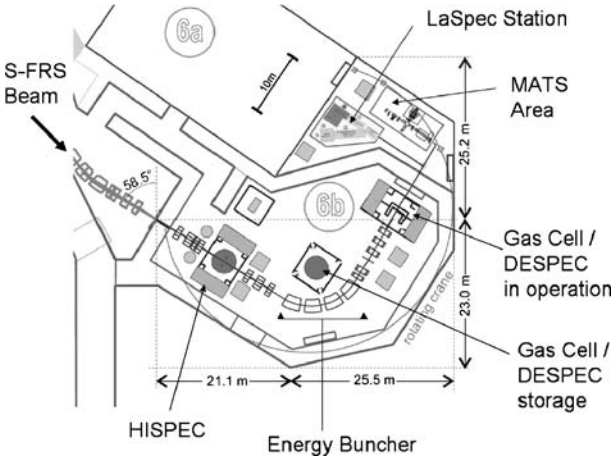

Fig. 1 Proposed layout of the low-energy-beam area at FAIR's super fragment separator (courtesy of M. Winkler, GSI)

spectroscopy) set-ups which are dedicated for γ-ray, charged particle and neutron spectroscopy on slow (3–150 MeV/u) and implanted ions, respectively. The DESPEC set-up is located behind the energy buncher, a dispersive separator stage that has been designed to drastically reduce the energy spread and thus the range straggling of the hot fragments. DESPEC can be replaced by an ion catcher device, with both devices installed on an air cushion system to facilitate an exchange between the two experimental stations.

Two possible ion catcher devices have so far been discussed and are now tested for installation. The first one is a gas-filled stopping cell, based on the standard IGISOL technology but upgraded to handle the high fragment energies of up to 100 MeV/u. A full scale gas catcher chamber with 1.2 m length and 25 cm diameter, designed for projectile energies of up to about 500 MeV/u [11], is presently being tested at GSI. The second possibility is an ion catcher device operated with superfluid helium. It has been recently demonstrated that 100 keV recoiling ^{219}Rn ions, originating from the decay of ^{223}Ra, were stopped and thermalized within 1 μm of this superfluid [15]. The stopped ions formed spontaneously "snowballs" which could be guided with electric fields to the liquid–gas surface, leading to an optimized surface extraction efficiency of 23%. A third type of ion catcher device has been proposed in the literature recently: Injection of the beam into an inverse cyclotron [16, 17]. Whether such a solution might be favorable for the GSI set-up will be carefully investigated and discussed.

3 Beam preparation and transport

The beam transport from the gas cell to the spectroscopy station is approaching its final design. We propose to extract the ions from the gas cell into a transport beamline which is at a negative potential of approximately 10 kV. This provides a beam energy sufficient for efficient beam transfer without the complications of a large gas cell on a high potential. A similar system has already been realized at MSU. The transport beamline will include a sector magnet for mass separation, to isolate those isotopes desired for investigation and also to remove reaction products of the

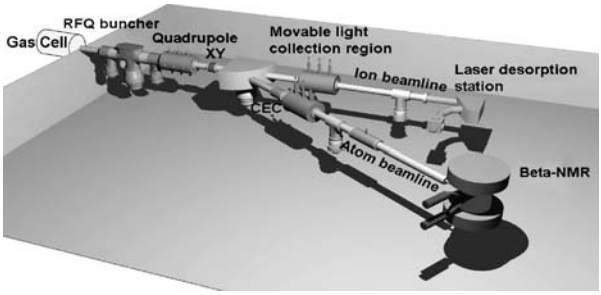

Fig. 2 Schematic layout of the proposed LaSpec spectroscopy station. The separator system, e.g. a magnetic sector field, between gas cell and RFQ cooler and buncher is not shown (CEC = Charge exchange cell)

ions with gas contaminant molecules (such as water, etc.). The beam will then be injected into a radiofrequency quadrupole (RFQ) buncher and cooler unit in which the ions can be stored and cooled by collisions with a neutral buffer gas. After a few ms cooling time the ions are bunched at the point of lowest potential, close to the exit, from which they can be extracted as a short pulse of a few microseconds length. Such cooler and bunchers are already operated routinely, e.g., at the ISOLTRAP facility [18] and at Jyväskylä [19]. The ion bunch is again accelerated into a beamline at lowered potential. A switch box will be used to distribute the beam to the LaSpec station or the MATS (Mass measurements with an advanced trapping system) set-up. As the MATS station needs to stop the ions again in a Penning trap, this is the preferred transport system. Typical collinear spectroscopy requires an ion beam at 40–60 keV. Hence, we will use a fast drift tube, which will be quickly raised in potential to up to +60 kV while the ions are passing through. After leaving the drift tube the bunches are accelerated and the subsequent transport line can be kept at ground potential.

4 The LaSpec station

The LaSpec collaboration intends to construct a number of complementary experimental devices which will provide a complete system with respect to the physics and isotopes that can be studied. A rough sketch of the proposed station is shown in Fig. 2. It includes the following techniques and capabilities, which are all discussed in detail in other contributions to this workshop.

Collinear laser spectroscopy: Collinear laser spectroscopy has been the workhorse for high-precision laser spectroscopy on short-lived isotopes for many years [1–3, 20]. Early work was mainly done on atomic systems, as their absorption lines were often in the visible region and therefore more readily accessible. Fast atomic beams are produced by charge exchange of ion beams in a cell containing a low pressure alkali-metal vapour. In some cases even metastable states are resonantly populated in the exchange process which provided more easily accesible transitions than those from the atomic ground state. Although the absorption lines of ions are typically in the deep blue and ultraviolet regions of the spectrum, suitable laser light can now be produced by frequency doubling or frequency mixing of cw lasers. Thus, a highly robust and universal spectroscopy is provided. The LaSpec set-up will provide one

short beamline dedicated to the spectroscopy of ions and a second, longer one, that is optimized for the spectroscopy of neutral systems. It is longer in order to make efficient optical pumping possible. A common optical detection region will be constructed that can be moved easily between the two beamlines. In combination with the RFQ cooler and buncher for background suppression, optical detection can be applied to ion species provided with yields as low as 100 ions/s as it has been demonstrated recently at Jyväskylä [13]. Another very interesting feature with respect to the RFQ cooler and buncher, is the population of excited, metastable ionic states using pulsed lasers inside the buncher. This will further extend the possibilities of collinear ion spectroscopy to cases where transitions from the ground state are not accessible with cw lasers [21]. In the atomic beamline, other sophisticated detection techniques are combined with collinear spectroscopy and provide single-particle detection and therefore better efficiency, such as collisional or resonance ionization.

Optical pumping and β-NMR: A particularly successful combination that has often been employed is the production of polarized beams of atoms and ions by optical pumping with subsequent β-asymmetry detection and β-NMR. This is a well-established method for the determination of nuclear magnetic dipole and electric quadrupole moments. The technique has been especially favoured for light elements [22] but has also been applied to a range of cases where high precision has been required to explore the nuclear structure (such as measuring small admixtures of intruder components in a wavefunction). The method combines optical pumping with nuclear magnetic resonance and β-decay asymmetry spectroscopy. Recently such spectroscopy has been used to determine the quadrupole moment of ^{11}Li to high accuracy using yields of only a few thousand ions/s [23] and the magnetic dipole and electric quadrupole moments of ^{8,9}Li [24]. The strength of this technique was again recently demonstrated with the determination of the ground-state spin and magnetic moment of ^{31}Mg [25]. The method can be used for all β-decaying (non-zero spin) isotopes with half-lives between approximately 5 ms and 20 s. Generally, β-NMR is able to deliver quadrupole moments with higher accuracy than those obtained from standard laser spectroscopy. However, laser spectroscopy and hyperfine structure investigations are necessarily the first step prior to attempting optical pumping.

Resonance Ionization Laser Ion Source (RILIS): Resonance ionization of atoms combined with the detection of the produced ions is a very efficient method in the study of rare isotopes [26]. During the last decade, it has been used for a broad range of applications, e.g., laser ion sources to produce ion species which were not accessible by other methods [27], in-source laser spectroscopy [28], and ultra-trace detection of cosmogenic and radio-toxic isotopes [29]. Its most prominent features are the efficient ionization process with resonant intermediate and autoionizing states, the elemental, isotopical, and sometimes even isomeric selectivity [30] and the large detection efficiency for the produced, charged particles. The use of laser ion sources at nuclear structural facilities has been demonstrated, advanced and developed to a point where it is the favored production mechanism by the ISOLDE group, CERN (and presently used for over 60% of all experiments). In the case of gas-jet ion sources, a careful systematic development both off-line and on-line has been achieved by the LISOL group of the University of Leuven [31].

At the FAIR facility's Low Energy Branch, a resonance ionization laser ion source will add to the selectivity inherent in the production method of the S-FRS and ion catcher device. In the stopping cell, whether it be a gas-filled or a superfluid helium catcher, the formation of singly- or doubly-charged positive ions is expected, as the first ionization potential of the stopping gas – usually helium – lies significantly above the first and often second ionization potential of all other elements. Nevertheless under on-line conditions with plasma present, and any small contaminations of H_2, N_2, O_2 and H_2O in the sub-ppm range, the charge state may be further reduced leading to neutralization by three-body recombination processes. These loss mechanisms to a neutral state can be a significant drawback to the IGISOL technique, however the process can be converted to an advantageous one if subsequently an efficient and selective laser ionization of the neutralized species is achieved. The RILIS will be used to enhance the production of isotopic (or even isomeric) enriched or pure ion beams. A natural development to a laser ion source is the installation of a laser ion source trap (LIST) [32], which may be coupled to the ion catcher. One possible design of a LIST is based on a typical segmented and gas-filled RFQ ion trap. Any neutral species that exit the ion catcher may be selectively ionized with counter propagating high-repetition rate pulsed lasers. The large size of the gas cell, is a challenge to the application of such methods and whether there is a reasonable way in doing so will be carefully investigated.

Laser-Desorption Resonance Ionization (LDRIS): Radioactive ions or atoms can be deposited on an appropriate catcher, laser desorbed, and studied during a secondary (and resonant) laser ionization [33]. When used in conjunction with Time-Of-Flight (TOF) mass-separation [34] and decay-tagged photo-ion detection an extremely sensitive spectroscopy can be achieved. For cases with very low production yields, the technique is superior to fluorescence detection. Such spectroscopy has previously, and notably, been used to study isotopes where the radioactive species was deposited in chemical or cluster form. It was also used for cases where the species of interest was not directly available but precursor nuclei could be deposited [35]. At FAIR the technique will be applied to the study of heavy neutron-rich elements (Pb, Bi, Pt, Au…) and will provide an opportunity to extend the investigation of these elements beyond the neutron-deficient cases previously studied at ISOLDE [36–39]. The laser desorption station will be located at the end of the collinear ion beamline. Here, a commercial but adapted MALDI-TOF (Matrix-assisted laser desorption and ionization - time of flight) apparatus will be used. Two fast kickers will be used to translate the incoming ion beam after deceleration in horizontal or vertical direction in such a way that the extracted beam after implantation, desorption and laser ionization, can be separated and sent into the TOF system.

Spectroscopy in an Electron Beam Ion Trap (EBIT): An additional option for laser spectroscopy is a spectroscopy of highly-charged radioactive ions inside an electron beam ion trap. Such a device is an integral part of the MATS experimental set-up, located very close to the LaSpec spectroscopy station. Precision measurements of the hyperfine splitting of the atomic ground state can be performed to investigate, e.g., details of the nuclear magnetization distribution [40]. This might be particularly interesting in cases of rather short-lived isotopes that cannot be measured at the HITRAP setup, where it takes a few 10 s to prepare the cold highly charged ions [41, 42].

5 Summary

The future facility FAIR at GSI, Darmstadt, will provide beams of radioactive isotopes that cannot be produced elsewhere. The LaSpec collaboration (http://www.gsi.de/LaSpec), presently formed by 13 institutes from 7 countries, will exploit the possibilities for on-line laser spectroscopy of these species. Nuclear charge radii, spins, and electromagnetic moments of nuclear ground and long-lived isomeric states will be investigated using collinear laser spectroscopy, resonance ionization, β-NMR, and laser desorption.

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