

# **LASER spectroscopy for the study of nuclear properties**

## **LASPEC Collaboration**

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### **Abstract**

Using advanced Laser spectroscopy methods, nuclear ground state spins, moments, charge radii, of radioactive nuclei can be determined. The optical techniques, based on hyperfine structure splitting (HFS) or isotope shift measurements, yield *model-independent* information about the nucleus. Various experimental methods and concepts are proposed to take advantage of the exotic nuclei provided at low energy, including spectroscopy on trapped, highly-charged ions, which is a new approach for studies of nuclear and isotopic effects with high sensitivity.

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## **Table of contents**

<b>1. Introductory note</b>	<b>76</b>
<b>2. Physics case</b>	<b>76</b>
<b>3 Experimental scenarios</b>	<b>78</b>
<b>4. Implementation</b>	<b>79</b>
<b>4.1 Experimental area</b>	<b>79</b>
<b>4.2 Radiation environment</b>	<b>79</b>
<b>4.3 Cost estimate</b>	<b>79</b>
<b>4.4 Organization</b>	<b>79</b>
<b>4.5 Time schedule</b>	<b>79</b>
<b>4.6 Beam time</b>	<b>80</b>

## 1. Introductory note

The approaches described here to measure moments of the nuclear charge distribution are complementary to other scenarios intended at the new facility, like dielectronic recombination or electron scattering with the eA-collider.

## 2. Physics case

The optical techniques, based on hyperfine structure splitting (HFS) or isotope shift measurements, yield *model-independent* information about the nucleus [1,2], and the theory of isotope shifts and HFS is sufficiently well understood to yield precise information on the size and shape of nuclei. On-line laser spectroscopy allows one to study the nuclear properties of ground and isomeric states of short-lived, exotic isotopes which are available in only small quantities. The properties that can be studied are

- the nuclear spin  $I$
- the magnetic moment  $\mu_I$
- the spectroscopic nuclear quadrupole moment  $Q_s$  and
- the changes in the mean-square nuclear charge radius  $\delta\langle r^2 \rangle$  between isotopes

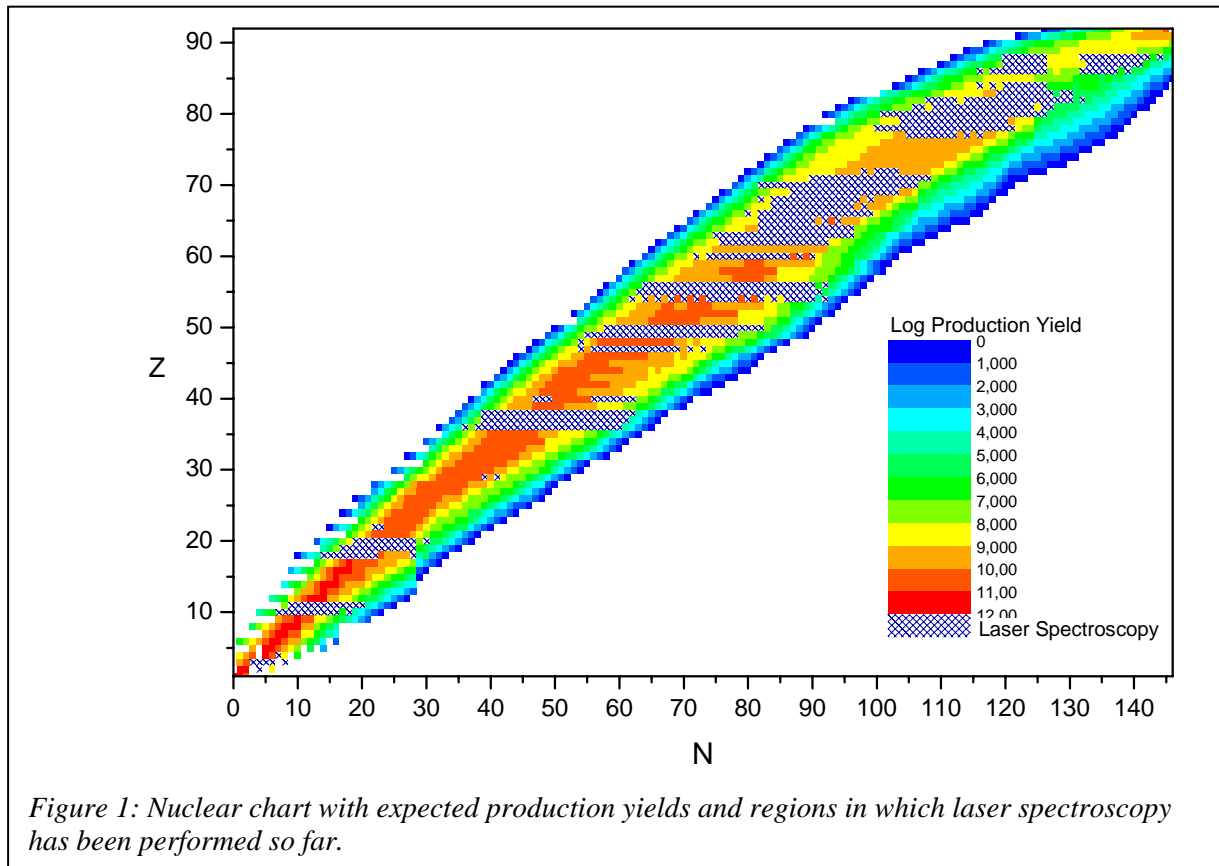
It should be noted that longer-lived isomers ( $T_{1/2} > 10\text{ms}$ ) are also accessible. These experimental data are highly accurate and the nuclear parameters can be extracted without a need of a nuclear model. Since the model-independent data are collected in long isotopic chains reaching far from the valley of nuclear stability, these data provide clear information on single-particle as well as collective nuclear effects and enable stringent tests of nuclear models. Furthermore, new phenomena might be discovered which do not show up in stable or long-lived isotopes or which can only be detected as deviation from systematic trends of neighboring isotopes. A striking example is the nuclear shape coexistence and shape transition detected by optical spectroscopy in the mercury region.

Today, mainly two laser techniques are applied: Resonance Ionization Spectroscopy (RIS) of neutral atoms and Collinear Laser Spectroscopy (CLS) of neutral atoms and of singly- and highly-charged ions. In general, the first technique offers the highest sensitivity while the second provides the highest resolution. The present limit for the minimum yield for collinear laser spectroscopy is of the order of 100 ions/s and the shortest-lived isotope investigated is  ${}^{11}\text{Li}$  [3] with a nuclear half-life of  $T_{1/2} = 9\text{ ms}$ . By resonance ionization spectroscopy, the HFS and the IS of radioactive atoms with a nuclear half-life as short as  $T_{1/2} = 1\text{ ms}$  ( ${}^{244\text{f}}\text{Am}$ ) has been determined at a production rate of about 10 ion/s [4]. In principle, isotopes with shorter ground-state half-lives would still be accessible by laser spectroscopy, which depends only on the production yield and not on the nuclear half-life.

Furthermore, magneto-optical traps are presently applied for atomic structure investigations of radioactive atoms [5]. This demonstrates that they could be used to study nuclear ground-state properties, utilizing the advantages of a localized, concentrated, and cold sample. Another application is the measurement of the  $\beta$ -neutrino correlation via a coincidence measurement of the recoil ion and the  $\beta$ -particle momenta [6,7] or the measurement of the asymmetry parameter of the  $\beta$ -decay of polarized nuclei [8]. Precise measurements of the angular correlations in  $\beta$ -decay allow one to search for new physics beyond the Standard Model, such as scalar, tensor, or right-hand contributions. Radioactive atom trapping has been confined to the alkali elements so far. However, trapping methods have been developed and employed for most of the stable alkaline earth elements, as well as the rare gases, where metastable states have been used. In the future, similar trapping schemes might be developed for other species as well.

Up to now, most of the optical investigations on short-lived isotopes were performed at ISOL facilities where the radioactive products have to diffuse out of the target matrix. Therefore, no or little information is available for nuclides with half-lives of less than 100 ms or for isotopes of elements which do not diffuse out of the target material because they are non-volatile or chemically reactive. Here, the universal, fast and chemically non-selective production technique of projectile fragmentation and fission

as applied at GSI, as well as the increased yields available at the planned new facility, will enable extension of the knowledge of nuclear ground state properties in isotopic chains to regions further away from the valley of nuclear stability. This is illustrated in Fig. 1.



Here, the expected yields for the different isotopes are plotted and the regions where laser spectroscopy has been performed on chains of radioactive isotopes are indicated. The most interesting regions close to the proton and neutron drip lines have only been reached in few cases. With the exception of titanium, nothing is known from laser spectroscopy on short-lived nuclei in the region of refractory elements around iron ( $Z = 26$ ) because of the lack of efficient production schemes at ISOL facilities. Similarly, there are gaps in the region of refractory elements around molybdenum ( $Z = 42$ ) and tungsten ( $Z = 74$ ). This clearly shows the potential of gathering new information about the ground state structure of nuclei on the Low-Energy Branch at the Super-FRS. Some special regions of interest are:

- the light refractory region
- high K-isomers
- the octupole region around  $^{222}\text{Th}$
- neutron-rich heavy systems

Table 1 summarizes the possibilities of laser spectroscopy at the Low-Energy Branch.

Table 1: Different laser spectroscopic schemes for radioactive nuclides at the planned GSI facilities. CLS: collinear laser spectroscopy; FS: fluorescence spectroscopy; RIS: resonance ionization spectroscopy; HFS: hyperfine structure; IS: isotope shift; R: resolving power; NAT: neutral atom trap; 1+: singly-charged ions.

Method	Charge state	Detection	Measured	Minimum No. of Particles	Minimum $T_{1/2}$	Resolution	Remarks
RIS	Neutral	Ions	HFS, IS	1/s	1 ms	Low	Directly in gas-filled stopping cell
FS (in ion trap)	1+	Photons	HFS, IS	$10^4$ stored	10 ms	High	Ion trap at room temperature
CLS	Neutral/1+	Various	HFS, IS	$10^2$ /s	10 ms	High	After reacceleration to a few 10keV
RIS	Neutral	Ions	HFS, IS	$10^4$ /s	10 ms	Medium	Accumulation and desorption
FS (in laser trap)	Neutral	Photons	HFS, IS	1 stored	10 ms	High	Restricted to some elements

### 3. Experimental scenarios

**Gas cell:** Inside the gas cell **resonance ionization spectroscopy** on the resulting neutral species is possible. The technique has been recently successfully demonstrated for the case of isotope shift measurements of superdeformed isomeric states in Am isotopes [4]. High sensitivity as well as a low half-life limit is obtained on the expense of resolution.

**Extracted beams:** To the low-emittance ion beams extracted from the stopping cell with an energy of several 10 keV **collinear laser spectroscopy**, resonance ionization spectroscopy, or other optical techniques can be applied on the singly-charged ions or, employing a charge exchange cell, on a fast atomic beam.

**Neutral atom trap:** such a trap can be used to perform laser spectroscopy with very high resolving power and isotopic selectivity. Presently, the technique is restricted mainly to noble gases and alkalis. Quite a number of atomic transition wavelengths, atomic life-times, HFS and hyperfine anomalies have been determined recently for francium isotopes [9]. Although single-atom sensitivity is reached, the efficiency for loading neutral atom traps has to be increased. This is one of the results expected from the European RTD network NIPNET.

**EBIT measurements:** The ions stored in the **EBIT** used for charge-breeding can be excited with both pulsed and cw tunable lasers. Forbidden transitions in the visible range have shown a high sensitivity to nuclear-size and QED effects [10,11], which can be exploited in this proposed setup to obtain nuclear spins and magnetization distribution information. Ti-like ions, which can be easily produced in the EBIT, are very amenable to this type of studies due to the flat scaling of the wavelength of the main forbidden line. Other configurations, such as B-like and Be-like, also offer a number of forbidden transitions with a high sensitivity to nuclear and isotopic effects, but with the additional advantage of the simpler atomic structure. In these cases, *ab initio* calculations can be carried out. By using a high-energy electron beam (up to 300 keV), the Low-Energy Branch EBIT should be able to produce hydrogen-like ions of heavy elements. Their ground-state hyperfine transitions have already been studied at the LLNL SuperEBIT [10], although without laser excitation. The application of laser spectroscopic techniques to radioactive trapped ions seems therefore straightforward, and it promises a great increase in experimental precision. The MPIK group is already testing such a setup at the Heidelberg EBIT. The use of laser excitation allows to manipulate the trapped ions through the hyperfine structure of the resonantly excited

transitions. The ions can be also be optically pumped in short times, and nuclear polarization can be achieved in this way. The polarized nuclei can be studied in the EBIT, or extracted from it and delivered to other experiments. Therefore, there is a compelling case for the inclusion of a laser beamline to the EBIT laboratory, or for a dedicated EBIT laser-spectroscopy setup.

## 4. Implementation

### 4.1 Experimental Area

The set-up will be installed in the Low Energy Cave.

Width: 3 m      Length: 6 m      Height: 3 m

**Laser Laboratory:** ~30 m<sup>2</sup>, cooling water and high power connection

### 4.2 Radiation Environment

No special requirements (experiments are performed with only a few thousand ions per second)

### 4.3 Cost Estimates

Laser System:	
- Pump laser	150 kEUR
- TiSa	150 kEUR
- Frequency doubler	50 kEUR
- Frequency Stabilization	50 kEUR
Detection System	50 kEUR
Vacuum components	150 kEUR
Optics	50 kEUR
<b>SUM</b>	<b>650 kEUR</b>

Note: The costs given here are exemplary for a typical laser system needed for a collinear laser spectroscopy setup mentioned above. Different setups for other experimental opportunities will require a different cost scheme. Moreover, there will be several places at the International Accelerator Facility for Beams of Ions and Antiprotons at GSI, where laser spectroscopy with pulsed or cw-lasers is planned. Some of these setups can certainly be combined and the possibility for fiber transport to different experimental areas should be evaluated. Thus detailed costs cannot be specified at this early stage.

### 4.4 Organisation and Responsibilities

To be identified. In any case, the conceptual layout of the setup will be established as a combined effort with the Penning trap collaboration(s) in order to efficiently use the available resources and to reach optimum performance and physics capabilities.

### 4.5 Time schedule

Overall preparation period: ~ 3-4 years

The complete setup can be tested, operated, and optimized off-line with test ion sources.

#### 4.6 Beamtime

The setup will be permanently installed at the Low-Energy Branch. Experimental campaigns of about 4 weeks per year (overall, split in periods of typically one week each) should be envisaged and will be ideally be combined with other experiments using reaccelerated beams and same or similar nuclides.

#### References

- [1] H.-J. Kluge and W. Nörtershäuser, *Spectrochimica Acta B* 58, 1031-1045 (2003).
- [2] E.W. Otten, *Nuclear radii and moments of unstable isotopes*, in *Treatise on heavy-ion science*, D.A. Bromley, Editor. 1989. p. 517-638.
- [3] E. Arnold *et al.*, *Phys. Lett. B* 197, 311-314 (1987).
- [4] H. Backe *et al.*, *Phys. Rev. Lett.* 80, 920-923 (1998).
- [5] G.D. Sprouse *et al.*, *Nucl. Phys. A* 701, 597-603 (2002).
- [6] J.A. Behr *et al.*, *Phys. Rev. Lett.* 79, 375-378 (1997).
- [7] A. Gorelov *et al.*, *Hyperf. Int.* 127, 373-380 (2000).
- [8] S.G. Crane *et al.*, *Phys. Rev. Lett.* 86, 2967-2970 (2001).
- [9] J.S. Grossman *et al.*, *Phys. Rev. Lett.* 83, 935-938 (1999).
- [10] I. I. Tupitsyn *et al.*, *Phys. Rev. A* **68** (2003) 022511
- [11] I. Draganic *et al.*, *Phys. Rev. Lett.* **91** (2003) 183001