Performance of Dye and Ti:sapphire laser systems for laser ionization and spectroscopy studies at S³

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Abstract

The novel and sensitive In-Gas Laser Ionization Spectroscopy (IGLIS) technique enables high-precision laser spectroscopy of the heaviest elements and isotopes very far from stability that are produced in fusion-evaporation reactions at in-flight separators. Powerful and dedicated laser systems are required in these facilities to realize in-gas jet laser spectroscopy with optimal spectral resolution and efficiency. The performance with respect to the requirements for IGLIS studies at the low energy front-end of the Super Separator Spectrometer (S³) at GANIL, France, of Dye and Ti:sapphire laser systems is investigated. In addition, a number of specific experimental cases on key isotopes of the elements Ag, Sn, Ac, and No are discussed in detail.

Keywords: Resonance ionization spectroscopy, in gas laser ionization and spectroscopy, in flight separators, Dye laser, Ti:sapphire laser

Introduction

In-flight separation of fusion-evaporation products gives access to neutron-deficient isotopes in and near the $N = Z$ and the proton drip lines as well as in the actinide and super-heavy element (SHE) regions that can be used, e.g., for nuclear and laser spectroscopy studies. The in-gas laser ionization and spectroscopy (IGLIS) techniques will be applied at the Super Separator Spectrometer (S³) facility in GANIL [1–3] and at the MARA (Mass Analysing Recoil Apparatus) facility in Jyväskylä [4, 5], among others, to perform such studies. Plans also exist to apply the IGLIS technique at the KISS facility in KEK [6] to study refractory isotopes around the $N = 126$ shell closure produced in multi-nucleon transfer reactions [7]. Whereas laser spectroscopy inside the gas cell has routinely been applied for the last ten years [8–11], the online proof-of-principle of the in-gas-jet ionization and spectroscopy method was only recently demonstrated [12, 13] with a follow up campaign of characterization studies that are currently ongoing at the IGLIS laboratory in KU Leuven [14] to reach an optimal performance [15] on the study of exotic nuclei.

In this context, resonant multi-step in-gas-jet laser ionization [16] will be applied to produce radioactive ion beams (RIBs) of high purity for their use in combination with other experimental nuclear techniques, and also to perform laser spectroscopy studies of heavy elements with an unprecedented spectral resolution, whereby ground and isomeric-state properties such as

nuclear spins, magnetic moments, and charge radii can be extracted [17, 18]. The main advantage of resonance ionization laser ion sources, through which the atom of interest is finally ionized by means of laser excitation, is the high attainable sensitivity and selectivity.

A powerful and versatile laser system is important to reach the anticipated performance in ionization efficiency and spectral resolution for a variety of different elements. Dye lasers as well as Ti:sapphire based solid state lasers are in use for spectroscopic investigations and as all-purpose resonant ionization laser ion source (RILIS) at hot cavity Isotope Separator on-line (ISOL) facilities [19–21].

This article investigates the individual characteristics of Dye and Ti:sapphire laser systems as main components of the laser ion source and spectroscopic tool at the S³ Low Energy Branch (LEB) facility. Thus, the performance of the two laser systems is evaluated in terms of the requirements for efficient and high-resolution resonant laser ionization and spectroscopy experiments. Finally, a number of specific experimental cases on key isotopes intended for laser spectroscopy studies in the initial experimental campaigns of the S³-LEB facility are surveyed.

The IGLIS technique at the S³-LEB

At the S³-LEB the fusion-evaporation residues, separated in-flight from the primary beam and preselected by S³ [3], will be stopped in a buffer gas cell placed at the spectrometer's focal plane for laser spectroscopy studies and experiments at low energies [2]. Laser ionization of the isotopes of interest

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Figure 1: Schematic layout of the IGLIS setup at the S^3 -LEB in SPIRAL2. Laser ionization will take place either in the gas cell or in the supersonic gas jet for higher selectivity and spectral resolution [16].

will take place either inside the gas cell or in the supersonic gas jet formed by a de Laval (i.e. convergent-divergent) nozzle, depending on the intended application. A schematic layout of the IGLIS set-up at the S^3 -LEB is shown in Fig. 1. Two complementary laser systems will be used for IGLIS studies. A Ti:sapphire-based laser system that is currently being commissioned at GANIL (see Fig. 2) and a dye laser system similar to that in full operation at KU Leuven [14] (see also Sec. e). After photo-ionization, the ions will be confined and separated from the gas jet by a radiofrequency quadrupole (RFQ) ion guide, which will transport them through the high pressure jet chamber towards the extraction RFQ acting as a pumping barrier. Owing to a pressure of up to 0.1 mbar in the jet chamber in combination with a high gas flow, additional differential pumping is required to reach a vacuum better than 10^{-5} mbar needed for mass filtering and detection of the ion beam.

The in-gas-cell laser ionization method has been applied on-line on radionuclides from accelerator-driven fusion or fission reactions at LISOL [8, 22], TU Munich [23], GSI [24, 25] and KISS, RIKEN [26] whereas off-line studies have been performed at Jyväskylä [27] and PALIS, RIKEN [28]. Because of the low gas-flow velocities within the gas cell of a few 3 m/s, a pulse repetition rate of 100–200 Hz is sufficient to efficiently excite and ionize the atoms. Nevertheless, spectroscopic studies are affected by the high pressure environment, which introduces a collisional broadening that limits the final spectral resolution to a few GHz [7, 9–11].

For higher spectral resolution, the laser spectroscopy will be performed in the low-temperature and low-density supersonic gas jet directly after the gas cell exit [2]. An improvement in spectral resolution of more than one order of magnitude was

demonstrated off-line using stable Cu isotopes [16] and on-line for $^{214,215}\text{Ac}$ at the LISOL facility [12, 13], as well as very recently for stable Pt isotopes at the KISS facility [29]. To optimize the resolution while retaining highest efficiencies, the properties of the jet as well as the final experimental conditions and characteristics of the gas jet are being explored at the IGLIS laboratory in KU Leuven [14, 15].

In a well-formed gas jet at Mach 8 the collisional broadening is nearly eliminated and contributes with about 20 MHz to the budget of the total linewidth. The remaining line broadening mainly originates from the gas temperature of about 15 K, which results in a spectral width of $\Gamma_{\text{Doppler}} = 300$ MHz for ^{63}Cu excited by the 326 nm transition. The total jet velocity is kept practically constant for high Mach numbers ($M > 5$) and is mainly determined by the stagnation temperature and the mass of the carrier gas. It is found to be 550 m/s for argon at a stagnation temperature of 300 K. Lasers with high-repetition rates in the order of 10 kHz are therefore necessary. To reduce the sensitivity on any remaining jet divergence the spectroscopy laser can be aligned anti-collinear ($\parallel$) as indicated in Fig. 1. The high power, ionization laser will then irradiate the jet perpendicularly ($\perp$) preventing unwanted ionization inside the gas cell. This laser has to cover an area of about 55 mm in length and the jet diameter in height (e.g. ~ 5 mm for $M = 7$) to interact with each atom in the jet. The Mach number M of the jet defines its final temperature T and thus the spectral resolution, as well as gives an indication of the jet diameter [16]. Table 1 compares the interaction areas of different configurations and also lists area enhancement factors compared to hot cavity-based laser ion source applications, where most information on saturation of individual transitions is available. For the ionization transition the illuminated area will increase up to a factor of 79 for a gas jet with Mach 12. Taking into account that the ion-

Figure 2: Schematic layout of the Ti:sapphire laser system at the S³-LEB. Two Nd:YAG lasers will be employed to pump four Ti:sa cavities. Two of these cavities are frequency-tuned by birefringent filters whereas a third one uses a grating for frequency selection and scanning. In the last cavity the amplification of a continuous-wave single-mode seed laser takes place resulting in a pulsed narrow-bandwidth radiation that can be used for high resolution in-gas-jet spectroscopy experiments. The output laser light from all cavities can be frequency doubled (SHG) or tripled (THG) using non-linear optical crystals such as BBO.

Figure 3: Possible arrangement for multi reflection of the ionizing laser beam to increase the power density along the illumination area of about 55 mm while preventing unwanted ionization by the access of high-power radiation into the gas cell.

120 ionizing transition requires full saturation for highest sensitivity, a
multi-reflection of this laser beam could be employed as shown
in Fig. 3. Nevertheless, the feasibility of such an arrangement
depends on the pressure and temperature homogeneity of the gas
jet which are investigated [15]. For the same conditions
125 the spectroscopic transition in anti-collinear arrangement has
an 11-fold increased interaction area.

Resonant laser ionization

Resonant laser ionization uses the atomic level structure to stepwise excite and photo-ionize a neutral atom by resonantly-tuned laser radiation as schematically shown in Fig. 4. This technique was explored by Lethokov and Hurst [30, 31] and features an inherent elemental selectivity as well as a high efficiency due to the large cross sections for resonant excitation processes and the efficient ion manipulation and detection. Because of these advantages the technique is employed for a multitude of applications, including trace detection [32, 33], efficient ionization of rare isotopes [34–36], and spectroscopic investigations [18, 37, 38]. The bottleneck of this method is the final ion-

izing transition. The cross section for non-resonant laser ionization into the continuum ($\sigma_{\text{cont}} \approx 10^{-17} \text{ cm}^2$) above the first ionization potential (IP) is orders of magnitudes smaller compared to resonant excitation ($\sigma_{\text{res}} = \frac{\lambda^2}{4\pi} \approx 10^{-10} \text{ cm}^2$). Alternatively, resonant excitation of high lying bound Rydberg states ($\sigma_{\text{Ry}} \approx 10^{-12} \text{ cm}^2$) or auto-ionizing (AI) resonances ($\sigma_{\text{AI}} \approx 10^{-15} \text{ cm}^2$) above the IP can be applied. Rydberg states allow to precisely determine the IP, as, e.g., shown for At and Ac [39, 40], but are rather sensitive to environmental conditions such as pressure and electric fields. Owing to the high quantum number of the excited valence electron, Rydberg states feature long lifetimes and therefore narrow spectral profiles. AI resonances are short-lived bound states above the first IP involving more than one electron decaying into an ion–electron pair and enable a resonant enhanced excitation and ionization, making these structures an ideal tool for resonant ionization applications. The only drawback arises from the fact that not all elements feature AI resonances and that, in general, the knowledge on these structures is limited.

The generally low cross section of the ionizing transition requires high-photon fluxes within the lifetime of the atomic states, therefore typically pulsed lasers with ns pulse lengths and high energy per pulse are used. For high efficiencies the involved transitions with cross section σ have to be saturated with photon fluences $\Phi \gtrsim \sigma^{-1}$, assuming that the laser pulse is shorter than the relaxation time. The larger cross section for resonant transitions σ_{res} allows for saturation energy fluences I_{sat} as low as a few 10 nJ/cm^2 across the natural linewidth Γ while for non-resonant ionization fluences exceeding 1 mJ/cm^2 are required. Nevertheless, the required laser power can be significantly larger depending on the specific experimental conditions. For an ensemble of atoms with a Doppler broadening Γ_{Doppler} that is larger than the laser bandwidth, additional saturation broadening of the transition is required so that all atoms

Table 1: Dimensions of different geometries and the according areas which have to be illuminated using argon. Hot cavity ionization has the smallest interaction area and is used as reference.

set up	diameter		area
	mm	mm ²	
hot cavity	∅ 3	7.1	1
gas cell [†]	∅ 5	19.6	2.8
gas jet (Mach 7)	∅ 5		
laser ⊥ jet		275 [‡]	39
laser jet		19.6	2.8
gas jet (Mach 12)	∅ 10		
laser ⊥ jet		550 [‡]	79
laser jet		78.5	11

[†] ionization in transverse geometry to the gas cell exit channel

[‡] assuming an interaction length along the jet of 55 mm

can be addressed. In a closed level scheme the power saturated linewidth Γ_{Sat} is given by

$$\Gamma_{\text{Sat}} = \Gamma \sqrt{1 + \frac{I_{\text{Laser}}}{I_{\text{sat}}}} \stackrel{!}{=} \Gamma_{\text{Doppler}} \quad (1)$$

and should be made equal to ($\stackrel{!}{=}$), or match, the Doppler distribution. For a residual Doppler width of $\Gamma_{\text{Doppler}} = 200$ MHz and a transition linewidth of $\Gamma = 1$ MHz a laser intensity I_{Laser} of about $400 \mu\text{J}/\text{cm}^2$ is therefore required to maintain a high efficiency. Here, optical transitions with a larger transition strength, given by the Einstein A-factor A_{ki} , and thus with an increased natural linewidth can be beneficial to reduce the requirements in pulse energy.

Resonant laser ionization is used for efficient and selective ionization of exotic radionuclides from hot-cavity targets and gas filled stopping cells [7, 20, 27, 34–36]. The process of resonant laser ionization provides high efficiencies for a wide range of elements [21, 36, 41], limited by the availability of the required laser radiation for the first excitation transition. The unique and well-defined level structure of each element provides a Z-selective ionization, and in combination with a mass-to-charge-ratio separation, isotopic ion beams of high purity can be produced. As most elements feature a multitude of optical accessible transitions as compiled in, e.g., [42, 43], the ionization scheme can be adapted to the available laser system. For the determination of an ionization scheme, however, some considerations should be taken into account. (i) Larger transition strengths A_{ki} are in general beneficial for an efficient excitation. (ii) The resonant transition must be strong compared to other radiative decays of the excited level. (iii) The low cross sections of the ionization steps require a high photon flux and therefore often the fundamental laser radiation of Dye and Ti:Sapphire lasers is used. In hot cavity RILIS applications a three step ionization scheme using lower energetic photons is additionally advantageous as high power ultraviolet (uv) laser

Figure 4: Schematic principle of resonant laser ionization with different ionization processes.

radiation tends to non-resonantly ionize molecules or elements with a low IP which creates an additional source of background.

Resonance Ionization Spectroscopy

The technique of resonant laser ionization is also applied to study fundamental atomic and nuclear physics. The energetic position of atomic levels makes it possible to identify, e.g., ionization potentials and to test models and numeric calculations in highly correlated electron systems [39]. The isotope-dependent shift and the splitting from the hyperfine structure (HFS) of these levels originate from the interaction between the atomic electrons and the nucleus and enable the study of fundamental ground-state properties in nuclear physics [18, 44]. The sensitivity of atomic transitions to the structure of the nucleus significantly depends on the electron wave functions of the atomic levels. This reduces the number of suitable optical transitions for RIS and therefore puts stronger requirements to the laser system. To perform sensitive measurements of nuclear-ground state properties the level HFS should ideally be resolved with the available spectral linewidth of the employed laser system and the existing broadening mechanisms. For hot-cavity applications a resolution of a few GHz results from the thermal velocity distribution of the atoms, whereas collisions in a buffer-gas filled stopping cell usually broaden the transition lines by a few 10 MHz/mbar [11]. This limitations can be improved when applying RIS in a fast beam [38, 45–47], a perpendicular arrangement of an atom beam and laser beams [48] or in a supersonic gas jet [15, 16]. For such applications, a suitable narrow bandwidth laser system is required and the laser power should enable a saturation broadening of the spectroscopic transition which is comparable to the Doppler profile to achieve highest efficiencies. If the residual Doppler broadening is sufficiently small, resonance ionization also enables addressing much weaker transitions in comparison to fluorescence tech-

niques [49]. The ionizing transition, in contrast, has to be fully saturated to obtain the highest efficiency and the laser system has therefore to provide sufficient laser power. Although, in general, two-step schemes are preferable, three-step ionization schemes might be considered as well. In the latter case, the intermediate transition which usually is in the visible or IR wavelength range can be used to study magnetic and quadrupole moments with higher precision as the Doppler broadening scales directly with the transition's frequency. In this line, the intermediate transition in a three-step scheme of Po was used for spectroscopy in hot-cavity RIS [50]. Nevertheless, such an operation has to be tested thoroughly off-line to exclude systematic effects arising from coherent two photon excitation.

Laser system

The application of the IGLIS technique at the S³-LEB aims for laser spectroscopy studies with sufficient resolution to precisely determine the hyperfine atomic parameters as well as for efficient laser ionization in the gas-cell and gas-jet environments. A prerequisite for these investigations is the availability of tunable and high-pulse-energy laser radiation with the possibility of narrow bandwidth operation. Especially, the high velocity of the atoms in the gas-jet method requires high-repetition pulse rates of about 10 kHz. Ti:sapphire based solid-state lasers and dye lasers can be used to generate tunable laser light. Both high-repetition laser systems on their own, and also combined, have shown their capability as universal RILIS at hot-cavity ISOL facilities [19, 36, 51] proving an efficient ionization of a multitude of elements. A dye laser system is implemented in the IGLIS laboratory at KU Leuven, aiming to fully characterize the in-gas-jet ionization method [14] and features a wide wavelength coverage, high-pulse energies and narrow bandwidth. On the other hand, a Ti:sapphire laser system requires less maintenance and is already available at GANIL [52]. This section reviews the main characteristics (summarized in Tab. 2) of the two laser systems.

Dye lasers

Dye lasers use a solution of dye molecules solved in an organic solvent as active medium that absorbs laser light from a pump laser and emits coherent tunable light at a lower photon energy. Due to the large gain for stimulated emission of the dye molecules, lasing occurs already with low quality laser cavities. Owing to the large gain and the short lifetime (ns) of the excited molecular level the laser light is instantaneously emitted with the pump laser pulse. The length of the generated laser pulse is defined by the pulse duration of the pump pulse, which is typically about 8–10 ns. The spectral bandwidth of high-power lasers is typically in the order of 1–10 GHz. For pulsed Dye lasers the oscillator cavity design is most often realized with a grating as frequency selective element operated at low powers. Bandwidths down to the Fourier limit of about 50 MHz can be achieved when substituting the oscillator cavity with a narrow bandwidth continuous wave (cw) seed laser in a pulsed-dye amplifier, but this requires in addition the pump

laser to operate in single mode [53]. The laser light emitted from the oscillator or from the seed laser can then be amplified in additional stages using the same pump laser. The large optical gain of the dyes allows to scale the laser light power easily with the available pump power. For repetition rates up to 200 Hz, Excimer lasers at e.g. 308 nm (XeCl) or 248 nm (KrF) as well as solid state Nd:YAG lasers at e.g. 532 nm (second harmonic) or 355 nm (third harmonic) are available for pumping. These lasers are able to provide average energies per pulse of more than 100 mJ. For high-repetition pulse rates of 1–20 kHz, pump sources are typically solid state lasers such as Nd:YAG lasers. Here, pump powers of 90 W (9 mJ at 10 kHz) of 532 nm laser radiation or 36 W of 355 nm laser radiation are available at the IGLIS Laboratory in Leuven with Edgewave Innoslab Nd:YAG-lasers. This results in dye laser powers of up to a few 25 W (2.5 mJ) depending on the gain of the dye, as shown in Fig. 5. The achievable wavelength in the fundamental covers 370–900 nm, considering both pump options at 532 nm and at 355 nm and about 30 different dyes. With the generation of second harmonics, all wavelength down to 205 nm can be realized, while the available power is reduced.

In summary, the Dye laser system generates tunable light over a wide spectral range with high-pulse energies that makes it possible to cover nearly all potential cases. Furthermore, for some of the cases the power will exceed the requirements for spectroscopic investigations. Disadvantages are the degeneration or aging of some dyes which lead to non-constant laser powers and require a regular maintenance of the system. The general tuning range of the system is effectively determined by the dye, and to a lesser degree the solvent, in use. The organic solvents are flammable and some dyes are toxic or their toxicity is unknown posing therefore additional hazards.

Titanium:sapphire lasers

Ti:sapphire lasers use the band structure of Ti³⁺ ions in a sapphire host crystal. Pumped with the, e.g. 532 nm light from the second harmonic of a Nd:YAG laser, the population can be inverted and lasing can occur from 680 to 1000 nm. In comparison to dye lasers the gain is significantly lower and the lifetime of the inversion is 3.2 μs. To reach the lasing threshold a medium quality resonator is required. Frequency selection can be achieved either with a grating or a combination of coated mirrors, birefringent filter (BRF) and etalons. A Ti:sapphire laser system for resonance ionization and spectroscopy has been designed and optimized at Mainz university [54, 55] and is employed at different RIB facilities [21, 52, 56].

This laser system features an effective spectral bandwidth of a few GHz for high-power applications with a temporal laser pulse length of 35–50 ns. The bandwidth can be reduced to about 1 GHz, corresponding to 3–4 cavity modes, using a second thick etalon [57]. Further reduction to single mode operation is possible when injection locking the cavity to an external narrow bandwidth cw seed laser. This enables a spectral bandwidth of 10–20 MHz [58, 59], but additional experimental efforts are needed for the cw laser, as well as for the locking of the pulsed cavity.

Because of the low gain of the active medium and the damage

Table 2: Summary of the main characteristics of Dye and Ti:sapphire lasers for operation at a 10 kHz repetition rate in RILIS and RIS application.

	Dye laser	Ti:sapphire laser
Active Medium	> 25 different dyes	Ti:sapphire-crystal
host material	organic solvent	solid state
Pump laser	Nd:YAGx2(532 nm), up to 9 mJ Nd:YAGx3(355 nm), up to 3.6 mJ	Nd:YAG x2(532 nm), up to 2 mJ
Spectral range	370–620 nm , 550–900 nm	680–1000 nm
harmonic generation	205–450 nm	205–330 nm & 345–495 nm
Pulse energy	<2 mJ	<0.5 mJ
Pulse duration	8 ns	40 ns
Bandwidth	1.5–3 GHz ^a 50 MHz ^{b,d}	1–10 GHz ^a 10 MHz ^{c,d}
Maintenance	renew dye solution	none

- ^a Spectral multi mode structure
^b Spectral single mode structure, pulsed amplification of cw seed laser
^c Spectral single mode structure, injection locking of cw seed laser
^d Tuning and availability depends on cw-master laser

thresholds of the crystal surfaces and the resonator optics the pulse energy is not as widely scalable as for dye lasers. The current University Mainz cavity design can be pumped with powers of up to 20-25 W of 532 nm laser light at a repetition rate of 10 kHz, resulting in output powers above 5 W (0.5 mJ at 10 kHz) in the maximum of the gain profile at 800 nm. Post amplification of the fundamental laser radiation has not yet been exploited for such a laser design, but has been used for ns-Ti:Sapphire lasers at lower repetition rates, see, e.g., ref. [60]. With the generation of higher harmonics, lower wavelengths can be generated with a corresponding loss in power as summarized in Fig. 5. Especially the second harmonic output can be generated efficiently by intra-cavity doubling [61] allowing for laser powers of up to 2 W (0.2 mJ). Gaps appear in the wavelength region from 330-345 nm and 495-680 nm. Although there are options to cover this range with frequency mixing techniques [62], Raman shifting [63], and other solid state lasers such as chromium-forsterite [64], this has unfortunately not yet been investigated to a stage of reliable and standard operation.

Besides the limitations in wavelength coverage and maximal laser power, Ti:sapphire laser systems have shown a comparable performance to the Dye lasers when applied as resonant laser ion source [65]. Part of the reason is that due to the multitude of atomic levels in each element the chosen excitation and ionization path can be adapted to the laser system available. To provide highest photon flux the ionization step - ideally resonant - is often realized in the Ti:sapphire fundamental wavelength region of 680–1000 nm applying three step ionization schemes for elements with an IP around 6 eV. The Ti:sapphire laser system has advantages in the infrared region above 900 nm and the beam profile of Ti:sapphire lasers is close to TEM₀₀ and significantly better than the beam profile from Dye laser systems. Furthermore, is the solid state Ti:sapphire laser system

Figure 5: Wavelength coverage and available laser powers for Dye and Ti:sapphire-lasers. The pump laser specifications for the Dye laser system are taken from the IGLIS laboratory at KU Leuven.

maintenance free and allows for comparable conditions over extended running periods.

Application to experimental cases

After summarizing the requirements for RIS in the gas jet environment and the comparison of the Dye and Ti:sa laser systems in terms of their performance, these considerations will be applied to a number of experimental cases proposed as first experiments at the S³-LEB. Here, the region of the 4d-transition elements from Zr to Sn featuring isotopes near or at the N=50

Figure 6: Possible ionization schemes for the envisaged laser spectroscopy studies at the S^3 -LEB within the scope of Day 1 experiments. For transitions arriving at checked levels, all necessary information is available. Excitation steps marked with a wrench require additional information, e.g. on level energies, saturation powers, or HFS splitting. A questions mark indicates that the transitions was already successfully applied in RIS but the sensitivity to nuclear properties and the saturation behavior have not been studied satisfactorily. Wavelengths are given in vacuum.

shell closure, the $N=Z$ as well as the proton drip lines are considered. As these elements show a refractory character, such investigations will complement the research at hot-cavity ISOL facilities. In addition, the very heavy and superheavy nuclides are also regarded, as they are of highest interest to understand nuclear shell stabilization effects, to which the latter owe their existence, as well as for probing atomic theory for such highly correlated systems. Available information from previous experiments and from the literature will be used in this context to estimate the laser requirements for in-gas-jet laser spectroscopy studies at the S^3 -LEB facility. In addition, the expected yields for some of the considered isotopes at the focal plane of S^3 (gas cell entrance window), as well as at the gas-jet environment, are listed in Tab. 3.

Silver ($Z=47$)

In RILIS and spectroscopy applications in a hot cavity typically three-step ionization schemes with various intermediate levels have been applied to produce and study the silver isotopes [66–69]. Nuclear-charge radii and moments of the neutron-deficient silver isotopes $^{101-106m}\text{Ag}$ were measured with laser fluorescence techniques at the GSI on-line mass separator [70] whereas the isotopes $^{97-101}\text{Ag}$ were studied at LISOL using in-gas-cell spectroscopy with two-step resonance ionization [10]. In the latter experiment only the ground-state splitting ($J=1/2$) of up to 40 GHz could be resolved but not the splitting of the first excited state at 30472.8 cm^{-1} ($J=3/2$) that was mainly masked by collisional broadening due to the high pressure inside the gas cell (see bottom panel in Fig. 7). IGLIS studies in a gas jet produced by a de Laval nozzle with Mach 8 will enable to resolve the upper state splitting, giving access to the nuclear

Figure 7: (Bottom panel) Ionization scheme employed to study the $^{97-101}\text{Ag}$ isotopes at LISOL [10] and comparison of the attained spectral resolution in those experiments and the expected performance of in-gas-jet studies on ^{97}Ag . (Upper panel) Search for AI resonances at KU Leuven from the state at 30472.8 cm^{-1} . The intensity pattern (red dots) clearly follows the available pulse energy as the non-resonant ionization is not saturated, thus limiting the efficiency.

spin and to information on the nuclear deformation via the spectroscopic quadrupole moment. The yields from S^3 (see Tab. 3) are expected to extend the investigation towards more neutron-deficient isotopes. Although challenging, especially the properties of the high-spin isomers of the $N=Z$ nucleus ^{94}Ag are of particular interest.

The atomic transition for spectroscopy at 328.16 nm is in principle available for both laser systems, although at the edge of the spectral range covered by Ti:sapphire lasers. Especially when aiming to illuminate an extended volume, the saturation conditions have to be studied in more detail. Referring to the saturation measured to 1.6 μJ in vacuum for an excitation with a broad bandwidth [67], laser powers around 5 μJ (50 mW at 10 kHz repetition rate) are required for the envisaged anti-collinear ($\parallel$) arrangement of the laser beam with respect to the gas jet. As no suitable AI resonances are known so far, a two-step ionization requires high-power laser radiation with a wavelength below 326 nm for non-resonant ionization, as for non-resonant laser ionization at least two orders of magnitude higher pulse energies compared to resonant transition are required. In the reported LISOL experiments [10] 20 mJ average energy per pulse radiation at 308 nm was insufficient to saturate the non-resonant transition. Therefore, either laser light at 266 nm (Nd:YAG, forth harmonic) or laser light from a frequency-doubled dye laser is feasible, albeit the laser power of the latter is expected to be insufficient in saturating the non-resonant ionization step. To overcome this problem, a search for even-parity AI resonances was conducted at KU Leuven. In these experiments, which were performed in an atomic beam unit, the wavelength of the first step laser was fixed to 328 nm while the second step laser was scanned in the region 65 560–63 260 cm^{-1} , corresponding to 285–305 nm (see upper panel of Fig. 7). Unfortunately, no enhancement in ionization was observed. To some extent, these requirements are relaxed for three step ionization schemes as high power laser light at 532 nm from the SHG of a Nd:YAG laser provides higher photon fluxes, but the feasibility of such schemes in the gas-jet ionization has to be tested. Thus, new ionization schemes and their final efficiencies are being investigated at KU Leuven before performing on-line experiments and deciding for the ideal laser system.

Tin ($Z=50$)

Tin isotopes are of particular interest in studying fundamental forces in nuclear structure due to the closed $Z = 50$ proton shell and the two accessible doubly magic isotopes ^{100}Sn and ^{132}Sn . Neutron-rich tin isotopes including the doubly magic isotope ^{132}Sn which were released from an UC_x target at hot-cavity ISOL facilities have been studied [71–73]. The neutron-deficient tin isotopes can be produced by fusion evaporation reactions and will be studied at S^3 (see Tab. 3).

Because of the extended information available in literature the properties of atomic transitions suited for spectroscopic investigations are well known. The atomic ground state ($5s^25p^2\ ^3P_0$) features no hyperfine splitting. From selection rules, optically excited levels can only feature $J = 1$ and therefore split into three HFS levels for odd tin isotopes with nuclear spins $I > \frac{1}{2}$.

Two ground state transitions are reported and require laser radiation of 286.42 nm_{vac} and 254.73 nm_{vac} as summarized in Fig. 6. Both transitions are important for odd-tin isotopes as the information obtained from one transition—with only three hyperfine levels—is insufficient to determine the nuclear spin I , the A -factor, the B -factor, and the IS. For both transitions the HFS parameters have been measured in a series of isotopes [71, 72] and the electronic factors of the isotope shift are accessible from the measured charge radii in muonic atoms [74].

For an efficient ionization an AI resonance is reported at 61 238.5 cm^{-1} , accessible with laser light of 454.9 nm from the level populated with 254 nm. This resonance has shown a large pressure shift and broadening inside a gas cell [2] which is consistent with its classification as member of a Rydberg series converging to the 4251.5 cm^{-1} excited $5s^25p\ ^2P_{3/2}^o$ level of Sn II [75]. In the case of the 286 nm transition an atomic level below, but close to, the IP had been used to enhance the ion yield in RIS of ^{132}Sn [73]. Owing to the weak electric fields present in the gas jet method this option might not be feasible, requiring thus to search for AI resonances above the IP in the range of 300–411 nm.

From a saturation power around 4 $\mu\text{J}/\text{cm}^2$ (40 mW/ cm^2) reported for the 286 nm transition in in-source RILIS applications [76, 77] a laser power of up to 5 μJ (50 mW) can be extrapolated for anti-collinear ($\parallel$) geometry. A laser power above 1 W for a perpendicular ($\perp$) overlap between the laser beam and the gas jet is required to saturate the ionization transition at 454.9 nm, but this has to be determined more precisely in off-line tests. The required wavelengths in all transitions are accessible from both laser systems, nevertheless Dye lasers will provide higher laser power densities for a better ionization efficiency.

Actinium ($Z=89$)

The atomic level structure of actinium is only fragmentarily reported [78]. Only few AI resonances were available for efficient ionization [79] while the HFS splitting of individual atomic levels was only evaluated in Ac II [80], which is not suitable for gas cell nor for in-hot cavity spectroscopy studies. Therefore, AI resonances have been studied in detail at the University of Mainz and TRIUMF using Ti:sapphire lasers [40, 81]. Here, ionization schemes including transitions with suitable HFS splittings were identified. The ground state transition at 438.57 nm_{vac} shows a large HFS splitting and has been studied off-line with high resolution using an injection-locked narrow bandwidth Ti:sapphire laser in a crossed beam arrangement with a hot cavity atomizer. Finally, the ionization scheme was applied in a hot cavity at TRIUMF [69, 82] and in-gas-cell at LISOL [11]. Because of the limited resolution only the HFS splitting of the upper level was resolved, which has a low sensitivity to the B -Factor and thus to the spectroscopic quadrupole moment. Finally, actinium was used to demonstrate on-line the in-gas jet method at LISOL resulting in a partial resolving of the ground state HFS with a resolution of 400 MHz using a Ti:sapphire laser system enabling the unambiguous determination of the nuclear spin of $^{214-215}\text{Ac}$ as well as their quadrupole moment [13]. Nevertheless, for high-resolution spectroscopy applications also an atomic transition at 418.43 nm leading to

Figure 8: High-resolution crossed-beam laser spectroscopy of ^{227}Ac performed at the University of Mainz on the ground state transition to an excited level at $23\,898.88\,\text{cm}^{-1}$ with $J = 5/2$.

an excited level at $23\,898.88\,\text{cm}^{-1}$ can be used as shown in Fig. 6. The HFS structure for this transition is shown in Fig 8 and from which HFS coupling constants of $A = -792(15)\,\text{MHz}$ and $B = 1193(15)\,\text{MHz}$ were determined at the University of Mainz. In total, the splitting of the upper level is not as large as for the 438 nm transition, but features a larger sensitivity to the quadrupole moment.

For in-source [82] and crossed-beam spectroscopy, both performed at high vacuum conditions, laser powers below 100 nJ (1 mW) were applied for the first step at 438 nm. Considering the change in illuminated area for the gas jet application as summarized in Tab. 1, pulse energies around $1\,\mu\text{J}$ (10 mW) for anti-collinear arrangement are required, which can be obtained from both laser systems. Similar considerations apply for the ionization step where laser powers around $100\,\mu\text{J}$ (1 W) for the resonant transition at 424 nm into an AI-resonance were clearly sufficient to provide high ionization efficiencies for spectroscopy in vacuum conditions as well as in the gas jet environment at LISOL [12]. Depending on the geometry in the envisaged perpendicular arrangement several watts of laser power are required. Nevertheless, the power specifications for both laser systems in this wavelength region differ only by a factor 2–3, and thus both systems are applicable.

Actinides up to fermium

The actinide elements are located close to the very end of the nuclear chart with extreme N/Z ratios and a heavy mass. This region features a unique playground in understanding the fundamental interaction responsible for the stability of the heaviest elements. Starting from the closed neutron shell $N=126$ the isotopes of the actinide nuclei are increasing in deformation up to the deformed sub-shell closure at $N=152$. Additional nuclear effects such as the localized occurrence of octupole deformation around $N=132$ [82] and the isomers in the heavy actinide region, which allow to probe single particle configuration of higher orbitals, are important for an in-depth understanding of underlying nuclear properties.

Atomic levels and transitions have been reported for the actinides up to the element fermium (Fm, $Z = 100$). For elements up to einsteinium (Es, $Z = 99$) fluorescence from spark and arc discharges was used to determine atomic levels [91]

whereas laser spectroscopy using dye laser was applied to determine the first IP of these elements [92]. Atomic levels in Fm were determined by laser spectroscopy on a purified sample of ^{255}Fm ($T_{1/2}=20\,\text{h}$) and enabled the identification of so far seven atomic levels [93, 94]. Detailed information on the sensitivity of atomic levels to nuclear properties is available for the actinides Th, U, Np and Pu where a large interest in nuclear applications triggered investigations on laser separation. In addition, the laser spectroscopy for nuclear properties of the heavy actinides was performed in Pu [95], the Am fission isomers [23, 96] as well as in Fm, where the HFS of two atomic transition was partly resolved [97]. The lack of stable isotopes that can be used as reference for the nuclear moments μ and Q is a further challenge in the investigation of nuclides in this region. Because of the large splittings, some information on the HFS is available for Bk and Es [91], which are suitable for both laser systems, but ionization schemes have not yet been tested. Therefore, except for the aforementioned Th, U, Np, Pu and Am off-line studies are mandatory to identify the ideal ionization scheme with a suitable sensitivity. These investigations are complicated by the fact that atomic calculations are difficult due to the large configuration space resulting from the open f -shell. Nevertheless, the open f -shell results also in a large density of atomic levels. This, however, might enable the selection of suitable ionization schemes for dye and Ti:sapphire laser systems.

Nobelium ($Z=102$)

Laser spectroscopy on the heavy actinides and the super-heavy elements is in general hampered by the available low production rates. The isotope ^{254}No has a cross-section of $2\,\mu\text{b}$ in the fusion evaporation reaction $^{208}\text{Pb}(^{48}\text{Ca}, 2n)^{254}\text{No}$ resulting in about 15 particles/s expected at S^3 (see Tab. 3). Laser spectroscopic investigations for nuclear properties on nobelium isotopes and isomers became possible after the identification of the $^1S_0 \rightarrow ^1P_1$ transition at $29\,961.5\,\text{cm}^{-1}$ at GSI [24] using the RADRIS technique [25]. The transition wavelength of $333.76\,\text{nm}$ could be obtained as the third harmonic of the fundamental laser wavelength at $1000.13\,\text{nm}$, which is at the very edge of the Ti:sapphire wavelength range limiting the pulse energy. Unfortunately, higher laser powers are required when using Ti:sapphire lasers as the lifetime of the excited 1P_1 state is only about 4 ns and thus significantly shorter than the laser pulse duration. Therefore, a frequency-doubled, pulsed amplified dye laser pumped with 532 nm laser radiation is needed to provide narrow bandwidth laser light with pulse powers around $10\,\mu\text{J}$. Non-resonant ionization into the continuum was measured to require a fluence of $3\,\text{mJ cm}^{-2}$ for saturation [98]. Nevertheless, this number should be treated carefully as also other levels, populated by collision-induced quenching, were involved in the ionization scheme [99] and might alter the requirements in the low-density gas jet environment. In general, a frequency-tripled Nd:YAG laser at 355 nm is feasible with photon energies exceeding the first IP, but high pulse energies of more than 3 mJ (30 W) are mandatory for high efficiency. In addition, Rydberg levels were also observed [24, 100], but the feasibility of using such levels for ionization in a gas jet are not

Table 3: List of some of the isotopes that will be studied by the IGLIS technique ordered by their atomic and mass numbers (first and second column, respectively) . The nuclear reactions and the cross sections taken from the literature are given from the third to the fifth column, respectively. The expected yields at the final focal plane of S³ (sixth column) and the ions for in-gas-jet spectroscopy studies at S³-LEB (last column) are also given.

Z	A	Reaction ^a	Cross sec. (μ b)	Ref.	Focal plane ^b (pps)	Gas jet ^c (pps)
47	94	$^{58}\text{Ni}(^{40}\text{Ca}, \text{p3n})^{94}\text{Ag}$	35	[83]	$7 \cdot 10^3$	5
	95	$^{58}\text{Ni}(^{40}\text{Ca}, \text{p2n})^{95}\text{Ag}$	470	[83]	$9 \cdot 10^4$	$7 \cdot 10^3$
	96	$^{60}\text{Ni}(^{40}\text{Ca}, \text{p3n})^{96}\text{Ag}$	790	[83]	$1.5 \cdot 10^5$	$1.2 \cdot 10^4$
	97	$^{60}\text{Ni}(^{40}\text{Ca}, \text{p2n})^{97}\text{Ag}$	4000	[83]	$7.5 \cdot 10^5$	$6 \cdot 10^4$
50	100	$^{58}\text{Ni}(^{50}\text{Cr}, 2\text{p6n})^{100}\text{Sn}$	0.5	[83]	70	4.5
	101	$^{50}\text{Cr}(^{58}\text{Ni}, 2\text{p5n})^{101}\text{Sn}$	210	[83]	$1.7 \cdot 10^3$	130
	102	$^{50}\text{Cr}(^{58}\text{Ni}, 2\text{p4n})^{102}\text{Sn}$	970	[83]	$8 \cdot 10^3$	620
	103	$^{50}\text{Cr}(^{58}\text{Ni}, 2\text{p3n})^{102}\text{Sn}$	3100	[83]	$2.5 \cdot 10^5$	$2 \cdot 10^4$
89	208+209	$^{197}\text{Au}(^{20}\text{Ne}, 8\text{n}+9\text{n})^{208,209}\text{Ac}$	2.5	[84]	60	0.5
	210+211	$^{197}\text{Au}(^{20}\text{Ne}, 6\text{n}+7\text{n})^{210,211}\text{Ac}$	250	[84]	$6 \cdot 10^3$	300
	212+213	$^{197}\text{Au}(^{20}\text{Ne}, 4\text{n}+5\text{n})^{212,213}\text{Ac}$	2500	[84]	60000	5000
90	215	$^{180}\text{Hf}(^{40}\text{Ar}, 5\text{n})^{215}\text{Th}$	2	[85]	400	30
100	250	$^{204}\text{Hg}(^{48}\text{Ca}, 2\text{n})^{250}\text{Fm}$	1	[86]	7	0.7
101	252	$^{238}\text{U}(^{19}\text{F}, 5\text{n})^{252}\text{Md}$	0.5	[87]	10	1
102	252	$^{206}\text{Pb}(^{48}\text{Ca}, 2\text{n})^{252}\text{No}$	0.52	[88]	4	0.4
102	253	$^{206}\text{Pb}(^{48}\text{Ca}, 1\text{n})^{253}\text{No}$	0.06	[88]	10	1
102	254	$^{208}\text{Pb}(^{48}\text{Ca}, 2\text{n})^{254}\text{No}$	2	[88]	15	1.5
102	255	$^{208}\text{Pb}(^{48}\text{Ca}, 1\text{n})^{255}\text{No}$	0.2	[89]	1	0.1
103	255	$^{209}\text{Bi}(^{48}\text{Ca}, 2\text{n})^{255}\text{Lr}$	0.45	[90]	3	0.3

^a Primary beam intensities given in [83].

^b The calculation of the yields takes 40% transmission in S³ for reaction asymmetry >0.15 and 15% for reaction asymmetry ≤ 0.15 .

^c The efficiency of the LEB is 10% (cf. Tab. 2 in ref. [2]) and the average transfer time up to the gas jet is taken as 250 ms.

yet evaluated, although the low-jet temperatures deem this unlikely. While a HFS in the isotope ^{253}No was already measured with an in-gas cell resolution of about 6 GHz [101], a fast technique with high spectral resolution is required to measure the deformation with sufficiently high precision and to study the properties of the K -isomers in $^{252,254}\text{No}$ [102, 103].

Mendelevium and elements beyond nobelium

The spectroscopy of mendelevium (Md, $Z = 101$) and for elements heavier than nobelium is hampered by the so far unknown atomic structure and the low production rates in heavy ion fusion evaporation reactions (cf. Tab. 3). Atomic lines and optical transitions have been calculated for Lr and Rf [104, 105]. While for Lr and Rf the precision of the calculation is expected to be suitable, the open f -shell in Md complicates the calculations and thus the reliability of the predictions. In the case of Lr some unambiguity on the atomic ground state configuration remains as the two lowest predicted level are rather close. Nevertheless, some evidence preferring the $s_{1/2}$ configuration over the $p_{3/2}$ is given from the determination of the first IP by surface ionization [106]. Due to large uncertainties in the level energies from atomic calculations a wide range tunability combined with high pulse energies in the order of 100 μJ is important. Therefore, a dye laser system is essential for the search of unknown atomic levels. As highest efficiency is crucial and the spectral resolution should be reasonably wide to allow for fast scanning of an extended wavelength region, this spectroscopy will be performed inside the gas cell to ensure perfect overlap of the atoms with the laser radiation. In any case, the ionization can be realized with high pulse energies from a tripled Nd:YAG laser at 355 nm. Similar activity in the search for atomic transitions in nobelium is ongoing at GSI in Darmstadt [107, 108]. Once an atomic transition is identified, which in itself represents a major milestone, this transition will be investigated in detail with higher resolution in the gas cell or the gas jet, for all the available isotopes.

Conclusion

For resonant laser ionization in the gas cell, as intended for the search and identification of atomic levels, the dye laser system is clearly the best choice. Because of the large collision rate in the high-pressure region a two step ionization scheme and a laser radiation of high power and short pulse duration is advantageous. Lower specifications in the available pulse energy demand a carefully chosen ionization scheme, narrowing thus the universality [65].

For most elements, where atomic levels are well known, and that are planned to be studied by in-gas-jet laser spectroscopy, the first and narrow-bandwidth spectroscopic transition can be realized with both laser systems, as the power requirements are lower. This is mainly due to the large resonant-excitation cross section in comparison to the ionization step, and also to the relatively small expansion factor of the anti-collinear laser beam in the gas jet method. In general, a suitable transition for the available wavelength-coverage of the laser system

can be chosen but there are cases, such as nobelium and silver, for instance, where the known or ideal first excited level is only reached with a dye laser system. A high average energy per pulse is necessary for photo-ionization as the illuminated area in perpendicular ($\perp$) arrangement increases significantly and the cross sections are orders of magnitude smaller than for atomic excitation. Especially, for elements with a high IP requiring laser radiation for the ionization transition in the UV range below 345 nm a dye laser system is better suited because of the significantly higher output power. For laser ionization in the regime of 340–450 nm and 680–1000 nm the performance of both laser systems is in general comparable.

Systematic off-line studies on atomic transitions to provide high-efficiency laser ionization in combination with a suitable sensitivity to nuclear properties is required. This is especially important in the first two years of operation of the $S^3\text{-LEB}$, when only the Ti:Sapphire laser system will be available. After this period, the $S^3\text{-LEB}$ laser system will combine the complementary performance of the Dye and Ti:Sa lasers as done at ISOLDE [21]. This will enable a continuous wide-spectral tunability and high-pulse energies available from dye lasers, for demanding spectroscopic investigations, as well as long-term stable operation and low-to-non-existing maintenance effort of the Ti:sapphire lasers. With such a laser system it will be possible to study isotopes around the $N = Z$ and the proton drip lines in the vicinity of $Z = 50$. In addition, an exploration of the refractory elements around molybdenum and tantalum, so far difficult to study with conventional high-resolution laser spectroscopy techniques, will become feasible. However, the most important contribution of the IGLIS technique will be for the actinide and transactinide elements. Based on the projected performance of the in-gas-jet method and on experimental and estimated cross sections (see ref. [13]) the number of isotopes that will be studied will significantly improve the current knowledge of the atomic and nuclear structure in the heavy and super-heavy element regions.

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References

- [1] A. Drouart, A. Amthor, D. Boutin, O. Delferrere, M. Duval, S. Manikonda, J. Nolen, J. Payet, H. Savajols, M.-H. Stodel, D. Uriot, Nucl. Phys. A 834 (2010) 747c–750c. doi:10.1016/j.nucphysa.2010.01.135.
- [2] R. Ferrer, B. Bastin, D. Boilley, P. Creemers, P. Delahaye, E. Liénard, X. Fléchar, S. Franchoo, L. Ghys, M. Huyse, et al., Nucl. Instrum. Methods B 317 (2013) 570–581. doi:10.1016/j.nimb.2013.07.028.

- [3] F. Déchery, et al., Nucl. Instrum. Methods B 376 (2016) 125–130. doi:doi.org/10.1016/j.nimb.2016.02.036. 760
- [4] J. Uusitalo, J. Sarén, J. Partanen, J. Hilton, Acta Physica Polonica B 50 (2019) 319. doi:doi.org/10.5506/aphyspolb.50.319.
- [5] P. Papadakis, I. Moore, T. Eronen, J. Liimatainen, T. Kalvas, J. Partanen, I. Pohjalainen, M. Reponen, S. Rinta-Antila, J. Sarén, J. Uusitalo, AIP Conference Proceedings 2011765 (2018) 070013. URL: <https://aip.scitation.org/doi/abs/10.1063/1.5053355>. doi:doi.org/10.1063/1.5053355. arXiv:<https://aip.scitation.org/doi/pdf/10.1063/1.5053355>.
- [6] Y. Hirayama, Y. X. Watanabe, N. Imai, H. Ishiyama, S. C. Jeong, H. Miyatake, M. Oyaizu, S. Kimura, M. Mukai, Y. H. Kim, T. Sonoda, M. Wada, M. Huyse, Y. Kudryavtsev, P. VanDuppen, Nucl. Instrum. Methods B 353 (2015) 4.
- [7] Y. Hirayama, et al., Phys. Rev. C 96 (2017) 014307.
- [8] Y. Kudryavtsev, T. Cocolios, J. Gentens, M. Huyse, O. Ivanov, D. Pauwels, T. Sonoda, P. V. den Bergh, P. V. Duppen, Nucl. Instrum. Methods B 267 (2009) 2908–2917. doi:doi.org/10.1016/j.nimb.2009.06.013. 705
- [9] T. Cocolios, A. N. Andreyev, B. Bastin, N. Bree, J. Buescher, J. Elseviers, J. Gentens, M. Huyse, Y. Kudryavtsev, D. Pauwels, T. Sonoda, P. V. den Bergh, P. V. Duppen, Phys. Rev. Lett. 103 (2009) 102501. doi:doi.org/10.1103/PhysRevLett.103.102501. 710
- [10] R. Ferrer, N. Bree, T. Cocolios, I. Darby, H. De Witte, W. Dexters, J. Diriken, J. Elseviers, S. Franchoo, M. Huyse, et al., Physics Letters B 728 (2014) 191–197. doi:doi.org/10.1016/j.physletb.2013.11.055.
- [11] C. Granados, P. Creemers, R. Ferrer, L. P. Gaffney, W. Gins, R. de Groote, M. Huyse, Y. Kudryavtsev, Y. Martínez, S. Raeder, S. Sels, C. Van Beveren, P. Van den Bergh, P. Van Duppen, K. Wrzosek-Lipska, A. Zadornaya, A. E. Barzakh, B. Bastin, P. Delahaye, L. Hijazi, N. Lecesne, F. Luton, J. Piot, H. Savajols, J.-C. Thomas, E. Traykov, R. Beerwerth, S. Fritzsche, M. Block, X. Fléhard, S. Franchoo, L. Ghys, H. Grawe, R. Heinke, T. Kron, P. Naubereit, K. Wendt, M. Laatiaoui, I. Moore, V. Sonnenschein, M. Loiselet, E. Mogilevskiy, S. Rothe, Phys. Rev. C 96 (2017) 054331. doi:doi.org/10.1103/PhysRevC.96.054331. 715
- [12] S. Raeder, B. Bastin, M. Block, P. Creemers, P. Delahaye, R. Ferrer, X. Fléhard, S. Franchoo, L. Ghys, L. Gaffney, C. Granados, R. Heinke, L. Hijazi, M. Huyse, T. Kron, Y. Kudryavtsev, M. Laatiaoui, N. Lecesne, F. Luton, I. Moore, Y. Martinez, E. Mogilevskiy, P. Naubereit, J. Piot, S. Rothe, H. Savajols, S. Sels, V. Sonnenschein, E. Traykov, C. V. Beveren, P. V. den Bergh, P. V. Duppen, K. Wendt, A. Zadornaya, Nucl. Instrum. Meth. Phys. Res. B 376 (2016) 382–387. doi:doi.org/10.1016/j.nimb.2015.12.014, proceedings of the (XVIIth) International Conference on Electromagnetic Isotope Separators and Related Topics (EMIS2015), Grand Rapids, MI, U.S.A., 11–15 May 2015. 720
- [13] R. Ferrer, A. Barzakh, B. Bastin, R. Beerwerth, M. Block, P. Creemers, H. Grawe, R. de Groote, P. Delahaye, X. Fléhard, et al., Nature Commun. 8 (2017). doi:doi.org/10.1038/ncomms14520. 725
- [14] Y. Kudryavtsev, P. Creemers, R. Ferrer, C. Granados, L. Gaffney, M. Huyse, E. Mogilevskiy, S. Raeder, S. Sels, P. V. den Bergh, P. V. Duppen, A. Zadornaya, Nucl. Instrum. Methods B 376 (2016) 345–352. doi:doi.org/10.1016/j.nimb.2016.02.040. 730
- [15] A. Zadornaya, et al., Phys. Rev. X 8 (2018) 041008. doi:doi.org/10.1103/PhysRevX.8.041008.
- [16] Y. Kudryavtsev, R. Ferrer, M. Huyse, P. Van den Bergh, P. Van Duppen, Nucl. Instrum. Meth. B 297 (2013) 7–22. doi:doi.org/10.1016/j.nimb.2012.12.008. 735
- [17] V. Fedosseev, Y. Kudryavtsev, V. Mishin, Phys. Scr. 85 (2012) 058104. doi:doi.org/10.1088/0031-8949/85/05/058104.
- [18] P. Campbell, I. Moore, M. Pearson, Progr. Part. Nucl. Phys. 86 (2016) 127–180. doi:doi.org/10.1016/j.ppnp.2015.09.003. 740
- [19] V. N. Fedosseev, L.-E. Berg, D. V. Fedorov, D. Fink, O. J. Launila, B. A. Marsh, R. E. Rossel, S. Rothe, M. D. Seliverstov, A. M. Sjödin, K. D. A. Wendt, Rev. Sci. Instrum. 83 (2012) –. doi:doi.org/10.1063/1.3662206. 745
- [20] J. Lassen, P. Bricault, M. Dombbsky, J. P. Lavoie, M. Gillner, T. Gottwald, F. Hellbusch, A. Teigelhöfer, A. Voss, K. D. A. Wendt, AIP Conf. Proc. 1104 (2009) 9–15. doi:doi.org/10.1063/1.3115616. 750
- [21] S. Rothe, B. A. Marsh, C. Mattolat, V. N. Fedosseev, K. Wendt, J. Phys. Conf. Ser. 312 (2011) 052020. doi:doi.org/10.1088/1742-6596/312/5/052020.
- [22] Y. Kudryavtsev, et al., Nucl. Instrum. Methods B 114 (1996) 350–365. doi:[doi.org/10.1016/0168-583X\(96\)00194-2](https://doi.org/10.1016/0168-583X(96)00194-2).
- [23] H. Backe, M. Hies, H. Kunz, W. Lauth, O. Curtze, P. Schwamb, M. Sewtz, W. Theobald, R. Zahn, K. Eberhardt, N. Trautmann, D. Habs, R. Repnow, B. Fricke, Phys. Rev. Lett. 80 (1998) 920–923. doi:doi.org/10.1103/PhysRevLett.80.920.
- [24] M. Laatiaoui, W. Lauth, H. Backe, M. Block, D. Ackermann, B. Cheal, P. Chhetri, C. E. Düllmann, P. van Duppen, J. Even, et al., Nature 538 (2016) 495–498. doi:doi.org/10.1038/nature19345.
- [25] F. Lautenschläger, P. Chhetri, D. Ackermann, H. Backe, M. Block, B. Cheal, A. Clark, C. Droese, R. Ferrer, F. Giaccoppo, S. Götz, F. Heßberger, O. Kaleja, J. Khuyagbaatar, P. Kunz, A. Mistry, M. Laatiaoui, W. Lauth, S. Raeder, T. Walther, C. Wraith, Nucl. Instrum. Methods B 383 (2016) 115–122. doi:doi.org/10.1016/j.nimb.2016.06.001.
- [26] H. Miyatake, M. Wada, X. Y. Watanabe, Y. Hirayama, P. Schury, M. Ahmed, H. Ishiyama, S. C. Jeong, Y. Kakiguchi, S. Kimura, J. Y. Moon, M. Mukai, M. Oyaizu, J. H. Park, AIP Conference Proceedings 1947 (2018) 020018. doi:doi.org/10.1063/1.5030822.
- [27] M. Reponen, I. Moore, T. Kessler, I. Pohjalainen, S. Rothe, V. Sonnenschein, in: Three decades of research using IGISOL technique at the University of Jyväskylä, 2014, pp. 295–309. doi:doi.org/10.1007/978-94-007-5555-0_23.
- [28] T. Takatsuka, H. Tomita, V. Sonnenschein, T. Sonoda, Y. Adachi, C. Sakamoto, H. Mita, T. Noto, C. Ito, S. Maeda, T. Iguchi, M. Wada, K. Wendt, I. Moore, Nucl. Instrum. Methods B 317 (2013) 586 – 589. URL: <http://www.sciencedirect.com/science/article/pii/S0168583X13006204>. doi:<https://doi.org/10.1016/j.nimb.2013.05.054>, xVith International Conference on ElectroMagnetic Isotope Separators and Techniques Related to their Applications, December 27, 2012 at Matsue, Japan.
- [29] Y. Hirayama, X. Y. Watanabe, M. Mukai, P. Schury, M. Ahmed, H. Ishiyama, S. C. Jeong, Y. Kakiguchi, S. Kimura, J. Moon, M. Oyaizu, M. Park, J. H. and Wada, H. Miyatake, Nucl. Instrum. Methods B (2019). In Press.
- [30] V. Letokhov, Laser photoionization spectroscopy, Academic Press Inc., Orlando, FL, 1987.
- [31] G. S. Hurst, M. G. Payne, Principles and applications of resonance ionisation spectroscopy, A. Hilger, 1988.
- [32] Z.-T. Lu, K. Wendt, Rev. Sci. Instrum. 74 (2003) 1169–1179. doi:doi.org/10.1063/1.1535232.
- [33] G. Hurst, M. Payne, Spectrochimica Acta Part B: Atomic Spectroscopy 43 (1988) 715–726. doi:[doi.org/10.1016/0584-8547\(88\)80104-6](https://doi.org/10.1016/0584-8547(88)80104-6).
- [34] G. Alkhazov, E. Y. Berlovich, V. Panteleyev, Nucl. Instrum. Methods A 280 (1989) 141–143. doi:[doi.org/10.1016/0168-9002\(89\)91282-5](https://doi.org/10.1016/0168-9002(89)91282-5).
- [35] L. Vermeeren, N. Bijmens, M. Huyse, Y. A. Kudryavtsev, P. Van Duppen, J. Wauters, Z. Qamhieh, P. Thoen, E. Vandeweert, R. Silverans, Phys. Rev. Lett. 73 (1994) 1935–1938. doi:doi.org/10.1103/PhysRevLett.73.1935.
- [36] B. A. Marsh, Rev. Sci. Instrum. 85 (2014) –. doi:doi.org/10.1063/1.4858015.
- [37] G. Alkhazov, A. Barzakh, V. Denisov, K. Mezilev, Y. Novikov, P. Panteleyev, A. Popov, E. Sudentas, V. Letokhov, V. Mishin, V. Fedoseyev, S. Andreyev, D. Vedeneyev, A. Zyuzikov, Nucl. Instrum. Methods B 69 (1992) 517–520. doi:[doi.org/10.1016/0168-583X\(92\)95309-F](https://doi.org/10.1016/0168-583X(92)95309-F).
- [38] C. Schulz, E. Arnold, W. Borchers, W. Neu, R. Neugart, M. Neuroth, E. Otten, M. Scherf, K. Wendt, P. Lievens, et al., J. Phys. B 24 (1991) 4831. doi:doi.org/10.1088/0953-4075/24/22/020.
- [39] S. Rothe, A. N. Andreyev, S. Antalic, A. Borschevsky, L. Capponi, T. E. Cocolios, H. De Witte, E. Eliav, D. V. Fedorov, V. N. Fedosseev, D. A. Fink, S. Fritzsche, L. Ghys, M. Huyse, N. Imai, U. Kaldor, Y. Kudryavtsev, U. Köster, J. F. W. Lane, J. Lassen, V. Liberati, K. M. Lynch, B. A. Marsh, K. Nishio, D. Pauwels, V. Pershina, L. Popescu, T. J. Procter, D. Radulov, S. Raeder, M. M. Rajabali, E. Rapisarda, R. E. Rossel, K. Sandhu, M. D. Seliverstov, A. M. Sjödin, P. Van den Bergh, P. Van Duppen, M. Venhart, W. Y., K. D. A. Wendt, Nature Commun. 4 (2013) 1835. doi:doi.org/10.1038/ncomms2819.
- [40] J. Roßnagel, S. Raeder, A. Hakimi, R. Ferrer, N. Trautmann, K. Wendt, Phys. Rev. A 85 (2012) 012525. doi:doi.org/10.1103/PhysRevA.85.012525.
- [41] Y. Kudryavtsev, R. Ferrer, M. Huyse, P. Van den Bergh, P. Van Duppen, L. Vermeeren, Review of Scientific Instruments 85 (2013) 02B915. doi:doi.org/10.1063/1.4850695.

- [42] A. Kramida, Y. Ralchenko, J. Reader, NIST ASD Team, Nist atomic spectra database (version 5.6.1), Online, 2019. doi:10.18434/T4W30F, available at <http://physics.nist.gov/asd>, accessed 01.06.2019.
- [43] R. L. Kurucz, B. Bell, Atomic spectral line database CD-ROM 23, 1995. Online, available at <https://www.cfa.harvard.edu/amp/ampdata/kurucz23/sekur.html>, accessed 01.06.2019.
- [44] K. Blaum, J. Dilling, W. Nörtershäuser, *Physica Scripta* 2013 (2013) 014017. doi:10.1088/0031-8949/2013/T152/014017.
- [45] Y. Kudryavtsev, V. Letokhov, *Applied Physics B* 29 (1982) 219.
- [46] K. Flanagan, K. Lynch, J. Billowes, M. Bissell, I. Budinčević, T. Cocolios, R. De Groote, S. De Schepper, V. Fedosseev, S. Franchoo, et al., *Phys. Rev. Lett.* 111 (2013) 212501. doi:10.1103/PhysRevLett.111.212501.
- [47] T. Cocolios, H. Al Suradi, J. Billowes, I. Budinčević, R. de Groote, S. De Schepper, V. Fedosseev, K. Flanagan, S. Franchoo, R. Garcia Ruiz, et al., *Nucl. Instrum. Methods B* 317 (2013) 565–569. doi:10.1016/j.nimb.2013.05.088.
- [48] R. Heinke, T. Kron, S. Raeder, T. Reich, P. Schönberg, M. Trümper, C. Weichhold, K. Wendt, *Hyperfine Interact.* 238 (2017) 6. doi:10.1007/s10751-016-1386-2.
- [49] R. P. de Groote, M. Verlinde, V. Sonnenschein, K. T. Flanagan, I. Moore, G. Neyens, *Phys. Rev. A* 95 (2017) 032502. doi:10.1103/PhysRevA.95.032502.
- [50] T. E. Cocolios, W. Dexters, M. D. Seliverstov, A. N. Andreyev, S. Antalic, A. E. Barzakh, B. Bastin, J. Büscher, I. G. Darby, D. V. Fedorov, V. N. Fedosseyev, K. T. Flanagan, S. Franchoo, S. Fritzsche, G. Huber, M. Huyse, M. Keupers, U. Köster, Y. Kudryavtsev, E. Mané, B. A. Marsh, P. L. Molkanov, R. D. Page, A. M. Sjoedin, I. Stefan, J. Van de Walle, P. Van Duppen, M. Venhart, S. G. Zemlyanoy, M. Bender, P.-H. Heenen, *Phys. Rev. Lett.* 106 (2011) 052503. doi:10.1103/PhysRevLett.106.052503.
- [51] J. Lassen, R. Li, S. Raeder, X. Zhao, T. Dekker, H. Heggen, P. Kunz, C. D. P. Levy, M. Mostanmand, A. Teigelhöfer, F. Ames, *Hyperfine Interact.* 238 (2017) 33. doi:10.1007/s10751-017-1407-9.
- [52] N. Lécse, R. Alves-Conde, E. Coterreau, F. De Oliveira, M. Dubois, J. L. Flambard, H. Franberg, T. Gottwald, P. Jardin, J. Lassen, F. Le Blanc, R. Leroy, C. Mattolat, A. Olivier, J. Y. Pacquet, A. Pichard, S. Rothe, M. G. Saint-Laurent, K. Wendt, *Rev. Sci. Instrum.* 81 (2010) 02A910. doi:10.1063/1.3279301.
- [53] C. Granados, et al. (2019). In preparation.
- [54] C. Mattolat, S. Rothe, F. Schweltnus, T. Gottwald, S. Raeder, K. Wendt, in: *AIP Conf. Proc.*, volume 1104, p. 114. doi:10.1063/1.3115586.
- [55] C. Geppert, *Nucl. Instrum. Methods B* 266 (2008) 4354–4361. doi:10.1016/j.nimb.2008.05.036.
- [56] J. Lassen, P. Bricault, M. Domsbky, F. Izdebski, J. P. Lavoie, M. Gillner, T. Gottwald, F. Hellbusch, A. Teigelhöfer, A. Voss, K. D. A. Wendt, *AIP Conf. Proc.* 1099 (2009) 769–773. doi:10.1063/1.3120151.
- [57] V. Sonnenschein, I. Moore, H. Khan, I. Pohjalainen, M. Reponen, *Hyperfine Interact.* (2014) 1–11. doi:10.1007/s10751-013-1000-9.
- [58] T. Kessler, H. Tomita, C. Mattolat, S. Raeder, K. Wendt, *Laser Phys.* 18 (2008) 842–849. doi:10.1134/S1054660X08070074.
- [59] V. Sonnenschein, I. D. Moore, S. Raeder, M. Reponen, H. Tomita, K. Wendt, *Laser Phys.* 27 (2017) 085701. doi:10.1088/1555-6611/aa7834.
- [60] R. Pohl, A. Antognini, F. Nez, F. D. Amaro, F. Biraben, J. M. Cardoso, D. S. Covita, A. Dax, S. Dhawan, L. M. Fernandes, et al., *Nature* 466 (2010) 213–216. doi:10.1038/nature09250.
- [61] M. Reponen, I. D. Moore, T. Kessler, I. Pohjalainen, S. Rothe, V. Sonnenschein, *Eur. Phys. J. A* 48 (2012) 45. doi:10.1140/epja/i2012-12045-2.
- [62] V. Sonnenschein, I. D. Moore, I. Pohjalainen, M. Reponen, S. Rothe, K. Wendt, *JPS Conf. Proc.* 6 (2015) 030126. doi:10.7566/JPSCP.6.030126.
- [63] K. Chrysalidis, V. N. Fedosseev, B. A. Marsh, R. P. Mildren, D. J. Spence, K. D. A. Wendt, S. G. Wilkins, E. Granados, *Optics Lett.* 44 (2019) 3924.
- [64] T. Gottwald, C. Havener, J. Lassen, Y. Liu, C. Mattolat, S. Raeder, S. Rothe, K. Wendt, *Rev. Sci. Instrum.* 81 (2010) 02A514 – 02A514-3. doi:10.1063/1.3273067.
- [65] R. Ferrer, V. Sonnenschein, B. Bastin, S. Franchoo, M. Huyse, Y. Kudryavtsev, T. Kron, N. Lécse, I. Moore, B. Osmond, et al., *Nucl. Instrum. Methods B* 291 (2012) 29–37. doi:10.1016/j.nimb.2012.08.023.
- [66] V. Fedosseev, L.-E. Berg, N. Lebas, O. J. Launila, M. Lindroos, R. Losito, B. Marsh, F. K. Österdahl, T. Pauchard, G. Tranströmer, et al., *Nucl. Instrum. Methods B* 266 (2008) 4378–4382. doi:10.1016/j.nimb.2008.05.038.
- [67] M. Reponen, T. Kessler, I. Moore, S. Rothe, J. Äystö, *The European Physical Journal A* 42 (2009) 509–515. doi:10.1140/epja/i2009-10830-6.
- [68] S. Rothe, T. D. Goodacre, D. Fedorov, V. Fedosseev, B. Marsh, P. Molkanov, R. Rossel, M. Seliverstov, M. Veinhard, K. Wendt, *Nucl. Instrum. Methods B* 376 (2016) 91 – 96. doi:10.1016/j.nimb.2016.02.024.
- [69] A. Teigelhöfer, Isotope shift and hyperfine structure measurements on silver, actinium and astatine by in-source resonant ionization laser spectroscopy, 2017. URL: <http://hdl.handle.net/1993/32217>, PhD thesis, Univ. of Manitoba.
- [70] U. Dinger, J. Eberz, G. Huber, R. Menges, R. Kirchner, O. Klepper, T. Kühl, D. Marx, *Nucl. Phys. A* 503 (1989) 331 – 348. doi:10.1016/0375-9474(89)90239-X.
- [71] M. Anselment, K. Bekk, A. Hanser, H. Hoeffgen, G. Meisel, S. Göring, H. Rebel, G. Schatz, *Physical Review C* 34 (1986) 1052. doi:10.1103/PhysRevC.34.1052.
- [72] J. Eberz, U. Dinger, G. Huber, H. Lochmann, R. Menges, G. Ulm, R. Kirchner, O. Klepper, T. Kühl, D. Marx, *Z. Phys. A* 326 (1987) 121–129. doi:10.1007/BF01283586.
- [73] F. Le Blanc, L. Cabaret, E. Cottureau, J. Crawford, S. Essabaa, J. Genevey, R. Horn, G. Huber, J. Lassen, J. Lee, et al., *Phys. Rev. C* 72 (2005) 034305. doi:10.1103/PhysRevC.72.034305.
- [74] C. Piller, C. Gugler, R. Jacot-Guillarmod, L. Schaller, L. Schellenberg, H. Schneuwly, G. Fricke, T. Hennemann, J. Herberz, *Phys. Rev. C* 42 (1990) 182. doi:10.1103/PhysRevC.42.182.
- [75] A. Nadeem, S. Bhatti, N. Ahmad, M. Baig, *Journal of Physics B: Atomic, Molecular and Optical Physics* 33 (2000) 3729. doi:10.1088/0953-4075/33/18/321.
- [76] Y. Liu, C. Baktash, J. R. Beene, H. Z. Bilheux, C. C. Havener, H. F. Krause, D. R. Schultz, D. W. Stracener, C. R. Vane, K. Brück, et al., *Nucl. Instrum. Meth. B* 243 (2006) 442–452. doi:10.1016/j.nimb.2005.09.014.
- [77] U. Köster, V. Fedoseyev, V. Mishin, *Spectrochim. Acta B* 58 (2003) 1047–1068. doi:10.1023/A:1012609515865.
- [78] W. F. Meggers, M. Fred, F. S. Tomkins, *J. Res. Natl. Bur. Stand* 58 (1957) 297–315. doi:10.6028/jres.058.037.
- [79] A. Waldek, N. Erdmann, C. Grüning, G. Huber, P. Kunz, J. V. Kratz, J. Lassen, G. Passler, N. Trautmann, in: *RESONANCE IONIZATION SPECTROSCOPY 2000: Laser Ionization and Applications Incorporating RIS*; 10th International Symposium, pp. 219–224. doi:10.1063/1.1405607.
- [80] M. Fred, F. S. Tomkins, W. F. Meggers, *Phys. Rev.* 98 (1955) 1514–1514. doi:10.1103/PhysRev.98.1514.
- [81] S. Raeder, M. Domsbky, H. Heggen, J. Lassen, T. Quenzel, M. Sjödin, A. Teigelhöfer, K. Wendt, *Hyperfine Interactions* 216 (2013) 33–39. doi:10.1007/s10751-013-0832-7.
- [82] E. Verstraelen, A. Teigelhöfer, W. Ryssens, F. Ames, A. Barzakh, M. Bender, R. Ferrer, S. Goriely, P.-H. Heenen, M. Huyse, P. Kunz, J. Lassen, V. Manea, S. Raeder, P. V. Duppen, *Phys. Rev. C* 100 (2019) 044321.
- [83] GANIL-SPIRAL2, Interactive Chart of ion beams. Version 1.1 (2016). URL: <http://u.ganil-spiral2.eu/chartbeams/>, last update 2018.
- [84] A. V. Yeremin, A. N. Andreyev, D. D. Bogdanov, G. M. Ter-Akopian, V. I. Chepigin, V. A. Gorskoy, A. P. Kabachenko, O. N. Malyshev, A. G. Popeko, R. N. Sagaidak, S. Sharo, E. N. Voronkov, A. V. Taranenko, A. Y. Lavrentjev, *Nucl. Instrum. Methods A* 350 (1994) 608.
- [85] R. Hingmann, H. G. Clerc, C. C. Sahn, D. Vermeulen, K. H. Schmidt, J. G. Keller, *Nucl. Phys. A* 404 (1983) 51.
- [86] R. D. Herzberg, *Private Comm.* (2015).
- [87] E. D. Donets, V. A. Shchegolev, V. A. Ermakov, *Sov. J. Nucl. Phys.* 2 (1966) 723.
- [88] Y. T. e. Oganessian, *Phys. Rev. C* 64 (2001) 054606.
- [89] A. Yeremin, *Phys. Part. Nucl.* 38 (2007) 492.

- [90] H.-W. Gaeggeler, D.-T. Jost, A. Tuerler, P. Armbruster, W. Bruechle, H. Folger, F.-P. Heßberger, S. Hofmann, G. Muenzenberg, V. Ninov, W. Reisdorf, M. Schaedel, K. Suemmerer, J.-V. Kratz, U. cherer, M.-E. Leino, Nucl. Phys. A 502 (1989) 561. doi:[https://doi.org/10.1016/0375-9474\(89\)90689-1](https://doi.org/10.1016/0375-9474(89)90689-1).
- [91] J. Blaise, J. Wyart, Tables Selected Constants 20 (1992) 412.
- [92] N. Erdmann, M. Nunnemann, K. Eberhardt, G. Herrmann, G. Huber, S. Köhler, J. Kratz, G. Passler, J. Peterson, N. Trautmann, et al., J. alloys compounds 271 (1998) 837–840. doi:10.1016/S0925-8388(98)00229-1.
- [93] M. Sewtz, H. Backe, A. Dretzke, G. Kube, W. Lauth, P. Schwamb, K. Eberhardt, C. Grüning, P. Thörle, N. Trautmann, P. Kunz, J. Lassen, G. Passler, C. Z. Dong, S. Fritzsche, R. G. Haire, Phys. Rev. Lett. 90 (2003) 163002. doi:10.1103/PhysRevLett.90.163002.
- [94] M. Sewtz, H. Backe, C. Dong, A. Dretzke, K. Eberhardt, S. Fritzsche, C. Grüning, R. Haire, G. Kube, P. Kunz, J. Lassen, W. Lauth, G. Passler, P. Schwamb, P. Thörle, N. Trautmann, Spectrochim. Acta B 58 (2003) 1077 – 1082. doi:10.1016/S0584-8547(03)00065-X.
- [95] A. Voss, V. Sonnenschein, P. Campbell, B. Cheal, T. Kron, I. D. Moore, I. Pohjalainen, S. Raeder, N. Trautmann, K. Wendt, Phys. Rev. A 95 (2017) 032506. doi:10.1103/PhysRevA.95.032506.
- [96] H. Backe, A. Dretzke, M. Hies, G. Kube, H. Kunz, W. Lauth, M. Sewtz, N. Trautmann, R. Repnow, H. Maier, Hyperfine Interactions 127 (2000) 35–39. doi:10.1023/A:1012690022283.
- [97] H. Backe, A. Dretzke, S. Fritzsche, R. G. Haire, P. Kunz, W. Lauth, M. Sewtz, N. Trautmann, in: Laser 2004, pp. 3–14. doi:10.1007/3-540-30926-8_1.
- [98] F. Lautenschläger, Laserspektroskopie an nobelium ($z=102$) in einer puffergaszelle, 2016. URL: <http://tuprints.ulb.tu-darmstadt.de/id/eprint/5709>, PhD thesis, TU Darmstadt.
- [99] P. Chhetri, D. Ackermann, H. Backe, M. Block, B. Cheal, C. E. Düllmann, J. Even, R. Ferrer, F. Giacoppo, S. Götz, F. P. Heßberger, O. Kaleja, J. Khuyagbaatar, P. Kunz, M. Laatiaoui, F. Lautenschläger, W. Lauth, E. M. Ramirez, A. K. Mistry, S. Raeder, C. Wraith, T. Walther, A. Yakushev, Europ. Phys. J. D 71 (2017) 195. doi:10.1140/epjd/e2017-80122-x.
- [100] P. Chhetri, D. Ackermann, H. Backe, M. Block, B. Cheal, C. Droese, C. E. Düllmann, J. Even, R. Ferrer, F. Giacoppo, S. Götz, F. P. Heßberger, M. Huyse, O. Kaleja, J. Khuyagbaatar, P. Kunz, M. Laatiaoui, F. Lautenschläger, W. Lauth, N. Lecesne, L. Lens, E. Minaya Ramirez, A. K. Mistry, S. Raeder, P. Van Duppen, T. Walther, A. Yakushev, Z. Zhang, Phys. Rev. Lett. 120 (2018) 263003. doi:10.1103/PhysRevLett.120.263003.
- [101] S. Raeder, D. Ackermann, H. Backe, R. Beerwerth, J. C. Berengut, M. Block, A. Borschevsky, B. Cheal, P. Chhetri, C. E. Düllmann, V. A. Dzuba, E. Eliav, J. Even, R. Ferrer, V. V. Flambaum, S. Fritzsche, F. Giacoppo, S. Götz, F. P. Heßberger, M. Huyse, U. Kaldor, O. Kaleja, J. Khuyagbaatar, P. Kunz, M. Laatiaoui, F. Lautenschläger, W. Lauth, A. K. Mistry, E. Minaya Ramirez, W. Nazarewicz, S. G. Porsev, M. S. Safronova, U. I. Safronova, B. Schuettrumpf, P. Van Duppen, T. Walther, C. Wraith, A. Yakushev, Phys. Rev. Lett. 120 (2018) 232503. doi:10.1103/PhysRevLett.120.232503.
- [102] R.-D. Herzberg, P. Greenlees, P. Butler, G. Jones, M. Venhart, I. Darby, S. Eeckhaudt, K. Eskola, T. Grah, C. Gray-Jones, et al., Nature 442 (2006) 896–899. doi:10.1038/nature05069.
- [103] R. Herzberg, P. Greenlees, P. Butler, G. Jones, I. Darby, S. Eeckhaudt, T. Grah, C. Gray-Jones, F. Heßberger, P. Jones, et al., Physica Scripta 2006 (2006) 73. doi:10.1088/0031-8949/2006/T125/016.
- [104] A. Borschevsky, E. Eliav, M. J. Vilkas, Y. Ishikawa, U. Kaldor, Eur. Phys. J. D 45 (2007) 115.
- [105] E. Eliav, S. Fritzsche, U. Kaldor, Nucl. Phys. A 944 (2015) 518.
- [106] T. Sato, M. Asai, A. Borschevsky, T. Stora, N. Sato, Y. Kaneya, K. Tsukada, C. E. Düllmann, K. Eberhardt, E. Eliav, et al., Nature 520 (2015) 209–211. doi:10.1038/nature14342.
- [107] M. Laatiaoui, H. Backe, M. Block, P. Chhetri, F. Lautenschläger, W. Lauth, T. Walther, Hyperfine Interact. (2013) 1–7. doi:10.1007/s10751-013-0971-x.
- [108] M. Laatiaoui, H. Backe, M. Block, F.-P. Heßberger, P. Kunz, F. Lautenschläger, W. Lauth, M. Sewtz, T. Walther, Europ. Phys. J. D 68 (2014) 1–6. doi:10.1140/epjd/e2014-40617-6.