Eur. Phys. J. A **15**, 35–39 (2002)
DOI 10.1140/epja/i2001-10220-2

THE EUROPEAN PHYSICAL JOURNAL A

Lasers in nuclear physics —A review

R. Neugart[a]

Institut für Physik, Universität Mainz, 55099 Mainz, Germany

Received: 21 March 2002 /
Published online: 31 October 2002 –

Abstract. Lasers have played an important role for the development of new spectroscopy techniques yielding spins, electromagnetic moments and charge radii of many unstable nuclei. More recently, similar techniques have been introduced to manipulate atoms and thus to prepare beams or samples of radioactive atoms for various applications including nuclear spectroscopy and decay studies.

PACS. 21.10.-k Properties of nuclei; nuclear energy levels – 29.27.Hj Polarized beams – 32.10.Fn Fine and hyperfine structure – 32.80.-t Photon interactions with atoms

1 Introduction

At a first glance there seems to be little relationship between the development of lasers and the progress of nuclear physics. Nuclear energies are several orders of magnitude higher than the photon energy of typical lasers. Nevertheless, important information on nuclei has been obtained from high-precision atomic spectroscopy. Atomic-spectroscopy techniques have also been used to polarize beams or to design sources of polarized nuclei.

Many new atomic-physics experiments have become possible with the unique properties of laser light sources. Among the most spectacular developments is the cooling and trapping of neutral atoms leading to the observation of atomic Bose-Einstein condensates. Atom traps are now used for precision spectroscopy on radioactive isotopes and for very clean β-decay studies. Resonance ionization spectroscopy (RIS) has not only permitted the extremely sensitive and selective detection of trace isotopes, but in the form of laser ion sources it has also provided means of producing new beams or cleaner beams for nuclear studies.

I shall try to follow this development and give a few examples of the different fields of laser application in nuclear physics.

2 Atomic spectroscopy and nuclear structure

Effects of nuclear moments and radii on atomic spectral lines were discovered in the thirties of the last century. Already before lasers came into play, classical optical spectroscopy, rf spectroscopy and special combinations of both had been used to measure nuclear spins, magnetic-dipole moments and electric-quadrupole moments of most stable isotopes. Information on mean-square charge radii had been obtained from optical and X-ray isotope shifts, from muonic atom spectroscopy, and even details of the nuclear charge distribution had been extracted from the form factors measured in electron scattering experiments.

In the beginning of the seventies, the desire to extend this research into larger regions of unstable nuclei met with the new development of sensitive laser spectroscopy techniques. Since then, various experimental methods have been introduced to cope with the production conditions and the low number of (short-lived) radioactive atoms. For extended regions of unstable nuclei, optical spectroscopy using modern light sources provides the only access to nuclear moments and radii.

The measured quantities are hyperfine structures of the atomic states involved in an optical transition. These depend on the nuclear spin, the magnetic-dipole interaction parameter A and the electric-quadrupole interaction parameter B. The A-factor is related to the nuclear magnetic moment μ_I by

$$A = \frac{\mu_I B(0)}{IJ}\,, \tag{1}$$

while the B-factor is related to the nuclear (spectroscopic) quadrupole moment Q_s by

$$B = eQ_\mathrm{s}V_{zz}\,. \tag{2}$$

The atomic quantities of these relations, the electron angular momentum J, the magnetic field of the shell electrons at the site of the nucleus $B(0)$ and the electric field gradient produced by the shell electrons V_{zz} are usually known from the stable isotopes. The relationship between the optical isotope shift $\delta\nu^{A,A'}$ and the difference of nu-

[a] e-mail: rainer.neugart@uni-mainz.de

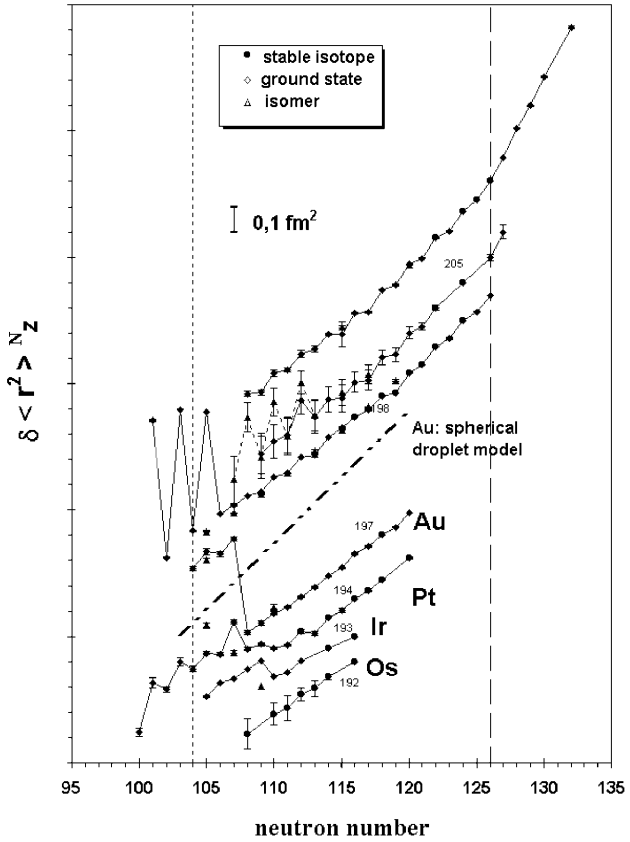

Fig. 1. Mean-square charge radii in the Hg region.

clear mean-square charge radii $\delta\langle r^2\rangle^{A,A'}$ between the isotopes A and A' of an element,

$$\delta\nu^{A,A'} = M\frac{m_{A'} - m_A}{m_{A'}m_A} + F\delta\langle r^2\rangle^{A,A'} \qquad (3)$$

contains an additional mass shift contribution (first term) which dominates for light elements and becomes nearly negligible for heavy ones. An accurate theoretical or semi-empirical calculation of the electronic factors is not trivial, and there is still a need to put the evaluation of radii from isotope shifts on a safer basis (see subsect. 4.1).

3 Optical spectroscopy

An illustrative example for the rich nuclear-structure information obtained from isotope shift measurements in the lead region ($Z \leq 82$) is shown in fig. 1. The spectacular jumps in the mean-square charge radii reflect a shape coexistence observed at neutron numbers $N = 100$ to 110. The plotted values are the result of three decades of work initiated by the pre-laser experiments on light odd-A mercury isotopes [1]. Since then, many different laser techniques have contributed to the full picture.

3.1 Resonance ionization spectroscopy

The most recent part of this work deals with the refractory elements below mercury. These are difficult to handle with the techniques of on-line isotope separation. On the other hand, the abundant production of neutron-deficient mercury isotopes also provides appreciable quantities of the (β^+- or α-) decay daughters.

The COMPLIS apparatus at ISOLDE [2] has been designed for laser spectroscopy investigations of such secondary products. Beams of Hg isotopes are guided to the apparatus where they are implanted into the surface layers of a carbon backing. After decay, the atoms are desorbed by an intense Nd:YAG laser pulse. The cloud of atoms leaving the backing is then subjected to a RIS (Resonance Ionization Spectroscopy) experiment. A narrow-band dye laser is used for spectroscopy in the first-excitation step, and two additional lasers are needed to reach the continuum. The created ions are accelerated, separated from the incoming beam in a magnetic field and counted. This technique has given access to the radioactive Au, Pt and Ir isotopes shown in the lower part of fig. 1.

3.2 Collinear laser spectroscopy

Collinear laser spectroscopy has become a working horse for the investigation of unstable isotopes, because it is ideally suitable for beams from on-line mass separators. The unique feature is a small Doppler width corresponding to the narrow longitudinal velocity distribution produced by electrostatic acceleration of ions. This gives high resolution and high excitation efficiency. Charge-exchange neutralization with alkali vapor gives access to the spectra of neutral atoms. In the simplest version relying on the detection of fluorescence photons, collinear laser spectroscopy is a rather universal method. This is why over 20 years it has yielded the moments and radii of hundreds of unstable nuclides.

A major shortcoming of photon detection is its inefficiency and sensitivity to background from the laser light. The particular interest in exotic nuclei with very low production yields has triggered the development of alternative detection methods (see, *e.g.*, [3]). Usually, these are specific for the particular atomic spectrum and for the decay properties of the isotopes.

An illustrative example is the recent experiment (fig. 2) performed on short-lived neon isotopes [4]. The 60 keV Ne^+ beam from ISOLDE is neutralized in a sodium vapor cell and excited from the preferably populated metastable $J = 2$ level. Optical pumping to the ground state occurs via a strong decay branch of the excited level. Now the detection makes use of the large cross-section for collisional ionization from the metastable level. The beam passes through a thin gas target, and singly charged ions and neutral atoms are separated and counted. Optical resonance appears as a drop of the ratio of both count rates. Weak beams of short-lived isotopes can be discriminated from the much stronger (stable) background beams by counting the β-radioactivity.

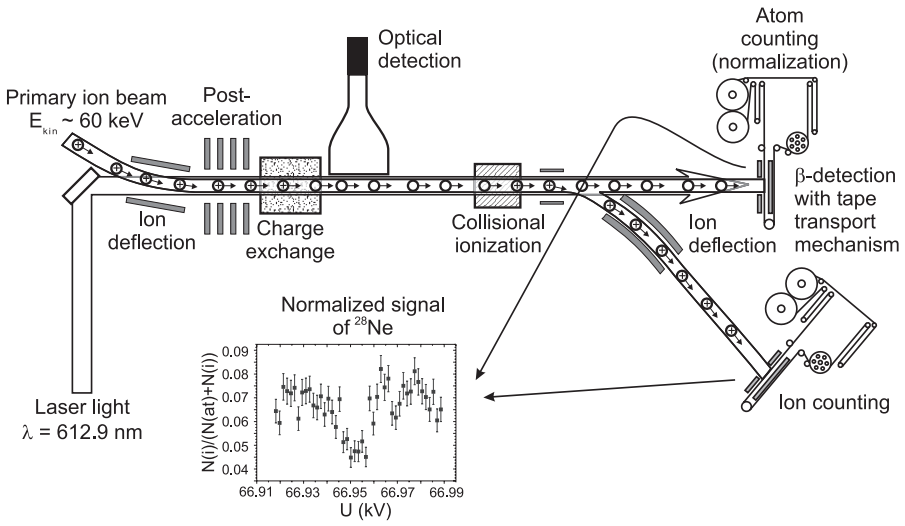

Fig. 2. Setup for collinear laser spectroscopy on short-lived neon isotopes.

It should be noted that the 1 MHz accuracy needed for the extraction of the small ($\sim$ 10 MHz) field shifts from the Doppler-shifted resonance positions requires the knowledge of the 60 keV beam energy to better than 1 eV. This accuracy has been reached by an absolute Doppler shift measurement.

The experiment has been performed on all unstable neon isotopes (except ^{27}Ne) from ^{17}Ne at the proton drip line to the neutron-rich ^{28}Ne for which about 40 atoms per second are produced. It addresses several interesting physics problems: i) A proton halo that has been postulated for ^{17}Ne will be probed very sensitively by the isotope shift. ii) The dependence of the radii on the neutron number can be relatively safely calibrated by muonic X-ray results on the stable isotopes. iii) The moments and radii give a valuable basis for comparisons with shell model and mean-field calculations. iv) ^{17}Ne together with ^{17}N forms one of the very few $T = 3/2$ nuclear mirror pairs for which the magnetic moments are known.

Collinear laser spectroscopy needs a beam of low kinetic-energy spread (typically 1-2 eV) as it is obtained from surface ionization or low-temperature plasma ion sources. This is a problem for the refractory elements for which the production of beams is based on the IGISOL concept [5]. Ions are transported from the target to the source by a helium jet and the extraction voltage at the skimmer electrode introduces a considerable energy spread which can only be reduced at the expense of beam intensity. The laser spectroscopy group at Jyväskylä has recently introduced a very efficient cooling system [5] consisting of a low-pressure gas-filled radio frequency quadrupole (RFQ). In addition to lowering the energy spread this device gives the possibility to bunch the beam and thus to reduce the continuous background from the laser light.

3.3 Doppler-free two-photon spectroscopy

For even lighter elements it will hardly be possible to resolve the field isotope shifts with standard methods of about 1 MHz accuracy. A very interesting case is lithium where one would like to measure the charge radius of the halo nucleus ^{11}Li with respect to ^{9}Li and the lighter isotopes. The field shift is of the order 1 MHz on top of a total isotope shift of 10 GHz. To get meaningful information on the halo structure of ^{11}Li, one needs this shift to about 100 kHz. A promising approach to reach this accuracy is pursued at GSI [6]. The idea is to prepare a thermal atomic beam and to use Doppler-free two-photon absorption for high resolution and a subsequent two-step photoionization process for the extremely sensitive detection.

The information on the halo structure of ^{11}Li will be complementary to the matter radii extracted from total reaction cross-sections at high energies. A neutron halo affects the charge radius indirectly through the center-of-gravity motion, and this is sensitive to correlation effects between the halo neutrons.

4 Beam and sample preparation

Apart from being a tool of nuclear-structure physics, the described methods of laser spectroscopy have been applied for the preparation of beams and atomic samples. These applications include the ion source development as well as the polarization of electronic and nuclear spins. Also laser cooling in combination with conventional storage techniques are involved in new experiments addressing fundamental aspects of the nuclear β-decay.

4.1 Laser ion source

The concept of a laser ion source has been described above in connection with the RIS experiments. Instead of using ionization as a sensitive detection of optical resonance, one uses the stepwise excitation and resonance ionization process for producing ions in a source which essentially consists of a heated tube. The outstanding advantages of

this scheme are a very high selectivity for the particular chemical element and to some extent for a certain isotope (or isomer) as well as a good efficiency, even for elements that are difficult to ionize in conventional sources.

At ISOLDE, the laser ion source has solved the problem of isobar contamination of many radioactive isotope beams [7]. Because of the unspecific production reaction, this used to be a problem mainly for the less volatile elements obtained from a hot plasma source. Thus, the laser ion source has enabled very clean nuclear spectroscopy experiments. So far suitable ionization schemes have been found for about 30, and beams of 13 elements have been used for experiments.

The laser ion source also has interesting aspects for very sensitive laser spectroscopy on the heavier elements [8], where the moderate resolution of pulsed lasers is sufficient. The experiment just consists in the detection of a beam as a function of the laser frequency.

4.2 Polarized beams

Polarized nuclear beams have interesting applications in different fields of physics. For selected atomic species such as the alkali and alkaline earth elements, high polarization is achieved by in-beam optical Zeeman pumping using circularly polarized laser light. This polarization process takes advantage of the features of collinear laser spectroscopy. Short-lived isotopes can be implanted into a suitable crystal, where the interaction of the nuclei with the lattice or with static and/or radio frequency magnetic field is observed in the β-decay asymmetry.

First experiments were performed on the short-lived lithium isotopes [9], leading to a measurement of the spin and the electromagnetic moments of ^{11}Li. More recently, the quadrupole moments of $^{26\text{-}31}$Na up to $N = 20$ were measured [10]. It was demonstrated that nuclear polarization of about 50% is achieved rather easily. Even the low power of a frequency-doubled cw dye laser pumping Be^+ ions was sufficient for a magnetic-moment measurement on ^{11}Be with a β-asymmetry in the percent range [11].

Such polarized beams of short-lived isotopes may, on the other hand, be used to study hyperfine fields in solids. Instead of measuring nuclear properties, one can use the implanted nuclei as probes for the interaction with the lattice surroundings. At ISOLDE this was demonstrated for ^{8}Li nuclei in Si and in ZnSe crystals. Similar experiments will be performed at TRIUMF, where a dedicated beam line for optical pumping polarization has been installed at the ISAC facility [12].

4.3 Magneto-optical trapping

Polarization also plays an important role in experiments planned for neutral atom traps. These experiments take advantage of the possibility to store a dense cloud of cooled atoms in a small volume of less than 1 mm^3. Precision spectroscopy on such ensembles of radioactive atoms will include studies of parity-nonconservation (PNC) effects [13,14]. Stored samples of radioactive free atoms also offer unique possibilities to study fundamental aspects of the nuclear β-decay. These include the search for right-handed currents and the test for time-reversal invariance [15].

So far, a viable concept for the on-line transfer of radioactive isotopes into a magneto-optical trap has been developed for the alkali elements. A primary ion beam is hitting an yttrium neutralizer foil, and the re-evaporated atoms are kept in the gaseous phase by dry-film coated glass walls. Under continuous rethermalization the lowest-velocity part of the thermal distribution is captured by the cooling force produced by 6 laser beams, propagating in opposite directions along three orthogonal axes and crossing in the magnetic-field minimum of an anti-Helmholtz pair of coils.

For clean experimental conditions it is favorable to transfer the cooled cloud to a second trap where the polarization axis is well defined and where detectors for recoiling atoms from β-decays can be installed. This system is operational at TRIUMF [15], where in decays of ^{37}K and ^{38}K the neutrino momentum and the β-ν angular correlation is measured with respect to the nuclear spin direction.

4.4 Relativistic heavy ions in storage rings

Not only ultra-low-energy atomic clouds, but also high-energy beams in big storage rings offer interesting features for laser spectroscopy. Atomic physics at accelerators mainly deals with highly charged ions for which the transition energies lie in the X-ray region. On the other hand, at relativistic beam energies it becomes possible to Doppler-shift the wavelength of conventional laser radiation into this region.

For example, a proposal at GSI [16] aims at the spectroscopy of heavy lithium-like ions. For U^{89+} the excitation energy from the $2s$ ground state to the $2p_{1/2}$ first-excited state is about 280.6 eV. With $\gamma = 23.9$ the Doppler shift

$$\hbar\omega_0 = \sqrt{\frac{1+\beta}{1-\beta}}\hbar\omega_{\mathrm{L}} \tag{4}$$

requires a photon energy of $\hbar\omega_{\mathrm{L}}$ of only 5.87 eV, corresponding to the UV wavelength of 211 nm.

The spectroscopy on lithium-like ions has interesting aspects for the calibration of isotope shift data on nuclear charge radii. Atomic calculations of lithium-like systems are very accurate. So differences of nuclear mean-square charge radii can be calculated reliably from the isotope shifts and used to determine accurate electronic calibration factors for the rich isotope shift data existing on the optical spectral lines of many isotopes and elements.

5 Conclusion

Although my selection of topics is somehow biased, it shows a wide and diversified field of laser applications in nuclear-physics experiments. The common aspect of all this work is the interaction of atoms with laser light. This

can be used not only to study nuclear properties from the atomic spectra, but also to manipulate the atoms used for various nuclear-physics experiments.

References

1. J. Bonn *et al.*, Z. Phys. A **276**, 203 (1976).
2. F. Le Blanc *et al.*, this issue, p. 49.
3. A. Klein *et al.*, Nucl. Phys. A **607**, 1 (1996).
4. W. Geithner *et al.*, *Laser spectroscopy measurement of isotope shifts and nuclear moments of short lived neon isotopes*, poster contribution, to be published in *Exotic Nuclei and Atomic Masses* (Springer-Verlag, Heidelberg, 2002).
5. P. Campbell *et al.*, this issue, p. 45.
6. F. Schmitt *et al.*, Hyperfine Interact. **127**, 111 (2000).
7. V.N. Fedoseyev *et al.*, Hyperfine Interact. **127**, 409 (2000); see also U. Köster *et al.*, *Production of intense RIBs using the ISOL technique*, to be published in *Exotic Nuclei and Atomic Masses* (Springer-Verlag, Heidelberg, 2002).
8. A.E. Barzakh *et al.*, *Charge radius and electromagnetic moments of* ^{153}Yb, poster contribution, to be published in *Exotic Nuclei and Atomic Masses* (Springer-Verlag, Heidelberg, 2002).
9. E. Arnold *et al.*, Phys. Lett. B **197**, 311 (1987); **281**, 16 (1992).
10. M. Keim *et al.*, Eur. Phys. J. A **8**, 31 (2000).
11. W. Geithner *et al.* Phys. Rev. Lett. **83**, 3792 (1999).
12. R.F. Kiefl *et al.*, Physica B **289-290**, 640 (2000).
13. D.J. Vieira *et al.*, *Natural atom traps for fundamental symmetry measurements*, talk at this conference; Hyperfine Interact. **127**, 387 (2000).
14. G.D. Sprouse *et al.*, Hyperfine Interact. **127**, 381 (2000).
15. A. Gorelov *et al.*, Hyperfine Interact. **127**, 373 (2000).
16. GSI Atomic Physics Proposal (2001).