LASERS AT ACCELERATORS

Past, Present and Future

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ABSTRACT

The application of lasers at accelerators is reviewed with emphasis on laser spectroscopy of short-lived isotopes and the determination of nuclear spins, moments, and changes of charge radii in long isotopic chains leading far off stability. Experimental techniques as well as future directions are discussed.

(General)

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Introduction

Lasers have become important tools at accelerators because of the high photon flux available, the spatial and temporal coherence, and, last but not least, the high cross section for resonant interaction between atoms and photons. There are four main applications of lasers to accelerator work which have evolved since the Seventies when the first commercial tunable lasers became available. These are, in chronological order :

- laser spectroscopy of radioactive isotopes
- Lamb shift experiments on hydrogenic heavy ions
- polarized beams and targets
- the cooling of heavy ions in storage rings.

On-line laser spectroscopy of radioactive ions [1] started in 1975 at Orsay with the investigation of sodium isotopes in the range of ^{21}Na to ^{25}Na [2]. In the very same year, the first laser experiment for the determination of the Lamb shift in heavy ions, namely $^{19}\text{F}^{8+}$, was reported [3]. It was also recognized at that time that laser light might be useful in order to achieve highly polarized atomic beams and targets for nuclear research via optical pumping (see, for example, Ref.[4]). However, the first experiments with laser-polarized, accelerated atomic beams were first performed in the Eighties [5], if one disregards the application of lasers for the production of polarized electrons in GaAs-sources as used in neutral current experiments [6,7] for search of parity violation. Scattering experiments with oriented ^{23}Na and ^7Li nuclei performed at the Tandem accelerator at Heidelberg [5] are now textbook examples for physics with polarized particles.

In the case of targets polarized by optical pumping, the achievable, low densities of polarized atoms still represent a problem. Presently, only ^3He and D targets provide the required target thickness for nuclear physics experiments. Such targets are only just now coming into operation [8,9]. Finally, the development of storage rings for accelerated heavy ions enabled the transfer of the concepts of laser cooling and precision spectroscopy which were first developed for low-energy ion traps to accelerator facilities [10].

Hence it can be concluded that lasers play an increasingly important role at accelerators. The present paper will concentrate on on-line laser spectroscopy of short-lived isotopes in long isotopic chains which has been extremely successful in the last two decades and enabled us to determine the nuclear ground state properties of around 500 nuclei in long isotopic chains.

I. We Can Expect Surprises!

To expect surprises is, of course, speculation, but is also partly based on experience from the past. Looking at the landscape of nuclei one sees the well investigated valley of stability surrounded by the longer-lived isotopes. More than 6000 nuclei are predicted to exist as bound quantum mechanical systems. About 2000 of those have been produced but less than 1000 are quite well investigated, so that in addition to, for example, the nuclear half life and the decay mode one also knows of some nuclear ground state properties such as the nuclear spin and some part of the level scheme.

Can we expect to know all the essentials in nuclear physics if we only have some 15% of the information which is principally accessible? Nuclear physics will not be turned upside down if another 15 % of the missing data or even the totally missing 85 % are added. But surely quite important ingredients of the behaviour of nuclear matter have escaped observation until now.

There are three different routes to follow in order to discover new effects. The traditional, highly successful ISOL-route (ISOL = isotope separator on-line) is to explore the nuclei in their ground state or at low excitation energies as function of proton or neutron number. The alternative route to high excitation energies is intensively followed up at heavy ion accelerators. Here, for example, the Coriolis-decoupled rotational bands and backbending have been discovered in the last two decades, as have quite recently super-deformed bands, which are rotational bands of strongly deformed nuclei with a ratio of the axis of the ellipsoid of 2:1, corresponding to a quadrupole deformation parameter of about $\beta = 0.6$. Similarly, strongly deformed nuclei are also known at low excitation energies as fission isomers.

In the N-Z plane, the playground of ISOL-techniques, the following surprises have been encountered during the last twenty years [1]:

- nuclear shape transitions and shape coexistence of states which are almost degenerate in energy;
- stable octupole deformation in the heavy radium isotopes, first observed by mass spectrometry and later also found to be manifested in the spin sequence, the magnetic moments and an inverted odd-even staggering of charge radii;
- breakdown of the concept of magic numbers as observed in the heavy sodium isotopes;
- discovery of the shell closure at $Z = 64$ leading to a double-magic shell-model nucleus ^{146}Gd ;
- and the more or less spherical shape of the very neutron-rich nucleus ^{11}Li for which an extremely large matter radius has been observed [11].

These examples suggest that one can almost guarantee to find new phenomena whilst carrying out nuclear physics at an ISOL-facility, admittedly with a rather low event rate of one big surprise every two to four years, however. But still, this is considerably higher when compared to the event rate of supernovae in our galaxy.

In order to find new phenomena, one must perform systematics. These new effects are generally a rather small deviation from a regular smooth trend which one has to establish beforehand. None of the surprises just mentioned would have been discovered without - sometimes boring - systematic investigations.

II. Model-Independence of Atomic Spectroscopy

All data determined by atomic spectroscopy are model-independent:

- The hyperfine structure splitting gives access to the nuclear spin I by the observation of the coupling between the electronic and nuclear momenta.
- The magnetic field produced by the electrons at the site of the nucleus and its interaction with the nuclear magnetic dipole moment μ_I leads to the magnetic hyperfine structure.
- The nuclear spectroscopic quadrupole moment Q_S modifies this splitting due to its interaction with the electric field gradient produced by the electrons at the site of the nucleus. It should be stressed that the spectroscopic quadrupole moment Q_S , the projection onto the quantization axis, is model-independent, whereas the intrinsic quadrupole moment Q_0 , the projection onto the symmetry axis of the nucleus, is model-dependent.
- A measurement of the isotope shift in an optical transition enables one to determine the change of the mean-squared nuclear charge radius $\delta\langle r^2 \rangle$. The atomic Coulomb potential is weakened if the nuclear charge distribution is extended by adding more neutrons.

These data represent key information for further interpretation of nuclear physics experiments. They must be determined as they are fundamental properties of existing quantum mechanical systems. They have to be collected and compiled in tables or appendices of books on nuclear physics. Once determined, they stay in the books forever or at least as long as no better experiments are performed. At some time in the future the nuclear data obtained by optical spectroscopy will definitely become essential for the analysis of an experiment or for a theoretical investigation.

III. Past and Present: Impact of Atomic Physics Experiments at Accelerators

III.1 Atomic Physics

It is not obvious that we can learn something on the physics of the electronic shell of an atom by going to an accelerator facility. Nevertheless, there are a number of results showing that it is worthwhile. Here, two examples will be given for use of nuclei far from stability in order to check atomic theory:

King Plot: If the isotope shift is composed of the nuclear volume effect (which one would like to extract for nuclear-physics purposes) and of the mass effect (which has two contributions: the easily calculable normal mass shift and the still unreliably calculable specific mass shift), the isotope shifts measured in two different optical transitions should lie on a straight line. The most rigorous test (Fig. 1) has been performed at ISOLDE by means of the very long string of radium isotopes [12]. Obviously, the atomic theory of isotope shifts is valid: No deviation from the straight line is observed even with a magnification by a factor of 100.

Unknown Atomic Level Schemes: Usually, it is much more convenient to study the atomic properties of atoms in the home laboratory than at an accelerator site. But sometimes this is not possible (or only after invention of very refined techniques [13]). An example for such a case is francium, where the longest-lived isotope, ^{212}Fr , has a nuclear half life of only 20 minutes. The level scheme of francium, the heaviest alkali isotope, could be partially established [14] in recent years at ISOLDE. Since relativistic effects play an important role in francium, this element represents one of the rare test grounds for relativistic atomic theories.

III.2 Nuclear Physics

In the following, one or two examples will be given for each model-independent quantity accessible by atomic spectroscopy on what can be learned on nuclear properties from atomic spectroscopy.

Nuclear Spin I: In case of the odd-A neutron-deficient cesium isotopes the measured spin sequence [15] is just as expected from the Nilsson model. Starting with ^{141}Cs near the neutron shell closure the first spins observed correspond to the shell model state $\pi g_{7/2}$. At ^{131}Cs the $[413]5/2$ Nilsson level shows up, then $[420]1/2$, and in the very neutron-deficient Cs isotopes the Nilsson orbits $[422]3/2$ and $[404]9/2$ are observed. This indicates strong deformation as later confirmed by laser spectroscopy. Hence: No surprise!

This is completely different in the case of the radium isotopes (Fig. 2): The experimentally observed spin sequence [16] can not be explained in the pure Nilsson model by only taking quadrupole deformation into account. One has to consider an additional degree of freedom, namely octupole deformation, to explain the observed spin sequence [17]. Additional evidence for octupole deformation comes from the measured magnetic moments and the inverted odd-even staggering of the isotope shift observed in $^{221}\text{Ra} - ^{225}\text{Ra}$ [16].

Magnetic moment μ_I : The magnetic moments are excellent probes for nuclear configurations. An illustrative example for the importance of systematics of magnetic-moment measurements represents the case of the platinum isotopes where the sign of the magnetic moment is decisive for the occurrence of shape triaxiality [18].

An example for the importance of a single measurement is that of a very pure nuclear configuration near a doubly-closed shell which allows one to determine the effect of core polarization on the magnetic moment. The ground state of ^{207}Tl is a $3s_{1/2}$ proton hole in the doubly-magic ^{208}Pb core. The magnetic moment of this nucleus is a test case for the theory of magnetic moments since it is only sensitive to the gyromagnetic ratio of the spin: For $l = 0$ the orbital-moment gyromagnetic ratio vanishes and the tensor term is also zero. Since meson exchange contributions are not expected, the magnetic moment of ^{207}Tl represents a unique test case for core polarization effects. The experimental result obtained by laser spectroscopy [19] shows a drastic deviation from the Schmidt value but agrees within 5 % with calculations [20] taking core polarization effects into account.

Spectroscopic Quadrupole Moment Q_S : One of the most recent, important measurements of a very specific, single nucleus concerns the spectroscopic quadrupole moment of ^{11}Li . The quadrupole moments for the unusual ^{11}Li and the nearly spherical ^9Li were found [21] to be almost identical ($Q_S(^{11}\text{Li}) = 1.10(16) Q_S(^9\text{Li})$). This result rules out the possible explanation that the extreme matter radius of ^{11}Li [11] is due to deformation. Nuclear deformation is also not supported by the measured spin and magnetic moment. Hence the most probable explanation is a neutron halo [22].

The quadrupole moments are not only indicators of nuclear deformation, they are also sensitive probes for the type of coupling of the valence nucleon to the core. The clearest example for the dependence of the spectroscopic quadrupole moment on the type of coupling is given by the $\nu_{13/2}$ isomeric states of mercury. Furthermore, this is an example for the importance of systematics. The experimental spectroscopic quadrupole moments of the $I = 13/2$ Hg isomers [23] are shown in Fig. 3 as a function of mass number. The open circles connected by a broken line fit the experimental values and are calculated by Ragnarsson [24] for a constant negative intrinsic quadrupole moment corresponding to $\beta = -0.12$. What is observed in the mercury isomers is not a change in deformation but a change in the type of coupling from a decoupled state in the heavy isomers to strong coupling which is obviously not yet reached in $^{185\text{m}}\text{Hg}$. Only for strong coupling is the simple Bohr-Mottelson projection formula suitable, whereas in the transitional nuclei the projection is much more complex. In the latter case, an expansion into Nilsson wave functions has to be applied which gives the information on the degree of strong coupling or decoupling.

Changes in Mean-Square Charge Radii $\delta\langle r^2 \rangle$: Figure 4 shows the charge radii of the Hg chain. With these experiments on Hg, optical spectroscopy at ISOL-facilities started twenty years ago. In addition, $\delta\langle r^2 \rangle$ values are given for the isotopic chains of Au and Pt. The steady gain of information during the last two decades is an excellent example of the close connection between scientific achievements and experimental developments. The charge radii of mercury were obtained in the early Seventies by the technique of β -radiation detected optical pumping [25] and later on by resonance fluorescence induced by spectral lamps [26], γ -RADOP [25], laser fluorescence spectroscopy in resonance cells [27], quantum beat spectroscopy [28] and finally collinear spectroscopy [23].

Purely by luck - because it was not predicted - a nuclear shape transition was found from slight oblate deformation to a strong prolate one [29]. The deformation in the light odd Hg isotopes was found to be of the same magnitude as that of the well deformed rare earth isotopes. This was completely unexpected for nuclei with an almost closed proton shell. Later, calculations showed that this shape transition is due to shape coexistence: A minimum in the energy-deformation curve at slightly oblate deformation and a minimum at strong prolate deformation are almost degenerate in energy and competing in becoming the nuclear ground state. In $^{185\text{m}}\text{Hg}$, two nuclear shapes coexist at similar half lives [30].

Similar experiments were performed on gold, first by laser resonance fluorescence spectroscopy in very hot sapphire cells [31], later on by resonance ionization mass spectroscopy [32] and again a sharp nuclear shape transition was found. A further increase of the sensitivity by using pulsed laser-induced desorption in combination with resonance ionization mass spectroscopy [33] enabled the determination of hyperfine structures and isotope shifts down to ^{183}Au [34,35]. This time, no shape staggering was observed due to the polarizing power of the $h_{9/2}$ unpaired proton.

Using the very same technique - pulsed-laser induced desorption in combination with resonance ionization mass spectrometry - the platinum isotopes have recently been investigated [36-38,18]. In the latter case, a smooth transition (Fig. 4) is observed from an oblate shape via triaxial deformation to a strong, mainly prolate shape, but the nuclei still remain triaxially deformed. Figure 5 shows the quadrupole deformation parameters of the neutron-deficient mercury, gold, and platinum isotopes derived from the measured isotope shifts or the deduced $\delta\langle r^2 \rangle$ -values [18]. Only absolute deformation parameters are obtained from isotope shift measurements. In addition, the charge radii are very insensitive to the triaxial-shape asymmetry parameter γ .

As seen in Fig. 5, the heavy isotopes are slightly deformed. Going away from the neutron shell closure at $N = 126$ one observes a steadily increasing quadrupole deformation. In the area around $\beta \approx -0.15$ Coriolis effects play a dominant role, whereas in the very neutron-deficient isotopes strong, dominantly prolate deformation is obtained for the isotopes of all three elements. This is, however, associated in the case of mercury with a drastic odd-even shape staggering. In gold one sudden change of the nuclear shape has been observed. In contrast to these two elements one finds a rather smooth transition to strong deformation in platinum. It is surprising how quickly the $Z = 82$ proton configuration loses its power to keep the nucleus spherical or only slightly deformed.

Today, the general behaviour of transitional nuclei is quite well understood. The static properties like, for example, the moments can be reproduced by models, but we still do not yet have a deeper understanding of the dynamics of transitional nuclei. It is still an open question why the nuclear states of the neutron-deficient mercury isotopes are so well localized in the shallow minima of the potential energy surface.

The charge radii of Sr and Rb isotopes are another example for dynamic properties of the nuclear system obviously not fully understood [39]. The charge radii below $N = 50$ can neither be reproduced by Hartree-Fock and Strutinski calculations nor by the Droplet model and the use of experimental $B(E2)$ values. Some mechanism is blowing up the nuclear radii which is not yet under control.

IV. Present and Future: ISOL-Facilities and On-Line Laser Techniques

Isotope Production: Up to now, the concept of an isotope separator with a thick target of the order of 100 g/cm^2 on-line at a high-intensity proton accelerator is the most powerful technique for the production of a broad range of nuclei far from stability below uranium. In addition, 1 GeV proton-induced spallation and fission reactions are very economical and rather universal production schemes: More than 60 elements with sometimes over 40 isotopes are accessible with yields up to 10^{11} ions per second and per mass number [40]. Only on the wings of the yield curves, where the diffusion time out of the target/ion source system are significant as compared to the nuclear half life, heavy ion reactions may provide higher production rates.

The broad spectrum of isotopes produced by proton-induced spallation or fission reactions is an important advantage in comparison to heavy-ion accelerators with respect to economy and availability. The trade-off for the broad but unspecific production is a higher demand for elemental and isotopic selectivity in the target/ion source system and for a high resolving power of the mass separator. The ion guide technique (IGISOL [41]) is presently closing the gap of refractory elements not volatile enough for conventional ion source technology and extends the applicability of ISOL-techniques to nuclei of shorter half lives. Its drawback is a rather low production rate. Finally, it should be mentioned that an ion beam with an energy of some 10 keV is quite adapted to the requirements of most atomic-physics experiments.

Heavy ion accelerators and fragment separators coupled are starting to compete with traditional ISOL-systems in the production of nuclei far from stability. Such combinations give access to short-lived isotopes near to the neutron drip line. Until now, however, no laser work has been performed at such facilities due to the beam properties unfavourable to optical spectroscopy.

Laser techniques: In atomic spectroscopy experiments on nuclei far from stability, two general strategies are to be followed:

- higher accuracies in order to also see smaller effects as, for example, tiny isotope shifts in the light isotopes, hyperfine anomalies or neutral current effects in radioactive isotopes,
- higher sensitivity in order to enable the study of nuclei still further away from stability.

Table 1 shows the experimental techniques applied to the study of short-lived isotopes in the early days of atomic laser spectroscopy at accelerators as well as the two schemes which have emerged out of many trials and errors to be most suited for optical spectroscopy at on-line isotope separators. These are collinear spectroscopy and resonance ionization spectroscopy (RIS) for which quite a number of variants or even combinations are listed in Table 1. The basic principle of the two techniques is as follows: Collinear spectroscopy is applied directly to the on-line ion beam. The laser beam is sent collinear to the fast ion beam. In general, the resonance fluorescence photons are detected. Since the energy spread is a constant of motion and determined by the spread in the ion source, the velocity spread decreases as the velocity increases. Because the velocity spread is responsible for the line width, the Doppler broadening is largely reduced and simultaneously the probability of interaction of the laser photons with the fast atoms is increased. This results in high ac-

curacy and sensitivity. The majority of new data on short-lived isotopes has been obtained by collinear spectroscopy at ISOLDE [42]. Further experiments have been performed at GSI/Darmstadt [43], UNISOR/Oak Ridge [44], TRISTAN/Brookhaven [44] and Daresbury [45].

Resonance ionization spectroscopy (RIS) has been applied in Leningrad to a large number of radioactive rare earth isotopes [46]. Resonance ionization mass spectroscopy (RIMS) and the combination of RIMS with pulsed-laser-induced desorption (RIMS/PLID) was applied at ISOLDE/CERN and ISOCELE/Orsay to short-lived gold and platinum isotopes [18,32-39].

Figure 6 shows the RIMS/PLID set-up used by us at CERN. The ISOL-beam is implanted into a target. The atoms are released from this target as a thermal, bunched atomic beam which is excited with laser light at wavelength λ_1 . But instead of looking for the resonance fluorescence as in the case of collinear spectroscopy with fluorescence detection, the atoms are further excited by λ_2 and finally ionized by laser light at wavelength λ_3 via an autoionizing state. The ions created in resonance are detected with high efficiency and mass selectivity by a time-of-flight spectrometer (Fig.7). Hence, background ions are suppressed very effectively.

Both techniques, collinear and resonance ionization spectroscopy are complementary and have their advantages and disadvantages. Collinear spectroscopy is applied directly to the (charge-exchanged) ISOL ion beam. Hence, any further manipulation of the ion beam is avoided. This advantage is at the same time a drawback, since only directly produced isotopes can be investigated. Resonance ionization spectroscopy, on the other hand, can also be applied in order to study daughter isotopes, even those of refractory elements as demonstrated for platinum isotopes. Collinear spectroscopy has been proven to have the highest sensitivity and resolution, but suffers from isobaric impurities in the ISOL ion beam. Hence, the availability of a high-resolution separator is essential especially for the study of nuclei very far from stability where isobaric impurities might be much more abundant than the isotope under investigation. Isobaric or isotopic impurities are of no major concern for resonance ionization mass spectroscopy due to the inherent selectivity of this method. On the other hand, resonance ionization suffers generally from the limited resolution because of the need of pulsed tunable laser light. Therefore, RIS will be applied in the future mainly for heavy isotopes where the hyperfine splittings and isotope shifts due to the nuclear volume effect are large. The lighter isotopes will be a domain of collinear spectroscopy.

The laser ion source is a special application of resonance ionization spectroscopy in order to ionize the atoms under investigation step by step resonantly in a hot cavity. The ions created in resonance are extracted out of the cavity by an electric field, accelerated, mass separated and detected. Figure 8 shows the set-up used in Mainz for trace detection of technetium isotopes for a solar neutrino experiment [47]. An ion source efficiency as high as 13% has been achieved in case of Tc with three dye lasers pumped by two copper vapor lasers at a repetition rate of 6.5 kHz. Such an ion source combines high efficiency with high elemental selectivity. In addition, the produced photo ions are bunched. This feature can be used for a further reduction of the background (Fig. 9), or for injection into accelerators or ion traps. A similar laser ion source has been recently installed and tested at ISOLDE [48].

V. Future Directions

Figure 10 shows the chart of nuclei with those isotopic chains marked which have already been investigated by laser spectroscopy. As one can see, nothing is known above radium and only little below krypton. Hence one important aim of future experiments should be the gain of more systematic information on transuranium and light isotopes. In the latter case, this is difficult because the isotope shifts as well as the hyperfine structure splittings become small. Nevertheless, it has been proven in the case of lithium and sodium that atomic spectroscopy can also be applied to light isotopes.

Light isotopes will enable us to perform atomic spectroscopy over a full neutron shell. Until now, we have only one example, the calcium isotopes, where the charge radius of ^{40}Ca and ^{48}Ca was found to be identical [1]. The reason is a change in the skin thickness as found by electron scattering experiments. The parabolic behaviour of the changes of mean-square charge radii with a maximum in the middle of the neutron shell was also clearly observed for the tin region [43]. It has been explained by Talmi in terms of core polarization of nuclei with closed proton shells by the active neutrons in the open shell. In addition to these systematic studies, special nuclei should be investigated like most neutron-rich, light isotopes.

Until now mainly the one-dimensional dependence of the ground-state properties was investigated, namely the dependence on the neutron number. By filling the still existing gaps (Fig. 10), the full, two-dimensional view of nuclear ground state properties will be obtained as function of neutron and proton number. For example, this will enable us to study isotonic and isobaric isotope shifts, the odd-even staggering in isotonic shifts and by this the expected parabolic behaviour of isotonic shifts of nuclei with a closed neutron shell but open proton shell.

Many surprises might be expected.

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Table 1. Comparison of different on-line techniques for study of short-lived isotopes. Outstanding performance, applicability or background conditions are in bold, good in standard, and less good ones in tilted letters. The numbers given as minimum yield are those cited in the literature or calculated for a nuclear half life of some seconds. The classification given here is not absolute but strongly depending on the isotope under investigation. RADOP: nuclear Radiation Detected Optical Pumping, LIOP: Laser-Induced Optical Pumping, CS: Collinear Spectroscopy, RIS: Resonance Ionization Spectroscopy, RIMS: Resonance Ionization Mass Spectroscopy, PLID: Pulsed-Laser-Induced Desorption. For details see text or Ref. [1].

Technique	Applicability	Example	Resolution [MHz]	Minimum Yield [s^{-1}]	Background/ detected part.
RADOP in cells	volatile elements	alkali Hg	10^3	10^3	asymmetry effect/ β , γ
Fluorescence spectroscopy in cells	inert elements	Hg, Au, Yb	10^3	10^3	stray light/ photons
Fluorescence spectroscopy in collimated beams	general	alkaline earths	10^2	10^8	dark current/ photons
LIOP in collimated atomic beams	surface ionizable elements	alkalies	10^2	10^6	opt. pumping effect/atoms or ions
CS with detection of fluorescence	general, direct use of ion beam	many elements	10	10^4	radioactivity/ photons
CS with detection by collisional ionization	high-lying metastable state	noble gases	10	10^2	isobars/ fast ions
CS with detection by charge exchange	metastable state of ions	Sr	10	10^2	isobars/ fast atoms
CS with coincidence of fluorescent photon and atom	<i>weak optical pumping required</i>	Sr, Ba	10	10^2	isobars/ fast atoms or ions
CS with detection by RADOP	<i>dedicated problems</i>	^{11}Li	10	10^2	asymmetry effect/ β , γ
CS with RIS detection	general, direct use of ion beam	Yb	10^2	10^6	isobars/ fast ions
RIS or RIMS	general, daughters, accumulation	rare earths	10^2	10^4	residual-gas ions/ ions
RIS/PLID	as above, refractory elements	Au, Pt	10^3	10^4	residual-gas and desorption ions/ ions

Figure Captions

Fig. 1: King plot of the radium isotopes with $208 \leq A \leq 230$ in the $\lambda = 482.6$ nm (RaI) and $\lambda = 468.3$ nm (RaII) transition. The circles show an enlargement of the scale by a factor of 100.

Fig. 2: Nilsson diagram of the neutron levels in radium as function of the quadrupole deformation β_2 . (a) without octupole deformation ($\beta_3 = 0$) and (b) with $\beta_3 = 0.08$ [17].

Fig. 3: Transition from strong coupling ($A \ll 185$) to decoupling ($A \gg 185$) as observed in the spectroscopic quadrupole moments of the $\nu_{13/2}$ isomers of neutron-deficient mercury isotopes. The full dots are the experimental values [23]. The open circles connected by a broken line are theoretical values [24] calculated in the particle-plus-rotor model with the quadrupole deformation parameter fixed at $\beta_2 = -0.12$.

Fig. 4: Changes of mean-square charge radii in the isotopic sequences of Hg, Au, and Pt as a function of mass number. Isomeric states are indicated by asterisks. The radii of ground states are indicated and connected by an eye-guiding line. In addition, the charge radii of isomeric states are given. The errors are smaller than the diameters of the symbols except for ^{183}Pt and ^{184}Au .

Fig. 5: Quadrupole deformation parameters $\langle \beta^2 \rangle^{1/2}$ of platinum, gold, and mercury isotopes as a function of mass number as calculated from the measured isotope shifts. The guiding line is connecting the ground states. In addition, the quadrupole deformation parameters of the isomeric states are given.

Fig. 6: Schematic diagram of resonance ionization mass spectroscopy in combination with pulsed-laser-induced desorption for the investigation of Au and Pt isotopes. The mass-separated Hg ion beam is implanted into a wheel made of graphite. After decay to the daughter nuclei Au or Pt, the wheel is turned. The atoms are evaporated by pulsed-laser-induced desorption, resonantly step-wise excited, ionized, and finally detected with the help of a time-of-flight spectrometer.

Fig. 7: Time-of-flight spectrum as obtained in the case of ^{186}Pt . The mass separated ion beam of ^{186}Hg was implanted into the target wheel. After decay via Au to Pt, ^{186}Pt was laser-desorbed, resonantly stepwise excited and ionized. The ions were detected mass selectively by a time-of-flight spectrometer. The stable Pt isotopes were observed as impurities in the target wheel made of high-purity graphite.

Fig. 8: Schematic diagram of the laser ion source for trace analysis of technetium. The sample under investigation is brought into a cavity heated by electron bombardment. Three laser beams for resonance ionization are injected through a hole into the hot cavity. The photo ions are extracted, accelerated and mass-selectively detected by a Mattauch-Herzog mass spectrometer.

Fig. 9: Mass spectrum of a ^{99}Tc sample contaminated by impurities of stable molybdenum isotopes. The mass spectra were obtained under different experimental conditions: with only surface ionization (top, lasers off), with additional photo ionization (middle, lasers on), and in the case of gated detection of the ion beam bunched by RIS with pulsed laser light (bottom).

Fig. 10: Chart of nuclei. Black squares represent stable nuclei. The boundary line encloses those isotopes which are known to exist. The neutron (vertical) and proton (horizontal) shell closures are indicated as well as the regions of strong deformation (enclosed by curved lines). Those isotopes are marked (dotted areas) which have been investigated by optical spectroscopy in long isotopic chains leading far off stability.

Fig. 1

Fig. 2

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Fig. 3

Fig. 4

Fig. 5

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Fig. 6

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Fig. 7

LASER SYSTEM

SOURCE ION OPTICS

MASS SPECTROMETER

Fig. 8

Fig. 9

Fig. 10