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R. Neugart

Inst. für Physik, Universität Mainz, D-6500 Mainz, FRG

and the ISOLDE Collaboration

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Rainer Neugart

Institut für Physik, Universität Mainz
D-6500 Mainz, Federal Republic of Germany

Laser spectroscopy measurements have yielded a wealth of new information about the moments and charge radii of unstable isotopes. The procedures of evaluating these moments from the magnetic dipole and electric quadrupole terms of the hyperfine structure are discussed. Examples are presented, with emphasis on the isotopic chains of odd-proton nuclei, and their essential features are put into the context of current theoretical model descriptions for spherical and deformed nuclei. Finally, new developments of extremely sensitive experimental techniques are discussed with regard to an application to nuclei very far from stability.

1. INTRODUCTION

One of the great merits of high-resolution laser spectroscopy is the access to the moments and radii of a large number of radioactive nuclei situated far in the slopes of the valley of β -stability. These measurements are based on the optical investigation of atomic hyperfine structures and isotope shifts.

Optical spectroscopy played an important rôle mainly in the beginning of nuclear moment research, when the hyperfine structure had been discovered and understood. More accurate and comprehensive work required dedicated techniques, and these came up with the invention of rf spectroscopy. Most of the precisely known moments of stable nuclides are the result of nuclear magnetic resonance (NMR), atomic and molecular beam magnetic resonance (ABMR) and optical-rf double resonance (OP, ODR) experiments. Compared to these methods the optical spectroscopy remained incompetent until the Doppler-free techniques of laser spectroscopy were introduced in combination with the tunable narrow-band cw dye lasers. Such techniques have the potential of being very sensitive, because the huge cross-section for electric dipole transitions at resonance,

$$\sigma = \lambda^2 / 2\pi \approx 10^{-10} - 10^{-9} \text{ cm}^2 \quad (1)$$

ensures high excitation probabilities, and the fluorescence photons can be detected with an efficiency of the order $10^{-3} - 10^{-2}$.

The pertinent experimental techniques are mostly based on collimated atomic beams, or on fast ion beams from (on-line) isotope separators which may be neutralized in a charge-transfer reaction. Using these fast beams, collinear laser spectroscopy in its several variants has proven most successful, because it can be applied to nearly any element. The features and applications of this technique are

comprehensively described in ref. [1]. A summary of the major work on radioactive nuclides is given in ref. [2], grouped with respect to the chemical elements and their properties relevant for atomic spectroscopy. This paper in addition describes a few experiments in which direct nuclear g -factor measurements had become possible by laser spectroscopy techniques. A recent review by E.W. Otten [3] covers the various aspects of nuclear structure physics raised from laser spectroscopy results and gives references to the work accomplished until 1987. (See also the earlier reviews at Hyperfine Interactions conferences [4,5].)

In addition to the spins, magnetic dipole and electric quadrupole moments, the optical high-resolution experiments also provide information about the radial distribution of the nuclear charge via the change in the mean square radius $\delta\langle r^2 \rangle$ as obtained from the isotope shifts.

I shall first discuss the implications of the (indirect) determination of nuclear moments from the hyperfine structures in a sequence of isotopes. Then, I shall give examples of results and their impact on nuclear structure physics and on the theory of nuclear moments. Finally, I shall demonstrate that new experimental techniques of extremely high sensitivity give good prospects for an extension of this work towards the limits of the presently known isotopes.

2. HYPERFINE STRUCTURE AND NUCLEAR MOMENTS

The interaction between the nuclear electromagnetic multipole moments of order $k \geq 1$ and the shell electrons is sufficiently well described by first-order perturbation theory including only the magnetic dipole and electric quadrupole terms,

$$W_F = \frac{1}{2} C A + \frac{\frac{3}{4} C(C+1) - I(I+1) J(J+1)}{2 I(2I-1) J(2J-1)} B \quad (2)$$

where $C = F(F+1) - I(I+1) - J(J+1)$. The contribution of higher-order moments is far below the natural linewidth resolution limit of optical spectroscopy, i.e. 1 - 10 MHz. Both interaction parameters, A and B , are proportional to the respective nuclear moments, which means that the measurement in different isotopes (with identical electron-shell parameters) yields ratios of the magnetic dipole and electric quadrupole moments.

2.1 Magnetic Dipole Interaction

Quantitatively, the magnetic dipole interaction constant is given by

$$A = \frac{\mu H(0)}{I J} (1+\epsilon) \quad (3)$$

Here, μ is the nuclear magnetic moment, $H(0)$ is the magnetic field of the shell electrons at the site of a point nucleus, and ϵ accounts for the spatial distribution of nuclear magnetism and the change of H over the nuclear volume,

$$\epsilon = \int \underline{\mu}(\underline{r}) \cdot \underline{H}(\underline{r}) d^3r / \mu H(0) - 1 \quad (4)$$

This volume correction reaches a few percent for the contact interaction of s-electrons in heavy atomic systems.

Now, the comparison of different isotopes 1 and 2 is based on the ratio of the A-factors

$$\frac{A_1}{A_2} = \frac{\mu_1 I_2}{\mu_2 I_1} \frac{1+\epsilon_1}{1+\epsilon_2}, \quad (5)$$

and since ϵ_1 and ϵ_2 are only small corrections, we can write

$$\frac{A_1}{A_2} = \frac{\mu_1 I_2}{\mu_2 I_1} (1 + {}^1\Delta^2), \quad (6)$$

where ${}^1\Delta^2 = \epsilon_1 - \epsilon_2$. This latter quantity is called the (differential) hyperfine structure anomaly. Although ${}^1\Delta^2$ is a difference of small corrections for the two isotopes, it can be of the same order as ϵ , because ϵ depends rather critically on the composition of the nuclear magnetic moment of spin and orbital parts (Bohr - Weisskopf effect) [6]. A thorough presentation of the theoretical and experimental status of our knowledge about hyperfine anomalies can be found in the review by Büttgenbach [7].

In practical laser spectroscopy work, the hfs anomaly is usually neglected for the evaluation of nuclear moments, and empirical estimates (see, e.g. [8]) are used to include the corresponding uncertainty in the errors. Only in exceptional cases these errors exceed 1 %. Thus the accuracy of magnetic moments from laser spectroscopy is quite satisfactory for any quantitative comparison with nuclear theory. On the other hand, the understanding of hfs anomaly effects is an interesting problem in itself. It is only poorly developed because of the lack of systematic experimental data including sequences of isotopes. (Note that sequences of stable isotopes mainly consist of doubly-even ones.) To improve this situation, one should measure the A and g_r -factors independently, with preference for the regions where the atomic and nuclear structure is reasonably well understood. The required 10^{-3} - 10^{-4} accuracy is particularly difficult to achieve in measurements of g_r factors which involve the observation of the small interaction between the nuclear moment and an external magnetic field. Following the classical methods one may seek the solution in the design of an especially sensitive ABMR apparatus. For this technique, alkali elements are the most favourable candidates, and there is a project going on at ISOLDE, which aims at the systematic investigation of hfs anomalies in the caesium isotopes [9]. On the other hand, it can be hoped that nuclear orientation-NMR experiments [10] will become sufficiently accurate (see also the invited paper by J. Wouters).

Recently achieved direct g_r -factor measurements on radioactive isotopes by modified laser spectroscopy techniques are described in ref. [2]. These experiments on ^{209}Rn [11] and on $^{213,225}\text{Ra}$ [12] were performed in a different context, namely to provide calibration values for the evaluation of the magnetic moments in the respective isotopic chains. Another example is ^7Li , where a collinear-beam RADOP experiment was combined with NMR [13]. This enabled the direct spin and magnetic moment measurement for an exotic light nucleus at the neutron drip-line and gives hope for a measurement of the quadrupole moment [14]. In principle, all these methods may be

improved to an accuracy yielding relevant information about hfs anomalies, but their scope is limited to a relatively small selection of elements and isotopes.

2.2 Electric Quadrupole Interaction

Let us now turn to the problem of evaluating nuclear quadrupole moments from the atomic hyperfine structure. The quadrupole interaction is described by the B-factor

$$B = e Q_{\bullet} V_{zz}(0) \quad (7)$$

where $Q_{\bullet}$ is the (spectroscopic) nuclear electric quadrupole moment, and $V_{zz}(0)$ is the electric field gradient produced by the shell electrons at the site of the nucleus.

In evaluating absolute nuclear quadrupole moments from eq. (7) one encounters the problem that independent calibration values are missing, because the quadrupole interaction cannot be measured in externally applied field gradients. The situation is most favourable in a few elements, where quadrupole splittings have been measured with high precision in the muonic atoms [15,16]. Here the quadrupole moments can be extracted from the hyperfine structure to an accuracy of about 1 %, if the splittings are sufficiently large. This is true, in particular for the deformed (stable) rare-earth isotopes. Still, in most cases the calibration has to rely on calculations of field gradients in the electronic atoms, and their accuracy depends very much on the nature and complexity of the atomic wave function [17]. Spectroscopic quadrupole moments are thus considered to be reliable within 5 - 30 % only.

Reaching the 5 % level of accuracy not only requires a measurement of the quadrupole interaction in simple atomic states (e.g. in the alkali-like spectrum), but also the careful analysis and comparison of core polarization and relativistic corrections in different theoretical and semi-empirical approaches. An instructive example is the recent investigation of quadrupole moments in the radium isotopes [18-20]. In a first approach the hyperfine structure and isotope shift in the RaI line $7s^2 \ ^1S_0 - 7s7p \ ^1P_1$ was measured by collinear laser spectroscopy for isotopes in the range $^{208-214}\text{Ra}$ and $^{220-232}\text{Ra}$ [18]. As the 1P_1 hyperfine structure depends sensitively on singlet-triplet mixing, the quadrupole moments (whose ratios were well determined) could only be estimated by adopting an intrinsic quadrupole moment from nuclear spectroscopy (BE2-value) and applying the strong-coupling projection formula for the deformed ^{229}Ra . The results later-on turned out to be correct within about 5 %. Two additional experiments on selected isotopes yielded the hyperfine structures of $7s7p \ ^3P_2$ in RaI and of $7p \ ^2P_{3/2}$ in RaII which were suitable for a proper calibration of the electronic parameter V_{zz} . In both these states the quadrupole interaction is determined by the $p_{3/2}$ electron whose $\langle r^{-3} \rangle$ expectation value may be extracted from the fine structure or the magnetic hyperfine structure by established semi-empirical procedures (see [17]). The semi-empirical values of V_{zz} have to be corrected for the Sternheimer shielding or antishielding factor [21] accounting for the retroaction of the nuclear quadrupole field on the electron shell. For the alkali-like system of singly ionized RaII the ab initio calculations by relativistic many-body perturbation theory (RMBPT) [22] provide an independent theoretical approach.

Table 1

Compilation of Q_μ -values in units of 10^{-24} cm² (barn). Columns 2 and 4 give the results of the semi-empirical analysis including Sternheimer correction of the fs in Ra II [20] and Ra I [19], respectively. The B/Q ratio obtained from the RMBPT calculation [22] together with the measured B-factors yields the values given in Column 3. The errors including estimated general scaling uncertainties are given in the second brackets. Ratios of quadrupole moments are accurate within the experimental errors.

Q _μ (b)				
A	fs Ra II	RMBPT	fs Ra I	B(E2)
221	1.978(7){106} ^{a)}	2.02 ^{b)}	1.907(7){198} ^{c)}	1.9 ^{d)}
223	1.254(3){66} ^{a)}	1.28 ^{b)}	1.190(7){126} ^{c)}	1.2 ^{d)}

^{a)} ref. [20], ^{b)} ref. [22], B-factors taken from ref. [20],
^{c)} ref. [19], ^{d)} ref. [18]

The experiment on neutral radium was performed in the transition $7s7p\ ^3P_2 - 7s7d\ ^3D_3$, with the metastable 3P_2 state populated in the charge-transfer neutralization reaction of the fast ion beam from ISOLDE [19]. For spectroscopy in the ionic resonance line $7s\ ^2S_{1/2} - 7p\ ^2P_{3/2}$ in the UV at 381.4 nm, the cw narrow-band laser radiation was frequency-doubled in a ring cavity [20]. The quadrupole moments resulting from the different analyses of the B-factors are compared in Table 1. They are all consistent within a few percent.

3. ODD-PROTON MOMENTS IN ISOTOPIC SEQUENCES

In the following sections we shall discuss a few examples that are typical for the results of laser spectroscopy: The spins and moments are obtained for complete sequences of isotopes, and a theoretical interpretation can profit from the fact that trends in the moments are often easier to explain than the absolute values of individual moments.

3.1 The $I = 1/2$ Ground States of $^{191-207}\text{Tl}$

The $I = 1/2$ sequence of thallium isotopes ranges at least from the $N = 126$ neutron shell closure down to $N = 104$. The magnetic moments of the longer-lived isotopes $^{195-205}\text{Tl}$ ($T_{1/2} > 1$ h) were measured already by the off-line ABMR technique [23]. They are about $1.6\ \mu_N$, i.e. 60 % of the $s_{1/2}$ Schmidt value, with the tendency of a slight decrease towards the lighter isotopes.

A quantitative understanding of the influence of different "quenching" effects on the single-particle value of $2.79\ \mu_N$ should start from the magnetic moment of ^{207}Tl which belongs to the family of single-particle or single-hole nuclei around the doubly magic ^{208}Pb . The moments of these nuclei had been the subject of several microscopic theoretical analyses, and for a long time ^{207}Tl remained the only candidate for which no experimental value was available. A

measurement was all the more important as this nucleus is the only example of a single $s_{1/2}$ particle or hole. Here the orbital part of the effective single-particle operator for the magnetic moment

$$\mu_{eff} = (g_s + \delta g_s) s + (g_l + \delta g_l) l + g_p [s \times Y^2]^{(1)} \quad (8)$$

vanishes as well as the dipole-dipole interaction term, and first-order core polarization (configuration mixing) accounts for most of the reduction of the spin part, δg_s .

For laser spectroscopy the access to the 4.8 m isotope ^{207}Tl was facilitated by the observation that one of the most abundant spallation products from the thorium carbide target at ISOLDE, ^{219}Fr with a half-life of 21 ms, gives rise to a strong ^{207}Tl beam from a hot surface ionization source (2400 °C), because the chain of α -decays via ^{215}At and ^{211}Bi occurs within a time which is faster than the diffusion in the target. The experiment [24] by collinear laser spectroscopy is straightforward. A sodium vapour cell is used to neutralize the ion beam, leaving most of the atoms in the resonantly populated $6p\ ^2P_{3/2}$ state. The excitation wavelength of 535 nm to $7s\ ^2S_{1/2}$ can be separated easily from the decay wavelength of 377.6 nm to the $6p\ ^2P_{1/2}$ ground state by means of optical filters, and therefore the optical detection is nearly free of background.

The measured magnetic moment, $\mu(^{207}\text{Tl}) = 1.876(5) \mu_N$, is rather close to the best theoretical predictions of $1.80 \mu_N$ from a configuration mixing calculation including pion-exchange contributions and coupling with vibrational states [25] and $1.935 \mu_N$ from an independent approach based on the theory of finite Fermi systems and an effective magnetic moment operator [26]. With this result it is now possible to explain independently the reduction of the $1/2^+$ ground state moments towards the lighter isotopes and thus end up with a quantitative theoretical explanation for the complete sequence.

For these nuclei farther away from the doubly closed shell, a shell model description of the moments becomes difficult because of the many modes of higher-order core polarization. Their effect can be taken into account by the inclusion of collective admixtures. In the $1/2^+$ thallium isotopes, the main contribution is expected from a coupling of the low-lying $d_{3/2}$ single-proton hole state to the first excited 2^+ states of the core which are observed in the Pb isotopes. This is described by an admixture of $(2^+ \times \pi d_{3/2}^{-1})1/2^+$ to the $(0^+ \times \pi s_{1/2}^{-1})1/2^+$ main component. Qualitatively, the considerable drop in the moments from $1.876 \mu_N$ for ^{207}Tl to $1.638 \mu_N$ for ^{205}Tl and the very small further decrease is suggested by the jump in the energy of the lowest 2^+ state from 4.1 MeV in ^{208}Pb to nearly constant values around 0.9 MeV for the lighter even-N isotopes.

This effect has been reproduced quantitatively by Arima and Sagawa [27] in the framework of the particle-vibration coupling model. The experimental moment of ^{207}Tl was taken as a reference value, and the change to ^{205}Tl and ^{203}Tl was ascribed to second-order core polarization including only excitations to the lowest 2^+ state. The results are presented in Figure 1, together with all known $1/2^+$ moments of the thallium isotopes. In addition to the results of ABMR and the ^{207}Tl experiment, these latter include two recent values continuing the general trend towards the lighter isotopes. The moments of ^{193}Tl and ^{191}Tl were measured in the frame of more extended laser spectroscopy studies - including the high-spin isomers and their large isomer shifts - at the UNISOR facility at

Figure 1. Magnetic moments of $1/2^+$ ground states in $^{191-207}\text{Tl}$. Theoretical results for ^{207}Tl are indicated: (1) and (2) from ref. [25], (3) from ref. [26], and the reduction by collective admixtures (dashed line) from ref. [27].

Oak Ridge [28] and the GSI on-line isotope separator [29]. It would be an interesting exercise to extend the calculations over the whole sequence of isotopes as a further quantitative test of the theory.

Magnetic moments arising from the same $s_{1/2}$ proton state are also found for the isomers of holmium and terbium just above the $N = 82$ neutron shell closure [30]. They show a similar, but much stronger reduction from $1.8 \mu_N$ to $1.2 \mu_N$ from $N = 82$ to 86 (see below).

3.2 The $I = 5/2$ Europium Isotopes

Looking for situations that are analogous to the thallium case one finds the long sequence of odd- A europium isotopes, $^{143-155}\text{Eu}$, which all have the spin $I = 5/2$. The experimental magnetic moments and spectroscopic quadrupole moments [31] are plotted in Figure 2. Except for the abrupt onset of deformation observed for $N = 90$ the moments show a behaviour which again reflects the collective effects increasing towards both sides of the neutron-shell closure, while at $N = 82$ the moments of ^{145}Eu reach 83 % of the Schmidt value and about twice the single-particle quadrupole moment for a $d_{5/2}$ proton. Similar to ^{207}Tl , the nucleus ^{145}Eu ($N = 82$) can be described by a $d_{5/2}$ single-proton hole state with the doubly-magic core of ^{146}Gd ($Z = 64$). From nuclear spectroscopy [32], as well as from the systematics of spins, moments and isotope shifts [33,34] there is strong experimental evidence for the rôle of $Z = 64$ as a magic proton number in the neighbourhood of the $N = 82$ shell closure. A rigorous theoretical analysis of these moments should be possible in analogy to the region around ^{208}Pb . This would include the detailed calculation of first-order core polarization and meson-exchange effects for ^{145}Eu and the variation of the second-order collective contributions over the range of neutron numbers from 78 to 88. Of course, this approach becomes inadequate for the strongly-deformed

Figure 2. Magnetic moments and quadrupole moments of $5/2^+$ ground states of the odd-A europium isotopes.

^{153}Eu and ^{155}Eu ($N = 90$ and 92) whose moments are fairly well accounted for by the Nilsson orbital $[413\ 5/2]$ with a deformation of $\beta_2 \approx 0.30$ [35].

In the context of the nuclei with a single proton or neutron (particle or hole) and a doubly magic ^{146}Gd core one should also consider ^{145}Gd which has a neutron hole of $s_{1/2}$ in the ground state and $h_{11/2}$ in the isomer [36], ^{147}Gd with an $f_{7/2}$ neutron [36], and ^{147}Tb with an $s_{1/2}$ and an $h_{11/2}$ proton in the ground state and the isomer, respectively [30].

3.3 Remarks on Transitional and Deformed Nuclei

All the measurements by laser spectroscopy in the rare-earth region between $Z = 63$ (europium) and $Z = 70$ (ytterbium) [30,31,34,36,37] mainly cover the transitional and the strongly deformed nuclei around and above $N = 90$. The moments of these are usually treated by models using a deformed basis for the single-particle states. In the region of strong deformation beyond $N = 90$ nearly all moments can be understood [35] in the Nilsson model, which means that the nuclear ground state is well described by the assignment of pure Nilsson orbitals. For the intermediate range of transitional nuclei, the particle-rotor model based on the representation of intermediately coupled states in a Nilsson basis has been rather successful [38,39]. In all these calculations the different modes of core polarization are subsumed under a general effective g-factor for protons and neutrons, $g_{\text{eff}} \approx 0.6\ g_{\text{free}}$. The particle-rotor approach has often been used to identify the nature of nuclear states when their structure was not obviously described by pure single-particle states in the spherical or the deformed scheme.

Figure 3. Magnetic moments of ground states (g) and isomers (m) in $^{147-165}\text{Ho}$ and $^{145-159}\text{Tb}$.

As an example for odd-proton nuclei the moments of the odd-A terbium and holmium isotopes are plotted in Figure 3. They reach from the $N = 82$ shell closure for ^{147}Tb and ^{149}Ho into the region of strong deformation which is found for the stable isotopes. As a consequence of the variation in the collective structure, the unpaired proton occupies first the $1h_{11/2}$ and the $3s_{1/2}$ shell model states in the ground state and the isomer, respectively - or vice versa. In the deformed region for neutron numbers $N \geq 90$ the $7/2^-$ ground state of the holmium isotopes is ascribed to the Nilsson orbital $[523 \ 7/2]$, and the $3/2^+$ ground state of the terbium isotopes is ascribed to $[411 \ 3/2]$. For $N = 88$ the intermediate $5/2^+$ nuclei ^{155}Ho and ^{153}Tb have similar properties as the isotonic ^{151}Eu (see above), except for the larger quadrupole moment. This indicates an intermediate situation between the shell model description by the $d_{5/2}$ state and the Nilsson model description by the corresponding $[402 \ 5/2]$ orbital which gives nearly the same magnetic moment. Quite naturally, these moments are also well reproduced by the particle-rotor model for a moderate deformation of $\beta_2 \approx 0.2$ with the main component of the wave function given by the above-mentioned Nilsson orbital. The striking similarities between terbium and holmium are obvious, and a discussion of differences in details needs some further analysis of these partly very recent results. (See also the contribution by G.D. Alkhazov et al. for the independent measurement of a few terbium moments.)

3.4 The $I = 9/2$ and $I = 1/2$ Indium Isotopes

To complete the discussion of long isotopic sequences of nuclear moments for states of the same spin and parity, I shall briefly describe the features of the odd-A indium ($Z = 49$) isotopes. Here the single-proton states correspond to a $p_{1/2}$ or a $g_{9/2}$ hole in the

closed $Z = 50$ shell. The ground state in all known isotopes is $9/2^+$, and the $1/2^-$ state is found as an isomer which could be investigated by laser spectroscopy from ^{113}In to ^{125}In [40]. From theory it is expected that these states show rather constant moments close to the Schmidt value of $-0.265 \mu_N$ for a $p_{1/2}$ proton, because the $p_{1/2}$ states are not affected by first-order core polarization (configuration mixing) [41]. However, the experiment shows a considerable change in these moments with increasing neutron number from $-0.21 \mu_N$ to $-0.43 \mu_N$. This is all the more exceptional, as the moments of the heavier isotopes lie beyond the Schmidt limit (Figure 4). An explanation would normally be sought in large collective second-order contributions, but no theoretical effort in this direction has so far been successful [42]. On the other hand, the moments of the $9/2^+$ ground states are fairly constant over the large mass range from ^{105}In to ^{127}In , with the only exception that the quadrupole moments tend to decrease for the heavier isotopes approaching the $N = 82$ shell closure. The constancy of the magnetic moments follows the expectation that collective admixtures be small for large spins, because other high-spin states are rather different in energy.

For the discussion of nuclear moments, and in particular the magnetic moments, I have chosen the odd-proton cases, because these offer the possibility to observe trends in the nuclear moments for the same proton state over a large range of neutron numbers. Close to magic proton numbers the structure of the nuclear ground or isomeric states remains fairly constant within a chain of isotopes. This facilitates the detailed examination of the sensitivity of the moments to small variations in the nuclear wave functions. On the other hand, the measurement of moments for chains of isotopes in the midshell regions often reveal complete changes in the structure of the nuclei.

Figure 4. Magnetic moments and quadrupole moments of the $9/2^+$ ground states and the $1/2^-$ isomers of the indium isotopes.

4. NEW EXPERIMENTAL DEVELOPMENTS

In nuclear moment research the experimental and theoretical progress has been closely connected to the development of experimental methods. Among the recent achievements I have mentioned several direct measurements of the g_r -factors of unstable nuclei, in particular those using modifications of current laser spectroscopy techniques (see [2]).

Apart from this special subject, a major effort is being undertaken to improve considerably the sensitivity of standard laser spectroscopy techniques that are used with short-lived unstable isotopes. Here, collinear fast-beam spectroscopy is potentially extremely sensitive, if the detection of fluorescence photons can be replaced by a selective detection of those atoms or ions which have undergone an excitation by the laser light. The advantages are obvious:

1. Fast ions or atoms are readily detected with high efficiency.
2. Photon background is eliminated and the background from radioactivity can be kept low.

As a first scheme of this type, multistep resonance photo-ionization [43,44] was introduced for samples of thermal atoms. Here the use of pulsed lasers with high power but low duty cycle ensures good ionization efficiencies. Experiments on radioactive isotopes were performed mainly on the decay daughters of the primary nuclides from on-line mass separators (see ref. [45] and the contribution by Th. Hilberath et al.) and on several rare-earth elements (ref. [37] and the contribution by G.D. Alkhazov et al.). With fast beams, however, the duty cycle losses become rather serious, and the advantage of high spectral resolution is lost by the limited laser linewidth. Nevertheless, such a scheme may be useful for experiments on the rare-earth elements whose spectra fit well to the spectral range of copper-vapour pumped dye lasers with high repetition rates of about 10 kHz [46].

On the other hand, the collision processes of fast atoms or ions with target atoms or molecules offer much simpler concepts of changes in charge state for the atoms which have interacted with the laser light. This possibility was already noticed in the early collinear-beam experiments on HD^+ ions by Wing et al. [47] and on Ba^+ by Gaillard et al. [48]. The basic idea is to selectively ionize or neutralize the atoms (ions) from a state which is efficiently populated in an optical pumping process. For example, the state dependence of the charge-transfer neutralization cross-section can be exploited for the very sensitive detection of resonance transitions in the singly-charged alkaline earth ions, as has been shown by Silverans et al. [49,50]. In Sr^+ the 5s-5p resonance excitation is followed by the decay into the metastable 4d levels, and thus leads to a significant increase in the fraction of neutral atoms formed in the passage of the beam through a sodium vapour cell. This has recently been used for measurements of the hyperfine structure and isotope shift of $^{88-100}\text{Sr}$ and ^{87}Sr in the experiments at ISOLDE [51] (see also the contributions by P. Lievens et al. and by L. Vermeeren et al.).

Here, we shall discuss in more detail the complementary scheme of state-selective collisional ionization [4,52] which is ideally suited for the spectroscopy of noble gas atoms.

Figure 5. Partial energy level diagram of xenon. The $6s [3/2]_2$ level is populated by charge exchange with caesium in the ground state. The optical pumping is indicated by arrows.

4.1 Ion-Detected Spectroscopy on Noble-Gas Elements

It is a common feature of the noble-gas spectra that the ionization energy is more than 10 eV for the ground state and only about 4 eV for the metastable first excited state in which one electron is promoted from the closed np valence shell to the next higher $(n+1)s$ shell. This involves a considerable difference in the cross-sections for electron stripping. Fig. 5 shows the relevant part of the energy level diagram for the example of xenon. A fast beam of metastable atoms in the $J = 2$ state of the $5p^5 6s$ configuration - designated $6s[3/2]_2$ - is prepared in the charge-transfer neutralization of the original ion beam with caesium vapour. Laser excitation to $6p[3/2]_2$ at 823.4 nm depopulates the metastable level and pumps the atoms via $6s[3/2]_1$ into the low-lying 1S_0 ground state. In passing the beam through a gas target, one ionizes predominantly the metastable atoms and thus detects the optical pumping as a drop in the ion current.

Fig. 6 gives a schematic view of the experimental setup used at ISOLDE. The front part including fluorescence detection is essentially identical with the standard apparatus that has been used

Figure 6. Experimental setup for collisional ionization detection.

extensively to study nuclear moments and radii. The differentially pumped stripping gas target has an effective thickness of 10 cm at a pressure of 10^{-3} to 10^{-2} mbar optimized for the individual gas. Ions created in this target are detected by a secondary-electron multiplier whose cathode is formed by a remote-controlled moveable metallic tape. This is indispensable for removing the considerable background from the radioactive decay of the nuclei collected on the detector during the experiment.

Another important source of background consists in the isobaric contaminations of the very weak beams of mass-separated radioactive atoms: Only to some extent are the neutralization and ionization reactions specific for the particular chemical element. For the "cold line" plasma ion source of ISOLDE it is found that after careful outgassing the beams of heavy Rn and Xe isotopes are very clean. Before discussing some results of the initial experiments on $^{116-119}\text{Xe}$, $^{141-146}\text{Xe}$ and $^{223-228}\text{Rn}$, I shall demonstrate the sensitivity for the example of the discovered new isotope, ^{146}Xe .

The resonance $6s[3/2]_2-6p[3/2]_2$ for the doubly-even isotope ^{146}Xe was measured with a beam of about 400 atoms/s from ISOLDE, and a signal-to-noise ratio of 5 was achieved within a total measuring time of 35 min for a scanning range of 20 times the linewidth. The position of this resonance, relative to the stable ^{136}Xe , gives the isotope shift. The measuring conditions are explained by a 50 % total transmission of the beam line and the apparatus, 50 % charge exchange and 10 % ionization efficiencies and a 50 % flop-out signal on the ion current. These numbers refer to a 2×10^{-3} mbar Cl_2 target used in most of the experiments. A constant background of about 10 counts/s is ascribed to the general radioactivity level of the experimental area and should be removed by more careful shielding. It is obvious that even without significant improvements beam intensities well below 100 atoms/s are sufficient for a measurement within reasonable time. This should be compared to the fluorescence detection limit for rare gases which is about 10^6 atoms/s in the far-red transitions that are accessible from the metastable state.

The results of the first experiments include the neutron-rich radon isotopes as continuation of the optical work presented at the last Hyperfine Interactions conference [54]. Here it appears that a significant change in the ground-state structure is reflected in the moments of $^{221,223,225}\text{Rn}$ which all have the spin $I = 7/2$. For ^{221}Rn this spin value is difficult to explain in combination with the almost zero magnetic moment and a small negative quadrupole moment. The key to such a state may be found in the transitional nature of this nucleus which should be soft in both the quadrupole and octupole degrees of freedom. On the other hand, ^{223}Rn and ^{225}Rn have nearly identical moments [55] which can be accounted for by assuming a $7/2^-$ orbital based on the $j_{15/2}$ configuration. The isotones ^{225}Ra and ^{227}Ra , on the contrary, have $I = 1/2$ and $I = 3/2$ which are interpreted in the reflection-asymmetric scheme [56].

The measurements on the most neutron-rich and neutron-deficient xenon isotopes have extended the range of results from fluorescence spectroscopy on $^{120-140}\text{Xe}$ to the longest isotopic chain, $^{116-146}\text{Xe}$ [53]. The neutron-rich isotopes ($82 \leq N \leq 92$) belong to the classical region of transition from spherical to deformed nuclear shapes which is crossed by the stability line along the lighter rare-earth elements. Xenon ($Z = 54$) is the element closest to the magic proton number $Z = 50$ for which isotopes around $N = 90$ can be reached, and

Figure 7. Hyperfine structure of ^{143}Xe (10^5 atoms/s) as recorded by the ion detector.

from the analysis of the isotope shifts it seems that these nuclei gradually develop deformed shapes like the neighbouring barium ($Z = 56$) [57]. The long sequence of isotopes below the magic neutron number $N = 82$ ranges beyond the midshell at $N = 66$ and shows an indication of the parabolic behaviour of (mean square) deformations which is observed close to magic proton numbers [40]. The magnetic moments and the quadrupole moments show very similar features as the barium isotopes [57], and a detailed comparison should reveal to what extent the deformation effects have to be ascribed to a dynamic collective motion rather than static deformation.

5. CONCLUSION

It is obvious from these first results, that the same experimental technique can provide many more data on the isotopes of other noble gas elements. Only in the light mass region (for argon and neon) one has to get rid of strong molecular beam contaminations by the use of a high-resolution mass separator. From a detailed investigation of the collisional ionization process one may find other groups of elements suitable for this non-optical detection scheme.

Even for the conventional fluorescence detection method, the coincident counting of photons and ions or atoms can be used to reduce the background considerably. This has been demonstrated by the Daresbury group on the strong resonance transitions of strontium [58] and barium [59], for which a large photon detection probability is achieved over a short distance, i.e. within a narrow time window.

A particularly interesting field has been opened up by the recent experiments on very light nuclides [13,14] where the properties of ^7Li have given rise to a vivid discussion. Here, the combination of optical pumping in a fast beam with the implantation and detection of polarization by the β -decay asymmetry is especially favourable because of the short half-lives and long relaxation times.

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