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HEAVY ION PHYSICS

Laser spectroscopy : a powerful tool for the determination of the global properties of the ground and isomeric states

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Abstract. Laser spectroscopy allows the measurement of the nuclear moments and of the changes along isotopic series in the mean-square charge radius of many radioactive nuclei in their ground and isomeric states. Results obtained in the mercury and tin regions are used to show that laser spectroscopy offers a powerful means to determine the shape and deformation of nuclei, structure of states, location of magic numbers and to point out effects of dynamics, pairing...

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1. Introduction

Laser spectroscopy is a powerful tool to determine the global properties of the ground and isomeric states of radioactive nuclei. Indeed the interaction between the nucleus and the electronic cloud induces small changes in the energy of the atomic transition. Then by studying atomic transitions through long isotopic chains, nuclear information can be obtained. However the frequency variation of the atomic transition (typically $\sim 10^6$ GHz) between two neighbouring isotopes is smaller than 1 GHz, thus high frequency resolution is required to point out such a small effect. The first section of this paper deals with the atomic quantities measured, i. e. the hyperfine structure of the atomic states involved in an atomic transition and the isotope shift, as well as their related nuclear data, namely the nuclear moments and the change in the mean-square charge radius. The second section presents the laser spectroscopy techniques the most often used to study the radioactive nuclei. In the third section, typical results are presented with the aim of underlying the contribution of laser spectroscopy to our understanding and knowledge of nuclear

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structure. Since the nuclear data obtained are very sensitive to both single-particle and collective properties, they provide not only a stringent test of nuclear models, but also a powerful means to determine shape and deformation of nuclei, structure of states, location of magic numbers and effects of dynamics, pairing...

2. Nuclear properties from atomic physics

The energies of the hyperfine levels characterized by the quantum number F ($\overrightarrow{F} = \overrightarrow{I} + \overrightarrow{J}$, with I the nuclear spin and J the electron angular momentum) are written as a linear combinaison of the coupling constants for the magnetic (A) and electrostatic (B) interactions :

$$W_F = W_J + \frac{AC}{2} + \frac{B[3C(C+1) - 4I(I+1)J(J+1)]}{8I(2I-1)J(2J-1)}$$

with $C = F(F+1) - I(I+1) - J(J+1)$, $A = \mu_I \frac{\overline{H_0}}{IJ}$ where μ is the magnetic moment and $\overline{H_0}$ the magnetic field at the nucleus, and $B = eQ_S\overline{\varphi_{JJ}(0)}$ where Q_S is the spectroscopic quadrupole moment and $\overline{\varphi_{JJ}(0)}$ the electric field gradient at the nucleus.
The hyperfine transitions verify the following selection rules : $\Delta F = 0, \pm 1$ except $0 \rightarrow 0$ transitions. From the energy of the hyperfine transitions one can extract the hyperfine constants A, B, A', B' associated with the initial and final atomic levels. Then the magnetic and spectroscopic quadrupole moments can be deduced provided the atomic quantities $\overline{H_0}$ and $\overline{\varphi_{JJ}(0)}$ are known. $\overline{H_0}$ and $\overline{\varphi_{JJ}(0)}$ depend only on Z and are generally determined from the moments of the stable nuclei. The μ and Q_S values obtained in this way have to be corrected for the hyperfine anomaly and the Steirnheimer effect, respectively. Assuming axial symmetry, the intrinsic quadrupole moment Q_0 can be deduced from the spectroscopic quadrupole moment using the relation : $Q_0 = Q_S \frac{(I+1)(2I+3)}{3K^2 - I(I+1)}$. And a direct determination of the deformation of the nucleus is obtained from : $Q_0 = \frac{3}{\sqrt{5\pi}} Z R_0^2 < \beta > (1 + \frac{2}{7}\sqrt{\frac{5}{\pi}} < \beta > + \ldots)$, with $R_0 = 1.2\ A^{\frac{1}{3}}$ fm the nuclear radius. More details can be found in [1,2].

The isotope shift is the displacement of the centers of gravity of the hyperfine spectra between two neighboring isotopes. When the number of nucleons varies, changes are induced in the atom, namely in the reduced mass of the nucleus plus electron system, in the correlations between the electrons and in the charge distribution inside the nucleus giving rise to the normal mass shift $\delta\nu_{NMS}^{A,A'}$, specific mass shift $\delta\nu_{SMS}^{A,A'}$ and field shift $\delta\nu_{FS}^{A,A'}$. The mass shift dominates in light nuclei, it is small in heavy elements and can be estimated [3]. The $\delta < r_c^2 >$ is related to the field shift by : $\delta\nu_{FS}^{A,A'} = F \times k \times \delta < r_c^2 >$. F, the electronic factor of the atomic transition is usually obtained by MCDF calculations or by a King plot; k is taken from [4]. If the charge radius is known for one isotope, generally the stable ones, then the charge

radius of the other isotopes can be deduced from $\delta < r_c^2 >$. Moreover if the nucleus is uniformly charged and has an axial and quadrupole deformation, the variation of the deformation can be obtained from $\delta < r_c^2 >$ [2]. Provided that the deformation is known for one isotope, the deformation can be deduced for the other isotopes.
It is worth noting that, in most cases, for the odd or odd-odd nuclei, the deformation parameter can be extracted independently from the hyperfine structure and from the isotope shift. This offers a test of the axial symmetry and stiffness of the nucleus.

3. Experimental techniques

The laser spectroscopy techniques the most often applied for the study of radioactive nuclei are the collinear spectroscopy on fast atomic beams (COLLAPS at ISOLDE/CERN [5]) and the resonance ionization spectroscopy. In the first case, the resolution is excellent but this technique is limited to elements directly produced as beams by separators. In the second case, the resolution is not so good but this technique can be used to study daughter isotopes when it is associated with pulsed laser desorption (COMPLIS [6]) and has an excellent sensitivity when performed directly in the ion source [7–9].
An example of recent experimental improvement is the upgrade of COMPLIS, called SIINODE, that has been installed in order to add to the high selectivity obtained by resonance ionization the power in the isotope identification given by γ-spectroscopy. In this working mode the frequency of the laser used for the first excitation step is not scanned but fixed to a value corresponding to a resonant transition. The ions created are collected on a tape to produce radioactive sources which are transported in front of a γ-detector. This working mode allows us to attribute unambiguously the hyperfine lines to the ground or isomeric states provided the γ-rays occuring in the ground and isomeric decays are different. Figure 1 shows the results of an experiment performed on ^{129}Sn which proves that the $\nu 2$ resonant transition belongs to both ^{129g}Sn and ^{129m}Sn.

4. Typical results from laser spectroscopy

Figure 2 shows the $\delta < r_c^2 >$ observed in the isotopic series with $Z \leq 80$. The most striking feature is the changes observed near mid shell. These variations decrease with Z but are still obvious in iridium and are directly related to shape transitions, shape coexistences and deformation changes. In the light Hg isotopes, one can note the effect of the well known shape transitions between the odd nuclei strongly deformed and the even-even ones that are still nearly spherical. In ^{185}Hg, $\delta < r_c^2 >$ is very different for the ground state and for the isomeric state. This shows that different shapes can coexist in the same nucleus depending on the structure of the odd particle coupled to the core. In gold and iridium, the influence of the coupling of the odd proton that brings deformation in the light nuclei is clear again. In the

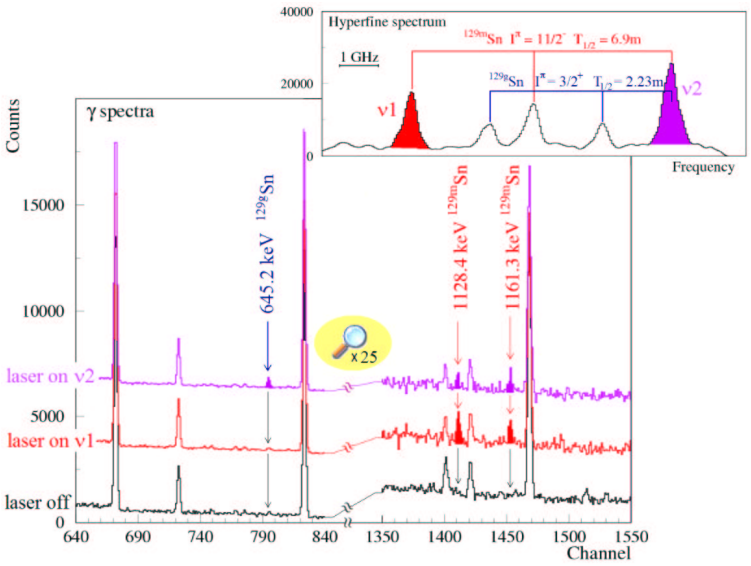

Fig. 1. Hyperfine spectrum measured with COMPLIS on ^{129}Sn and γ spectra recorded with SIINODE.

light platinum isotopes, there is a shape staggering. The even-even nuclei have a triaxial shape, which smoothes the $\delta < r_c^2 >$ curve as compared to what is observed in Hg, but the odd ones are axial, prolate and well deformed. The shape of the odd light Pt isotopes is clearly established for the high spin state in ^{183m}Pt and ^{185g}Pt. Indeed, in both cases the deformation parameters extracted from Q_0 and from $\delta < r_c^2 >$ are very similar, which proves that the nucleus in these states has an axial symmetry.

Figure 2 shows the $\delta < r_c^2 >$ curves obtained in the isotopic series with Z $\geq$ 50. In all cases, a slope change is observed at N = 82, signing the location of the magic number. All these N = 82 neutron-magic nuclei are spherical. And the kinks at N = 82 indicate the ability of the nucleus for having deformation when the neutron number is no more magic. The more Z differs from the magic number 50, the stronger the kink is, indicating it becomes easier for the nucleus far away from N = 82 to get deformation. Recently at CERN with COMPLIS, we have studied the neutron rich tellurium isotopes (Z = 52). With a Z value very close to 50 the $\delta < r_c^2 >$ curve obtained still exhibits a kink. The proton magic tin nuclei are expected to be spherical and rather stiff against deformation. Thus in tin no kink is expected at N=82. Experimentally, the N = 82 closed shell has not been crossed and the existence of the kink at N = 82 in tin is still an open question. From the $\delta < r_c^2 >$ we have determined, using the radius values of the stable isotopes obtained in muonic experiments [12], the charge radius of the tin nuclei up to the doubly-magic nucleus ^{132}Sn. Figure 3 shows the difference between the charge radii calculated and the experimental values. The ^{132}Sn charge radius is well reproduced

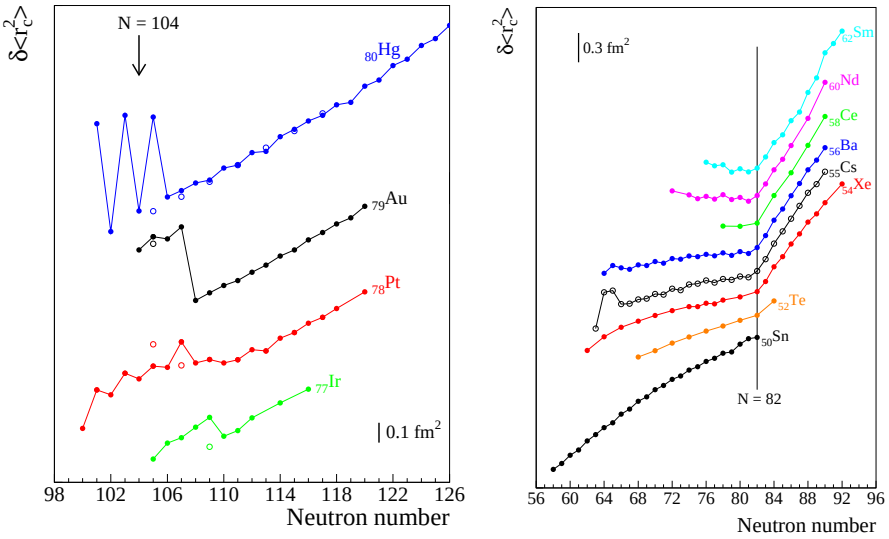

Fig. 2. $\delta < r_c^2 >$ in the Hg and Sn regions [10, 11].

in all approaches. However, the static approaches fail in describing the tin nuclei far away the doubly-magic nucleus. On the contrary, the results of the dynamical approaches and in particular of the Hartree-Fock Bogoliubov calculations performed with the D1s force are in quite good agreement with the experimental values. This shows that the dynamical effects are very important in these magic nuclei.

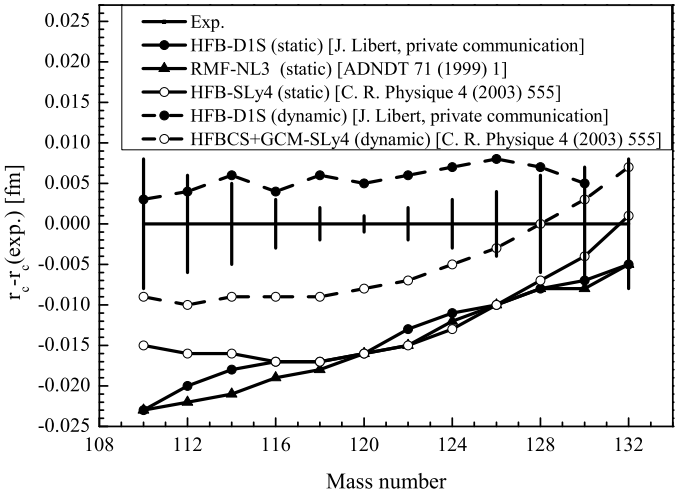

Fig. 3. Difference between theoretical and experimental charge radius in tin.

5. Conclusions

Laser spectroscopy has been used for nuclear physics since about thirty years. Since then, many isotopic series have been studied [10]. During all these years, the challenge was always to improve efficiency and frequency resolution. This challenge still continues. For example, for the collinear spectroscopy, at Jyväskylä an ion cooler-buncher has been added in order to allow measurements on ion beams as low as 150 per second [11, 13, 14]. Such a system combining collinear spectroscopy and an ion cooler-buncher is under discussion to be installed at the ALTO facility in Orsay. Concerning the resonance ionization method, the most significant and recent progress has been obtained by applying it directly in the laser ion source. Firstly used at Gatchina to study the ytterbium and thullium isotopes [15], this method has been very recently used at ISOLDE to measure the isotope shift in lead down to ^{182}Pb that is produced at the rate of 1 atom per second [16]. At present this method is restricted to elements having a high isotope shift because of the frequency resolution limited by the velocity distribution of the atoms inside the ion source leading to a large Doppler broadening. Using Doppler-free two-photon spectroscopy, high resolution is expected to be recovered and the method could be applied to many elements [17]. Then the RIS method in the ion source will become very attractive combining high efficiency and high resolution.

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