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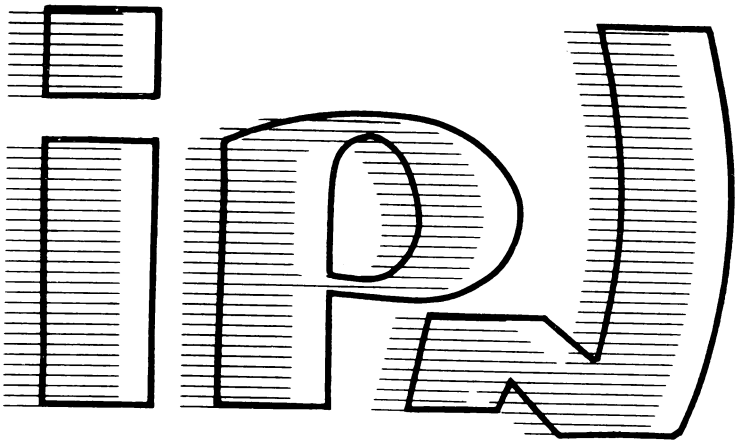

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Two laser spectroscopy methods to extract nuclear ground state properties are presented. The first one, collinear laser spectroscopy, has been used to measure the nuclear moments and the isomeric shift of the isomer ^{178m2}Hf produced in microweight quantities at the Dubna cyclotron. The second one, using multi-step photoionization (COMPLIS), is well suited to measure the same quantities for elements not directly produced by isotope separators.

1 Introduction

Measurements of hyperfine structure and isotope shifts have provided a wealth of information on nuclear spins, magnetic and quadrupole moments, and nuclear charge radii variation. One of the most versatile and widely applicable techniques available for such studies is collinear spectroscopy on fast atomic beams provided by isotope separators. The advantage of such a technique is the good efficiency obtained (around 10^{-4}) and the high resolution (from 20 to 60 MHz) due to the reduced velocity spread in the direction of acceleration.

We have performed collinear spectroscopy on an isomeric beam of ^{178m2}Hf, produced as a microweight sample (10^{13} atoms) in Dubna. The nuclear moments μ_I and Q_s and the change in the nuclear mean square charge radius relative to the ground state were measured [1].

However, this technique cannot be applied for elements not directly available from the target-ion sources of separators. A technique of ion beam implantation followed by RIS (Resonance Ionization Spectroscopy) has been used in such cases for the studies of the laser-desorbed radioactive daughter elements [2]. The system COMPLIS[3] (COllinear spectroscopy Measurements using a Pulsed Laser Ion Source) has been installed at the ISOLDE-Booster facility. Daughter products from the implanted ISOLDE beam are prepared as pulsed mass-separated ion beams by laser desorption and selective ionization. This scheme is used for Doppler-reduced pulsed laser spectroscopy on Au and Pt isotopes. The efficiency obtained is of the order of 10^{-5} and the resolution reaches 250 MHz due to the velocity spread in the desorbed atom cone.

2 Collinear laser spectroscopy on the ^{178m2}Hf isomeric beam

2.1 Nuclear properties

The ^{178}Hf nucleus belongs to the well-known region of permanently deformed rare-earths. Three isomers are known in this nucleus : the 0^+ ground state, an 8^- state of $4s$ half-life at 1.15 MeV and the 16^+ state of $31y$ at 2.45 MeV excitation energy [4–6]. Static calculations performed by P. Quentin *et al.*[7] indicate that two $I^\pi=8^-$ levels can be interpreted as 2-qp neutron and 2-qp proton states each with K=8. From these configurations, a positive parity state I=K=16 can be built and is thus to first order a pure 4-qp state.

2.2 Experimental method

The experiment was carried out in two steps : the production of the Hf sample and the laser spectroscopy measurement. Enriched ^{176}Yb (96 %) was irradiated by a 100 μA, 36 MeV α-particle beam from the U-200 cyclotron in Dubna producing $^{178m2+g}$Hf via the ^{176}Yb(^{4}He,2n) reaction. The hafnium was chemically separated from the reaction products [8] and evaporated as chloride onto a quartz wool substrate. The resulting sample we used contained about 2 10^{13} atoms of ^{178m2}Hf *i.e.* 3 % of the total number of atoms in the sample. The Hf sample was placed inside the ion source of the PARIS mass separator of the CSNSM-Orsay. The ions were extracted, accelerated to 40 kV and mass-separated by the magnet. The $^{178m2+g}$Hf ions then entered a charge exchange cell filled with Na where they were neutralized (Fig.1). A fraction of the atoms

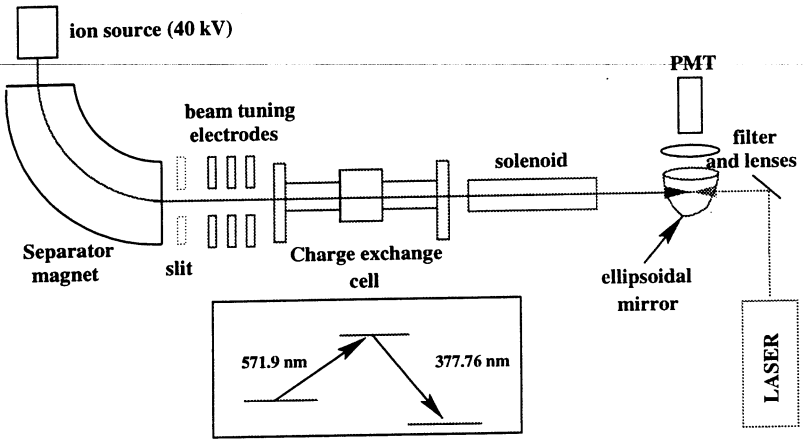

Figure 1: The collinear laser spectroscopy apparatus installed at the PARIS separator. Inset shows the atomic excitation and detection scheme used.

were thus in the $5d^26s^2\ ^3P_2$ metastable state used as the initial state of the optical transition also shown in Figure 1. The beam of a single-mode dye-laser operating at 572 nm was directed collinearly with the atomic beam to excite the atoms to the $5d6s^26p\ ^1P_1$ state. The atomic resonances were scanned via Doppler shift by a change of the beam velocity with a tuning voltage at the charge exchange cell entrance. The resonances were detected via the fluorescence light of the excited state decaying to the $^3F_2$ ground state at 378 nm. The light was collected by an ellipsoidal mirror and detected by a RCA 8850 PM tube. The experimental linewidth of 50 MHz FWHM was due to the residual Doppler profile. With calibrated Hf samples, we obtained a total detection efficiency of 10^{-4} photons per incoming atom.

2.3 Experimental results

Figure 2 shows the hyperfine structure of $^{178m2+g}$Hf. The nine lines that constitute the hyperfine spectrum of the isomer are visible as well as the single component of the ground state. From the frequency positions of each line relative to the ground state peak, we can independently extract the hyperfine A and B constants for the two atomic states and the isomeric shift $\Delta\nu$ in the $5d^26s^2\ ^3P_2 \rightarrow 5d6s^26p\ ^1P_1$ transition : A(^{3}P$_2$) = 159.5(2) MHz, B(^{3}P$_2$) = -2151(16) MHz, A(^{1}P$_1$) = -51.3(4) MHz, B(^{1}P$_1$) = 1235(10) MHz and $\Delta\nu_{178m2,178g}$ = -135(4) MHz. The value of A(^{3}P$_2$) leads to the magnetic moment : $\mu_I(^{178m2}Hf) = 8.16(4)\mu_N$. We calculated the magnetic moment

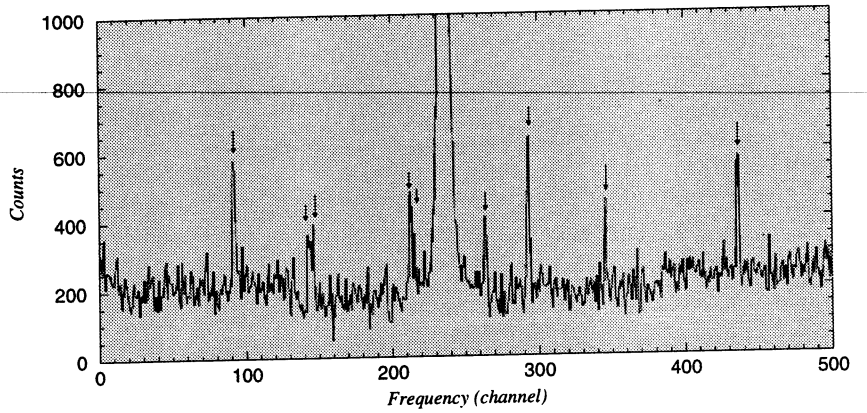

Figure 2: Hyperfine spectrum of $^{178m2+g}$Hf.

using a relation from the modified oscillator model of Ekström *et al*[9], which sums the g_k contributions from measured magnetic moments of neighboring odd nuclei. This calculation leads to a value of $8.17\mu_N$ which is in excellent agreement with the experimental result. From B($^3P_2$), we extracted the spectroscopic quadrupole moment : $Q_s(^{178m2}Hf) = 6.00(7)b$. This leads to $Q_o = 7.18(10)b$ (assuming strong coupling) and $\beta = 0.265(3)$. This result can be compared with the Hartree-Fock Bogoliubov calculations performed by M. Girod *et al.*[10] using the Gogny force, predicting to first order $Q_o = 7.36b$. From the isomeric shift $\Delta\nu_{178m2,178g}$ we extracted the mean square charge radius change : $\delta < r_c^2 >_{178m2,178g} = -0.059(9)fm^2$. The deformation of the ground state has been extracted from a measured B(E2) value to be $\beta(^{178g}Hf) = 0.280(2)$[11]. From this value and the experimental $\delta < r^2 >$, we obtain $< \beta^2(^{178m2}Hf) >^{1/2} = 0.270(3)$ which is in excellent agreement with the one extracted from the quadrupole moment.

3 The COMPLIS experiment

3.1 Experimental setup

The 60 kV Hg^+ ISOLDE beam is decelerated to 1 kV and collected on a graphite substrate (fig. 3). After a delay sufficient to obtain gold isotopes via β-decay, the daughter atoms are desorbed by a Nd:YAG laser and selectively ionized by a set of two pulsed tunable dye lasers. The atomic spectroscopy is performed on the laser excitation step ($5d^{10}6s\ ^2S_{1/2} \rightarrow 5d^{10}6p\ ^2P_{3/2}$) by scanning a single mode dye laser with pulsed intra-cavity amplification. The pulses delivered by this system are frequency tripled in order to obtain the

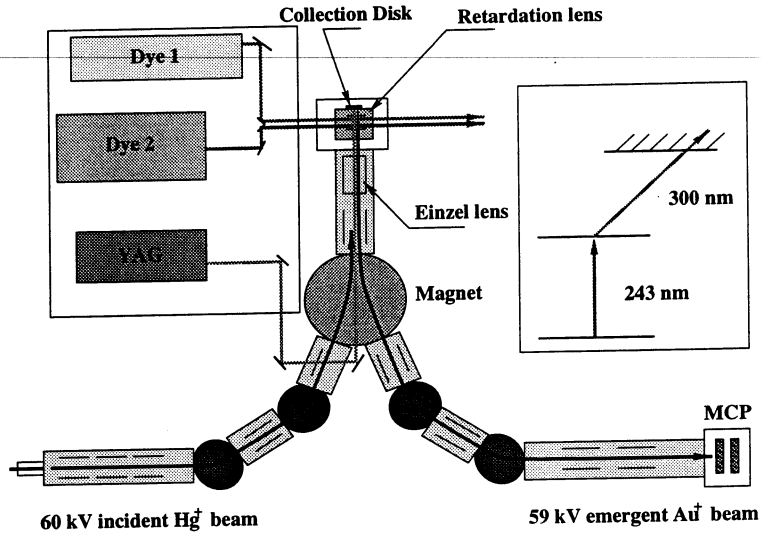

Figure 3: The COMPLIS experimental setup. Inset represents the RIS scheme used for gold isotopes.

243 nm UV wavelength. The ions are mass separated by magnetic and time-of-flight identification and are detected by micro-channel plates while scanning the laser frequency.

3.2 Experimental results

The hyperfine structure of the isotopes ^{191}Au, ^{193}Au, ^{195}Au and ^{197}Au have been recorded, and very recently those of ^{190}Au, ^{188}Au and ^{184}Au. The mean square charge radius variation, the magnetic moment and the spectroscopic quadrupole moment obtained for the odd-even isotopes are presented in Table 1. We have confirmed the values of the nuclear moments for the masses 197, 193 and 191 [refs.[12–14]] and measured for the first time the Q_s value of ^{195}Au. To extract the β deformation parameter from Q_s, the value of K has to be known. We have performed calculations in the framework of the rotor-plus-quasiparticle model assuming axial symmetry and using the quasiparticle wave functions obtained by Hartree-Fock+BCS calculations with the SIII Skyrme force [15]. Since these four isotopes all display very similar low energy level schemes, we choose as an example the case of ^{193}Au represented as ^{192}Pt core + p. The first excited energy levels are quite well reproduced and no K=1/2 orbital having a negative decoupling parameter appears near the

Table 1: Nuclear moments and mean square charge radius variation of some gold isotopes

Mass	I	$\Delta\nu^{197,A}$ (GHz)	$\delta < r^2 >^{197,A}$ (fm^2)	μ_I (nm)	Q_s (b)	β	$< \beta^2 >^{1/2}$
197	3/2	0	0	0.147(1)	0.549(16)	0.09	0.10
195	3/2	3.02(15)	- 0.077(4)	0.150(7)	0.62(6)	0.10	0.11
193	3/2	6.04(15)	- 0.153(4)	0.145(8)	0.69(8)	0.12	0.12
191	3/2	9.25(15)	- 0.234(4)	0.137(3)	0.76(3)	0.13	0.13

Fermi surface. It means that I=K=3/2 and this leads to a positive experimental Q_o : $Q_o = + 3.45b$ and consequently $\beta = + 0.120$. With the calculations we found $Q_o = + 3.57b$ and $\beta = + 0.123$ which is in perfect agreement with our experimental result in spite of the axial-symmetry limitation of the model. Furthermore, we calculated the magnetic moment of the $3/2^+$ ground state : $\mu =$ - 0.1 μ_N for $g_s = g_{sfree}$ and $\mu = 0.5\mu_N$ for $g_s = 0.6g_{sfree}$. This can be compared to the $\mu = 0.145\mu_N$ experimental value. This value is reached for $g_s = 0.85g_{sfree}$, whereas such an agreement cannot be found for an oblate $3/2^+$ state. This strongly suggests a prolate shape for these four nuclides. From the $\delta < r^2 >$ between these isotopes and a quadrupole moment measurement of ^{186}Au [2], we have extracted the values of $< \beta^2 >^{1/2}$ (see table 1) which are in nice agreement with the β extracted from the quadrupole moments.

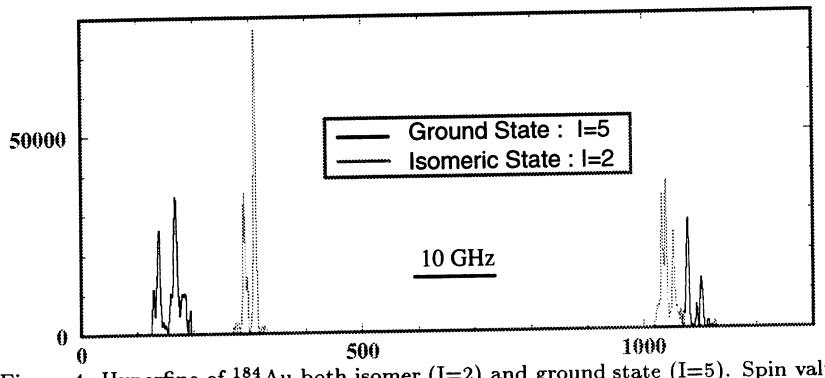

Figure 4: Hyperfine of ^{184}Au both isomer (I=2) and ground state (I=5). Spin values were known previously from ref.[16].

Fig. 4 represents the complete hyperfine structure of ^{184}Au ground state ($T_{1/2} \sim 40s$) and isomer ($T_{1/2} \sim 15s$). The analysis is in progress and the nuclear moments and the $\delta < r^2 >$ between the two states will be soon extracted.

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