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NUCLEAR SHAPE TRANSITION IN LIGHT GOLD ISOTOPES

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Abstract

The hyperfine structure and isotope shifts of short-lived gold isotopes with $185 \leq A \leq 190$ and the $11/2^-$ isomer of ^{189}Au have been investigated by application of on-line resonance ionization mass spectroscopy. A detection efficiency of $\epsilon = 10^{-8}$ for gold atoms was observed at a background of about one event per 1000 laser shots. The deduced charge radii show a drastic change between $A = 187$ and $A = 186$ which is interpreted as an onset of strong deformation ($\beta \approx 0.25$) in ^{186}Au and ^{189}Au due to the influence of the $\pi 1h_{9/2}$ intruder orbital.

Nuclear Moments $^{185,186,187,188,189m,189,190,191,192,193,195,197}\text{Au}$;
measured hfs, isotope shifts; deduced μ , rms charge radii, deformation parameters β , resonance ionization mass spectroscopy; on-line isotope separator

1. Introduction

The neutron-deficient gold isotopes are situated in the transitional region between the well-deformed rare-earth nuclei and the doubly-magic nucleus ^{208}Pb . In this region the phenomenon of shape coexistence is wide-spread and is seen, for example, in (i) the odd-even staggering of the nuclear charge radii of the mercury isotopes with $181 \leq A \leq 186$ ^{1,2)}, (ii) the shape coexistence in ^{185}Hg ³⁾, (iii) the odd-even staggering of the inertial parameters of the ground-state band of very neutron-deficient platinum isotopes⁴⁾ and (iv) the existence of lowlying 0_2^+ states in light platinum and mercury isotopes showing rotational bands with different inertial parameters compared to the ground-state bands^{5,6)}. Evidence for shape coexistence has also been observed for gold isotopes⁷⁻⁹⁾. Shape coexistence can be described by the excitation of nucleons across a shell gap into low-lying, deformation driving 'intruder' states^{7,10,11)}. Because intruder states usually are excited nuclear states, the study of ground-state properties is generally not affected by them. Exceptions to this rule are ^{185}Au and ^{186}Au where the $\pi 1h_{9/2}$ intruder state is believed to become the ground state of these nuclei^{8,12)}.

In this work the hyperfine structure (HFS) and isotope shift (IS) of the short-lived gold isotopes with $185 \leq A \leq 190$ and the $11/2$ isomer of ^{189}Au were investigated by application of on-line resonance ionization mass spectroscopy (RIMS)¹³⁾.

2. Experiment

Fig. 1 shows the atomic level scheme of Au. Gold ($Z = 79$) has a closed $5d^{10}$ shell and one electron in the outer $6s$ shell. Therefore it exhibits an alkaline-like spectrum. Due to the high ionization potential of 9.2 eV, the ground-state transitions are in the ultra-violet spectral range. In the experiment reported here, the hyper-fine structure and isotope shift in the $6s\ ^2S_{1/2} \rightarrow 6p\ ^2P_{1/2}$ ($\lambda = 268\text{ nm}$) D_1 line were investigated. In order to achieve a high detection efficiency the resonance was monitored by observing the photo ions created by the three-colour, two-step resonant process:

- (i) $6s\ ^2S_{1/2} \rightarrow 6p\ ^2P_{1/2}$ ($\lambda = 268\text{ nm}$)
- (ii) $6p\ ^2P_{1/2} \rightarrow 6d\ ^2D_{3/2}$ ($\lambda = 407\text{ nm}$)
- (iii) $6d\ ^2D_{3/2} \rightarrow \text{Au}^+ + e^-$ ($\lambda = 532\text{ nm}$).

Fig. 2 shows an overview of the entire experimental set-up installed at the on-line isotope separator ISOLDE at CERN/Geneva¹⁴⁾\$. The apparatus consists of three major devices: (i) the resonance ionization mass spectrometer, (ii) the laser system including the frequency calibrating elements and (iii) the data acquisition system.

\$ Since a target-ion-source system for direct production of Au isotopes does not exist presently, these nuclei were obtained as daughters of the corresponding Hg-isotopes, the latter ones being produced with yields of up to 10^{10} atoms per second and mass number by a $\text{Pb}(p,3\text{pxn})\text{Hg}$ spallation reaction¹⁴⁾. The nuclei investigated are short-lived with halflives in the range of minutes. Thus, the investigation had to be performed as an on-line experiment.

2.1 The Resonance Ionization Mass Spectrometer

The resonance ionization mass spectrometer is shown schematically in fig. 3. A detailed description of the system is given in ref. 15. The mass-separated Hg ions were implanted into an atomic beam oven. After a suitable time to let the Hg nuclei decay to the daughter isotope, a thermal atomic beam was formed. The gold atoms were photoionized as described above and the photo ions were detected mass selectively by a two-stage time-of-flight (TOF) spectrometer. The atomic beam, the laser beam and the TOF spectrometer were arranged in a perpendicular geometry (see fig. 3).

2.1.1 Atomic Beam Source

The atomic-beam oven had the form of a long cylindrical channel. Several diaphragms mounted along the ion-beam path were used in order to permit an adjustment of the ISOLDE ion-beam for optimum transmission. Radioactive Hg was collected in the oven for about 3 half-lives of the gold daughter isotope under investigation. Then a thermal atomic beam was formed by evaporating the radioactive sample. The shape of the oven caused a forward collimation of the resulting atomic beam with an opening angle¹⁶⁻¹⁸⁾ $\theta_{1/2} \approx 2D/L$ and it allowed an efficient use of the small amount of material. With a diameter $D = 3$ mm and a length $L = 15$ mm, a full angle of about 11° is calculated. The relation holds only if: (i) the mean free path of the gold atoms is larger than the channel length and (ii) the radioactive beam is implanted in the bottom of the channel and not in the wall. During a test run the latter point was checked. It was proved that 70% of the ion beam was transmitted and implanted in the bot-

tom.

The atomic-beam source was mounted on a water-cooled flange, as shown in fig. 4. The top of the oven was located 35 mm from the atom-laser interaction region, resulting in a diameter for the atomic beam in that region of about 20 mm. At the same point the diameter of the laser beams was 10 mm.

The atomic beam oven was made of graphite (EK 98, Ringsdorff) and was heated by a direct current of about 80 A. Temperatures of 1400°C were reached within periods < 1 min after switching on the power. The current was fed, via a central contact made of copper and molybdenum, to the oven and was conducted back to the vacuum feed-throughs by a plate and two stamps also made of molybdenum. The molybdenum/graphite contacts were performed by pressing the pieces onto each other. The central part was mechanically stabilized, and electrically as well as thermally isolated by an aluminum oxide tube. This tube itself was stabilized and centered by holders made of a titanium alloy (tikrutan LT 31, Krupp) and molybdenum. The titanium alloy was used to minimize heat conduction from the hot oven region to the O-ring-sealed mounting flange. Several heat shields, made of molybdenum foil, prevented the strong black-body radiation from heating the surroundings. Two collector electrodes, kept at potentials of +100 and -100 V, prevented thermal electrons and ions (which originate from the hot oven system) from reaching the atom-laser interaction region. The whole oven system was surrounded by a water-cooled oven housing. A number of holes in this housing provided sufficient pumping of the oven region. The oven flange was fixed with adjustment pins in order to center the oven

properly with respect to the ISOLDE beam line and the laser beam axis.

2.1.2 Time-of-Flight Mass Spectrometer

The TOF method makes use of the mass-dependent time of flight of ions accelerated in an electric field. In order to obtain a high mass resolution a time-focusing TOF spectrometer was used^{19,20}. The TOF spectrometer consisted of a two-stage acceleration region, a field-free drift tube, a 40° ion reflector and an ion detector. The acceleration part of the TOF spectrometer is shown in detail in Fig. 4. The potential defining plates and acceleration grids (molybdenum, transmission $\approx 92\%$, Eyring) and diaphragms for adjustment of the ISOLDE ion beam were fixed on an 'optical bench' consisting of four quartz rods ($d = 6$ mm) which were selected for straightness and sphericity. The proper relative location of all components was secured by spacers also made of quartz. The distance between the base plate (2000 V) and the first acceleration grid (1700 V) was 25 mm, which was the same as the distance between grid 1 and grid 2 (ground potential). The electrical potentials used are indicated in figs. 3 and 4. The atom-laser interaction region was shielded electrically by diaphragms set to an intermediate potential of 1850 V in order to homogenize the electrical field at the origin of the photo-ions. A field-free drift tube with an overall length of about 80 cm was attached to the acceleration region. The electrostatic ion reflector was installed to ensure a proper shielding of the detector against nuclear radiation from the contaminated oven acceleration region. Here, a high amount of radioactivity was accumulated during the on-line experiment. The detector was a tandem micro-channel

plate (8920ES, Varian).

The mass resolution of our RIMS spectrometer was limited by the imperfect ion optics of the acceleration region, which was not optimized with respect to mass resolution. A mass resolution of $m/\Delta m = 250$ at $A \approx 190$ was obtained during the run, corresponding to a half-width of the ion signal of 50 ns and a time of flight of 25 μ s. A time window for the mass under investigation of $\Delta t = 70$ ns turned out to be a good compromise between an optimum detection efficiency for the gold ions and a low-background counting rate.

2.2 Laser System and Beam Transport

2.2.1 Laser System

The light source used in the experiment was a Nd:YAG pumped dye laser system with a repetition rate of 10 Hz. The Nd:YAG pump laser was a Molelectron MY 32-10, up-graded by a homemade amplifier stage¹⁵⁾ delivering 650 mJ, 80 mJ and 25 mJ at 1064 nm, 532 nm and 355 nm, respectively. The $\lambda = 355$ nm beam was split, in order to pump two dye lasers. Dye laser L1 ($\lambda = 535$ nm) and dye laser L2 ($\lambda = 407$ nm) were pumped with 70 % and 30 % of the output at 355 nm. The wavelength of 268 nm was generated by frequency-doubling the output of L1 in an angle-tuned KDP crystal. Table 1 gives a compilation of the laser properties. Dye laser L1 was a Molelectron DL 16P which was modified in order to improve the bandwidth and the output power. The details of this laser are described elsewhere²¹⁾. The essential improvements consisted of the replacement of the oscillator etalon of low finesse by one of high finesse, synchronization of the cavity and etalon modes by a galvano plate and amplification of the oscil-

lator output by three additional amplifier stages. A laser bandwidth of $\delta\nu_{\text{LASER}} \leq 200$ MHz could be achieved (see tab. 1). The frequency tuning of the laser was accomplished by changing the pressure p in the laser cavity. The scanning speed was variable by use of different capillaries through which the pressure chamber was filled with nitrogen. Neglecting higher orders in p the frequency-pressure relation at $\lambda = 535$ nm is given by $\delta\nu = 152.04 \cdot \delta p$ with $\delta\nu$ in MHz and δp in mb²²⁾. A scanning speed of 650 MHz/s was used during the measurements reported here. The scanning was controlled by a minicomputer.

Frequency calibration of L1 was performed by means of a reference atomic beam of stable ^{197}Au and an iodine absorption cell. The laser-induced fluorescence of the stable isotope in the reference atomic beam was monitored perpendicular to the laser beam ($\lambda = 268$ nm) with a photomultiplier. The well-known hyperfine separation of the $6s\ ^2S_{1/2}$ ground state²³⁾ served for frequency calibration. The second dye laser L2 (Lambda Physik FL 2001) was also calibrated with the help of the reference atomic beam. Its wavelength was fixed at 407 nm corresponding to the $6p\ ^2P_{1/2} \rightarrow 6d\ ^2D_{3/2}$ transition.

2.2.2 Laser Beam Transmission System

Since the laser system and the RIMS spectrometer had to be separated by two floors at the ISOLDE facility, a transport system for the laser beams had to be developed. The beam of laser L2 ($\lambda = 407$ nm) was transmitted by an optical fiber with a Suprasil core (Fluosil-typ SS, $d = 0.5$ mm, Schott). With a fiber length of 20 m, a transmission of 60 % was achieved. The divergence of the outgoing beam was determined to be $\approx 14^\circ$ (full angle). The $\lambda = 268$ nm light was

strongly absorbed by the fiber, and the $\lambda = 535$ nm laser light at its fundamental frequency lost its focusability and polarization during transport in the fiber which are necessary for efficient second harmonic generation (SHG). Hence the light of L1 was transmitted by a telescope/mirror system to the SHG crystal. The crystal was placed in front of one of the entrance windows of the RIMS spectrometer about 25 m from the dye laser. For L3 ($\lambda = 532$ nm), the beam intensity exceeded the damage threshold of the fiber which was determined to about 10 mJ for a 15 ns pulse. Thus, L3 also had to be transmitted by a telescope/mirror system (transmission ≈ 60 %). The temporal overlap of the three laser beams was accomplished by optical delay lines for L1 and L3.

2.3 Data Recording

The frequency-dependent signals obtained from the reference atomic beam, the RIMS spectrometer and the iodine absorption cell were digitized by gated ADC's and transmitted via CAMAC to a minicomputer (LSI 11/23). In addition, the resonance-ionization signal was recorded in a single-ion counting mode by a gated discriminator and also fed into the computer via CAMAC. A 70 ns time-window was used as the gate signal set to the appropriate TOF of the isotope under investigation. A maximum of 500 channels was available for each of a maximum of six simultaneously measured signals. In addition, a transient recorder with a time resolution of 10 ns (TR 8818, Le Croy) stored the complete TOF spectrum. These data were stored in a second LSI 11/23. Fig. 5 displays a typical resonance signal from about 10^{12} atoms of ^{196}Au . In addition, the signals of the reference atomic

beam and the iodine absorption cell, used for frequency calibration, are shown. The simultaneously recorded TOF-spectrum is shown in fig. 6. The ^{197}Au peak in the TOF-spectrum results from stable gold which was added as a mass marker.

2.4 Detection Efficiency and Background

2.4.1 Detection Efficiency

The overall detection efficiency of the RIMS scheme described above was determined to be $\epsilon \approx 10^{-8}$, defined as the ratio of gold ions detected by the micro-channel plate (MCP) detector to the number of atoms collected in the oven. In the following, an estimate of the different contributions to the detection efficiency are given:

$2 \cdot 10^{-4}$	duty cycle of laser (for an atom traversing the region of interaction with the laser beams (diameter $D=10$ mm) within $2 \cdot 10^{-5}$ s, laser repetition rate = 10 Hz)
0.25	spatial overlap of atomic beam (diameter $d = 20$ mm) and laser beam ($D = 10$ mm)
0.25	probability to excite an atom from the ground state into the $6d \ ^2D_{3/2}$ state (50 % each step)
0.1	ionization probability for atoms in the $6d \ ^2D_{3/2}$ state
0.7	total transmission of grids in the TOF-spectrometer
0.3	detection efficiency of MCP and losses due to imperfect ion optics
0.5	population of the two hyperfine components of the ground state in thermal equilibrium
0.2	temporal and spatial overlap of laser beams (beam inhomogenities)

$2.6 \cdot 10^{-8}$	

It is evident that the main losses are due to the low repetition rate of the laser. A test of the power dependence of the ion signal has shown that the ionization step can be saturated with ten times higher power density. A gain in detection efficiency is feasible by production of a pulsed thermal atomic beam with laser desorption and by exciting autoionizing or Rydberg levels²⁴⁾.

2.4.2 Background

A background rate as low as one to three events per 1000 laser shots was observed. This applies for a 70 ns window set at the appropriate time for the mass under investigation under typical conditions during the run. The major part of the background stems from ionization of the residual gas by the intense laser light. Thermal ions originating from the hot oven system and radioactivity contribute each only about $1 \cdot 10^{-4}$ events per laser shot in the 70 ns window. Thus the background is dominated by events correlated to the laser shot as can be seen also from fig. 6. Comparing the signal of ^{186}Au with those of non-resonant ionization of residual gas, the necessity of the TOF-spectrometer is evident.

3. Hyperfine Structure and Isotope Shift

3.1. Hyperfine Structure

The interaction of nuclear moments with hyperfine fields produced by electron shells leads to the hyperfine splitting. Since $J = 1/2$ for both states in the investigated transition, only the magnetic dipole interaction has to be taken into account

$$E_{\text{hfs}}(F, I, J) = E_J + A/2 \cdot C, \quad (1)$$

with E_J = energy of fine-structure level, $A = \mu_I \cdot \langle H(0) \rangle / (IJ)$ and $C = F(F+1) - I(I+1) - J(J+1)$.

The nuclear magnetic moments of different isotopes are related to their A factors by

$$\mu_I = \mu_I' \cdot \frac{(1+\epsilon')}{(1+\epsilon)} \cdot \frac{A \cdot I}{A' \cdot I'} \quad (2)$$

In ^{197}Au , the ratio $\mu_I/(A \cdot I)$ has the value²³⁾ $3.1668 \cdot 10^{-5} \mu_N/\text{MHz}$. Due to the $\pi d_{3/2}$ proton configuration in ^{197}Au , the spin and orbital contribution to the magnetic moment almost cancel. Thus, ^{197}Au exhibits a large hyperfine anomaly. Ekström et al.²⁵⁾ report a value of $\epsilon^{197} = + 8.2 \%$. Hence, the only stable isotope, ^{197}Au , is not a suitable reference isotope for calculating the magnetic moment from the measured A factor via equation (2). The problem can be circumvented by using instead a hypothetical point-like ^{197}Au nucleus with the magnetic A factor A_{point} . Equation (2) can then be rewritten as

$$\left[\frac{\mu_I}{A \cdot I} \right]_{^{197}\text{Au}} = \left[\frac{\mu_I}{A_{\text{point}} \cdot I} \right]_{^{197}\text{Au}} \quad (3)$$

with $A_{\text{point}}(^{197}\text{Au}) = 3049.66 \text{ MHz}/(1 + \epsilon^{197})$. This procedure leads to

$$\mu_I = A \cdot I / 29005 \mu_N \quad (4)$$

with A in $\text{MHz}^{25)}$. For ^{198}Au , the nuclear magnetic moment and the A factor have been measured with great precision using ABMR²⁶⁾. After correction for diamagnetism²⁵⁾, a value of $[\mu_I/(A \cdot I)] = 1/28920(10) \text{ MHz}^{-1}$ is obtained for ^{198}Au . Since a small hyperfine anomaly is expected for ^{198}Au , the value given above is in good agreement with equation (4) and supports its application to the evaluation of the nuclear magnetic moment from the measured A factor.

3.2 Isotope Shift

The masses and nuclear charge distributions of different isotopes result in a frequency shift for an electronic transition 'i' of

$$\delta\nu^{A,A'}_i := \nu^{A'}_i - \nu^A_i = \delta\nu^{A,A'}_{\text{mass}} + \delta\nu^{A,A'}_{\text{field}} \quad (5)$$

between isotopes with mass number A and A' .

The mass effect $\delta\nu_{\text{mass}}$ consists of the normal mass shift (nms), which is due to the reduced mass, and the specific mass shift (sms), which is caused by correlations in the electron motion

$$\delta\nu^{A,A'}_{\text{mass}} = \delta\nu^{A,A'}_{\text{nms}} + \delta\nu^{A,A'}_{\text{sms}}. \quad (6)$$

The normal mass shift is given by²⁷⁾

$$\delta\nu^{A,A'}_{\text{nms}} = \nu_i / 1836.1 \cdot (A' - A) / (A \cdot A'). \quad (7)$$

The specific mass shift is estimated²⁷⁾ to be

$$\delta v^{A,A'}_{\text{ms}} = (0.3 \pm 0.9) \cdot \delta v^{A,A'}_{\text{nms}} \quad (8)$$

for a $ns \rightarrow np$ transition yielding, $\delta v_{\text{mass}} = -41(29)$ MHz in the D_1 -line for the isotope pair $^{197,195}\text{Au}$.

The field isotope shift is connected to changes of the nuclear charge distribution via

$$\delta v^{A,A'}_{\text{field}} = F_1^{A,A'} \cdot \lambda^{A,A'}, \quad (9)$$

where $F_1^{A,A'}$ is an electronic factor dependent on the electronic configuration involved and $\lambda^{A,A'}$ is the nuclear parameter, which is to first order the change of the nuclear mean-square charge radius $\delta \langle r^2 \rangle^{A,A'}$.

Several authors have calculated the electronic factor of the D_1 transition in gold by means of single- and multi-configuration Dirac-Fock theory. The results of these calculations are given in table 2. The discrepancy of about 30% between the ab initio values and the semi-empirical value is of the same order as in $\text{Ra II}^{28)}$ and $\text{Hg}^{29)}$. On the other hand, the F_1 values in mercury, obtained from data on muonic atoms and from electron scattering, are in good agreement with the MCDF value. Hence, the MCDF value was taken in the case of mercury for calculating $\delta \langle r^2 \rangle$ or λ from the experimental isotope shift data²⁹⁾. We follow the same procedure in order to get comparable results for gold and mercury, and use the MCDF value $F_{268} = -43.07$ GHz/fm² for evaluating the gold data in the 268 nm transition. A comparison of the change of the mean-square nuclear charge radii of $^{198,196}\text{Hg}$ ($\delta \langle r^2 \rangle^{198,196} = -0.0809(3)$ fm²) with the iso-

tones $^{197,195}\text{Au}$ ($\delta\langle r^2 \rangle^{197,195} = -0.076(6) \text{ fm}^2$) shows good agreement. Since these isotopes are believed to have quite similar nuclear deformations, this consistency supports our choice of F_{268} .

The change of the mean-square charge radius is connected to the nuclear parameter λ via²⁹⁾

$$\lambda_{A,A'} = \delta\langle r^2 \rangle_{A,A'} + (c_2/c_1) \cdot \delta\langle r^4 \rangle_{A,A'} + (c_3/c_1) \cdot \delta\langle r^6 \rangle_{A,A'} + \dots \quad (10)$$

where the corrections $c_k/c_1 \cdot \delta\langle r^{2k} \rangle$ account for the contribution of the radial moments with higher order to the field isotope shift.

According to the two-parameter approach, the variation of the radial moments $\delta\langle r^k \rangle$ can be decomposed into a spherical part and a deformation term

$$\delta\langle r^k \rangle = \delta\langle r^k \rangle_{\text{sph}} + \delta\langle r^k \rangle_{\text{def}}. \quad (11)$$

Recently, it was pointed out^{2,30,31)} that the corrections for higher order moments parametrized by the quantities x and y contribute in a different way to the spherical and deformation parts of the total change of the nuclear parameter λ . This effect was taken into account following the procedure as outlined in ref. 2.

The ratios c_2/c_1 and c_3/c_1 can be obtained from Seltzer²⁹⁾ or Rosen et al.³²⁾. Here, the values $c_2/c_1 = -1.19 \cdot 10^{-3} \text{ fm}^{-2}$ and $c_3/c_1 = 3.66 \cdot 10^{-6} \text{ fm}^{-4}$ are used³²⁾. Neglecting a slight mass dependence, $x = -0.067$ and $y = -0.089$ are obtained for the gold isotopic chain. The changes of the deformation parameters of different isotopes are extracted from the changes of the nuclear charge radii using equa-

tion (11). Absolute deformation parameters $\langle \beta^2 \rangle^{1/2}$ can be calculated using the theoretical quadrupole moment of ^{197}Au calculated by Möller and Nix³³⁾. This calculated value is in good agreement with the experimental value³⁴⁾ for ^{197}Au and the values of the neighbouring Hg and Pt nuclei. Using the well known relation³⁵⁾

$$Q_0 = 3/(5\pi)^{1/2} \cdot ZR^2 \cdot \beta(1 + 0.36\beta) \quad (12)$$

with $R = 1.2 \cdot A^{1/3}$ the deformation parameter of ^{197}Au is calculated to be $\beta = 0.11$. The absolute deformation parameters of the unstable isotopes are related to the value of the reference isotope by

$$\langle \beta^2 \rangle_A = \langle \beta^2 \rangle_{197} + \delta \langle \beta^2 \rangle_{197, A}. \quad (13)$$

4. Data Evaluation and Discussion of the Results

Data were obtained for the isotope shift and hyperfine structure in the D_1 line of ^{189}Au , ^{188}Au , ^{187}Au , ^{186}Au , ^{185}Au and $^{189\text{m}}\text{Au}$. The IS of ^{190}Au was remeasured and agrees within the experimental error with the value given in a previous publication²²⁾.

4.1 Fitting Procedure

A least-squares routine was used to fit a theoretical curve to the absorption lines of the iodine absorption cell, the resonance fluorescence signals of the reference atomic beam and the RIMS signals of the radioactive isotopes. The line profiles were convolutions of the Doppler profile ($\delta\nu_D \approx 400$ MHz for the geometry with atomic beam and laser beam perpendicular to each other) and the laser line shape ($\delta\nu_{\text{laser}} \leq 400$ MHz). Since the laser profile is unknown, a Gaussian was fitted to each hyperfine component of the signals of the reference atomic beam and the RIMS spectrometer. For the iodine absorption signal the line profile was dominated by the Doppler profile, which had a width of about $\delta\nu_D \approx 1$ GHz.

For ^{185}Au , ^{186}Au , $^{189\text{m}}\text{Au}$, ^{187}Au and ^{189}Au all the resonances of the four or three hyperfine components were well resolved. Thus, the HFS of the ground states and the excited $6p\ ^2P_{1/2}$ states could be obtained independently. The HFS of the excited states of ^{188}Au , ^{190}Au and ^{197}Au could not be resolved due to the small magnetic moments. Hence the A factor of the excited state was considered as a fixed parameter in these cases, and the ratio A_{6p}/A_{6s} was set to the corresponding value of ^{197}Au , where $A_{6p}/A_{6s} = 0.111(3)$ (refs. 23, 36) whereby hfs anomaly effects were neglected. The wavenumbers of the hyperfine components of all isotopes were determined relative to

the tabulated iodine absorption lines³⁷⁾. Table 3 gives a compilation of the absolute transition wavenumbers of the hfs components, the center of gravity, the deduced isotope shifts $\delta V^{197,A}$ and the A factors of the 6s $^2S_{1/2}$ and 6p $^2P_{1/2}$ states. Figure 7 gives a compilation of the observed hyperfine structure of the unstable isotopes and the resonances of the iodine absorption lines used for wavelength calibration.

The unknown signs of the magnetic moments of ^{188}Au , ^{186}Au and ^{185}Au were determined from the relative intensities of the hyperfine components. We found negative signs for the magnetic moments of ^{188}Au and ^{186}Au and a positive one for that of ^{185}Au . These signs are in agreement with the results of theoretical calculations performed by van Walle and Wouters³⁸⁾ (see section 4.2). Due to the huge hyperfine splitting of the excited state of $^{189\text{m}}\text{Au}$ it is unsafe to deduce the sign from the relative intensities of the hyperfine components. However, the assumption of a negative sign of μ_I leads to an unreasonably large isotope shift of $\delta\langle r^2 \rangle^{197,189\text{m}} = -0.652 \text{ fm}^2$. Such a value would exceed the droplet value for a spherical nucleus $\delta\langle r^2 \rangle_{\text{droplet}} = -0.421 \text{ fm}^2$ and would lead to $\beta^2 < 0$. Thus we assign a positive sign to the magnetic moment of $^{189\text{m}}\text{Au}$ in agreement with the Schmidt model.

4.2 Magnetic Moments and Nuclear Deformations of Neutron-Deficient Au-Isotopes

The magnetic moments calculated by applying equation (4) are listed in table 4 and compared with the values cited in the literature. The experimental error accounts for the uncertainty in the hyperfine anomaly ($-0.012/\mu \leq \epsilon \leq 0.012/\mu$ for odd-even nuclei and $-0.024/\mu \leq$

$\epsilon \leq 0.024/\mu$ for doubly-odd isotopes²⁵⁾). With the exception of ^{187}Au , reasonable agreement is observed.

Table 5 gives a compilation of the isotope shifts and the deduced nuclear parameters $\lambda^{197,A}$, $\delta\langle r^2 \rangle^{197,A}$, $\delta\langle \beta^2 \rangle^{197,A}$ and $\langle \beta^2 \rangle^{1/2}$ of all gold isotopes investigated optically (this work and ref. 22). The $\delta\langle r^2 \rangle$ values of the Au isotopes are shown in Fig. 8 together with the data for the Hg-isotopes²⁾. Fig. 9 displays the corresponding deformation parameters of the gold and mercury nuclei.

The most exciting feature of fig. 8 is the dramatic increase of the nuclear mean-square charge radius $\langle r^2 \rangle$ of the very neutron-deficient gold and mercury isotopes. In the mercury isotopes this has been interpreted as an onset of strong deformation¹⁾. The change in deformation and the odd-even staggering of the mean-square charge radii for $181 \leq A \leq 186$ have been reproduced theoretically by Frauendorf and Pashkevitch³⁹⁾ who used Strutinsky-type total potential energy (TPE) calculations.

Different theoretical approaches, assuming quasi-particle axial-symmetric core coupling (e.g. refs. 9, 33, 40-42) or quasi-particle asymmetric-core coupling (e.g. refs. 25, 43, 44), have been used to describe the deformation properties of the gold nuclei. In the following, the data obtained on deformation properties and magnetic moments are discussed for the different isotopes investigated.

^{185}Au

The value of $\beta = 0.24$ for the quadrupole deformation parameter, obtained in this work, confirms several assumptions and theoretical calculations made in the past. Desthuilliers et al.¹²⁾ and Ekström et al.²⁵⁾ suggested that ^{185}Au has a strong prolate deformation of

about $\beta = 0.27$, deduced from the spin assignment $I^\pi = 5/2^-$. Berg et al.⁴⁵⁾ have deduced $\beta = 0.22$ from the $B(E2)$ value of the $(9/2^- \rightarrow 5/2^-)$, $E = 8.9$ keV) intra-band transition. Porquet et al.⁴²⁾ report $\beta = 0.27$ from a rotor-plus-particle model calculation assuming axial symmetry. A Strutinsky-type Nilsson calculation by Riedinger et al.⁴¹⁾ resulted in a strongly prolate nuclear shape with $\beta = 0.25$. The ground state of ^{185}Au is believed to be the $5/2$ member of the $1h_{9/2}$ intruder band (see e.g., refs. 12, 46). The odd-proton spin $j = 9/2$ is aligned antiparallel to the rotation axis of the prolate ^{184}Pt core which has an angular momentum of $R = 2$. Thus, the ground state of ^{185}Au is a typical rotation-aligned $(j-2)$ state as discussed by Stephens⁴⁷⁾ and Meyer-ter-Vehn⁴³⁾. Porquet and coworkers⁸⁾ have calculated the relative contributions of Nilsson orbitals to the ground-state of ^{185}Au . The main contribution is the $3/2^-$ [532] orbital. Therefore, the odd-proton state is denoted as $\pi 3/2^-$ [532]. As a conclusion from the data discussed above, we can assign a positive sign to the deformation parameter and obtain $\beta = +0.24$ which corresponds to a strongly prolate-shaped nucleus.

The magnetic moment of ^{185}Au has been reproduced theoretically by van Walle et al.⁴⁸⁾ applying a Nilsson-plus-pairing model with Coriolis mixing. For $0.2 \leq \beta \leq 0.25$, a magnetic moment of $+2.2\mu_N \leq \mu_{\text{th}} \leq +2.5\mu_N$ is obtained. Ragnarsson et al.⁴⁹⁾ obtained $\mu(^{185}\text{Au}) = +2.13 \mu_N$ from a similar calculation using a particle-plus-rotor model and assumed $\beta = +0.29$, $\gamma = 20^\circ$ and $g_s = 0.6 \cdot g_s^{\text{free}}$.

^{186}Au

The ^{186}Au nucleus appears also to be strongly deformed (see table 5) with a deformation $\beta = 0.25$, similar to ^{185}Au . This value confirms

several assumptions made in the past. Ekström et al.⁵⁰⁾ suggested a large prolate deformation, using the spin assignment $I^\pi = 3^-$. Porquet et al.⁸⁾ explained the $I^\pi = 3^-$ ground state by the coupling of a $9/2^+$ [624] neutron with the odd proton $\pi 3/2^-$ [532]. The neutron level is assumed to be the same as the $9/2^+$ ground state of ^{185}Pt and is believed to be rather pure. Consequently, the ground state of ^{186}Au represents the case that the odd proton is rotation-aligned with respect to the rotation axis of the core whereas the odd neutron is strongly coupled with Ω being a good quantum number. The magnetic moment $\mu = -1.263(29)\mu_N$ measured in this work is in reasonable agreement with the value of $\mu = 1.07(13)\mu_N$ obtained by nuclear orientation. Applying the additivity relation of magnetic moments and making several assumptions on the Coriolis mixing effects, van Walle et al.⁴⁸⁾ obtained $\mu^{th} = -1.23\mu_N$ in good agreement with our value.

^{187}Au and ^{189}Au

The identical spin values $I^\pi = 1/2^+$ and the almost identical magnetic moments of ^{187}Au and ^{189}Au indicate a very similar nuclear structure of these isotopes. Ekström et al.²⁵⁾ reports a magnetic moment, measured by ABMR, of $\mu^{187} = +0.72(7)\mu_N$. This is in disagreement with our measurement. Usually the ABMR values are very reliable. However, the following facts strongly support our value: (i) three resolved hyperfine components have been observed in the spectra taken, which is in agreement with the selection rules for $F = 0,1 \rightarrow F = 0,1$ transitions ($I = 1/2$, $J = 1/2$); (ii) the value of ^{187}Au is comparable to the one of ^{189}Au , which has the same ground-

state spin $I^\pi = 1/2^+$; (iii) the center of gravity of the D1 line in ^{187}Au , as determined with our magnetic moment, leads to an isotope shift which reflects the expected smooth shrinking of the nuclear charge radius; (iv) the ratio of the hyperfine splittings of the atomic ground state and the excited $6p\ ^2P_{1/2}$ state is the same as in the stable isotope ^{197}Au .

A comparison of the magnetic moments of low-lying $1/2^+$ states in the iridium and gold isotopes supports our value further. The values of the magnetic moments of ^{187}Au and ^{189}Au measured in this work fit well into the systematics of the odd proton $1/2^+$ states ($\mu_{1/2^+}$: $^{191}\text{Ir}/0.515\ \mu_N$; $^{193}\text{Ir}/0.504\ \mu_N$; $^{197}\text{Au}/0.419\ \mu_N$; from ref. 51).

Ekström et al.²⁵⁾ deduced from the magnetic moment $\mu = 0.72\mu_N$ that the nuclear ground state is a mixture of the $\Omega = 1/2$ ($2d3/2$) and $\Omega = 1/2$ ($3s1/2$) Nilsson single-particle states and inferred from his value of the magnetic moment a triaxial shape with $\beta = 0.19$ and $\gamma = 35^\circ$. With our value of $\mu \approx 0.5\mu_N$, an extrapolation of the same calculation results in an oblate-shaped nucleus ($\gamma \approx 60^\circ$) and $\beta \approx -0.16$. This deformation is in agreement with the one deduced from our IS data (see table 5). In the meantime our value of $\mu(^{187}\text{Au})$ has been confirmed by an independent experiment⁷¹⁾.

A TPE calculation using the Strutinsky approach, by De Waele et al.⁴⁰⁾, gives a deformation of $\beta = -0.14$ for ^{189}Au . The unpaired proton occupies the $\Omega = 1/2$ ($2d3/2$) single-particle orbit according to this calculation. An axially-symmetric-model calculation⁴²⁾ results in large deformations of $\beta = -0.24$ or $\beta = -0.19$ for the $^{186}\text{Pt}(\otimes)\ \pi 1/2^+$ state or the $^{188}\text{Hg}(\otimes)\ (\pi 1/2^+)^{-1}$ state, respectively. The corresponding values for ^{189}Au are $\beta = -0.22$ and $\beta = -0.18$ ⁴²⁾.

^{189m}Au

The $11/2^-$ isomers in the odd-mass gold isotopes are most probably hole excitations coupled to the neighbouring even-even mercury cores. In this sense ^{189m}Au represents a $^{190}\text{Hg} \otimes |\pi 1h_{11/2}^- \rangle^{-1}$ state. The deformation of this state is expected to be similar to the deformation of the Hg core, in agreement with our measurement $\langle \beta^2 \rangle^{1/2} (^{189m}\text{Au}) = 0.15$ and $\langle \beta^2 \rangle^{1/2} (^{190}\text{Hg}) = 0.140^{(2)}$. Good agreement is also obtained by a comparison of the energy of the first rotational state of the decoupled band built on the $11/2^-$ state in ^{189m}Au and the energy of the $2_1^+ \rightarrow 0_1^+$ transition in the ^{190}Hg core⁽⁵²⁾. Toki and Faessler⁽⁴⁴⁾ have calculated the deformation properties of the $\pi 1h_{11/2}$ system in several neutron-deficient gold isotopes using a quasi-particle asymmetric-rotor model. They obtained for ^{189m}Au a triaxially-shaped nucleus with $\beta = 0.159$ and $\gamma = 34.1^\circ$. A similar calculation with an axially-symmetric rotor by Porquet et al⁽⁴²⁾ leads to a deformation of $\beta = -0.18$ for the $^{190}\text{Hg} \otimes |\pi 1h_{11/2}^- \rangle^{-1}$ state, which is in reasonable agreement with our value deduced from the IS measurements.

The magnetic moments of the $11/2^-$ isomers in the light Au and Ir isotopes show a very constant behaviour. They can be explained in the Schmidt model, where $\mu_I = [g_1 \cdot l + g_s/2] \cdot \mu_N$ holds. With $g_s = 0.5 \cdot g_{s, \text{free}}$, a value $\mu(11/2^-) = 6.40 \mu_N$ is obtained. The value $\mu = +6.186(20) \mu_N$, determined in this work, fits well into the systematics and is identical to the value cited by van Walle⁽⁴⁸⁾.

$^{188}, ^{190}\text{Au}$

An oblate deformation of ^{188}Au and ^{190}Au is suggested by Abreu et al.⁽⁵³⁾ from nuclear spectroscopy results. Hence, we assign a nega-

tive sign to the deformation parameter and obtain from the IS data a moderate oblate deformation of $\beta = -0.14$ for ^{190}Au and $\beta = -0.15$ for ^{188}Au .

The magnetic moments of our measurements are in good agreement with the values given in the literature (see table 4). From the relative intensities of the hyperfine components we are able to determine a negative sign of the moment of ^{188}Au , which is paralleled in $^{190}\text{Au}^{22)}$. The magnetic moments in the 1- ground states of $^{188,190,192}\text{Au}$ are explained by the $[(\pi 2d_{3/2}), (\nu 3p_{1/2})]^{25)}$ or $[(\pi 2d_{3/2}), (\nu 3p_{3/2})]^{53)}$ coupling of the unpaired nucleons.

4.3 Shape Transition in the light Gold-Isotopes

Shape coexistence is a well-established structural feature of the neutron-deficient Pt, Au, Hg, Tl, Pb and Bi isotopes. It is closely associated with intruder configurations⁷⁾. These configurations are formed by promoting one or more protons across the $Z = 82$ shell gap. Their low energies can be understood⁵⁴⁾ as resulting from a gain in pairing energy and a large increase in binding energy due to the residual interaction between protons and neutrons. It is the deformation-producing effect of the proton-neutron interaction^{55,56)}, which results in the larger deformation for the intruder configurations and hence the different shapes. The phenomenon can also be reproduced in descriptions using a deformed mean (single-particle) field (see e.g. refs., 7, 57)).

It is possible for the more deformed intruder configuration to become the ground state. This has been established in the even-mass⁵⁾ and odd-mass^{58,59)} Pt isotopes and the odd-mass Au isotopes^{7,60)} by detailed excited-state spectroscopy. $B(E2)$ values

deduced from lifetime measurements in the Pt isotopes^{5,61)} and the Au isotopes⁵³⁾ support this. This results in dramatic changes in ground-state properties at the crossing points where the intruder configuration becomes the ground state. This is shown schematically in fig. 10. In particular, large changes in the mean-square charge radius will occur at the crossing points. This is observed in the odd-mass Hg isotopes²⁾ where a strongly-deformed ground state and weakly-deformed excited state are observed^{2,3,62)} in ^{185}Hg and a weakly-deformed ground state and strongly-deformed excited state are observed^{2,3,63)} in ^{187}Hg .

The present results indicate that this is happening between ^{187}Au and $^{185,186}\text{Au}$. The detailed information^{7,53,60)} on excited states in the neutron-deficient Au isotopes also clearly shows a major change between the ground-state configuration of ^{187}Au and $^{185,186}\text{Au}$. However, the interpretation of patterns of excited states and $B(E2)$ values in terms of deformation is model dependent. The large change in mean-square charge radius, reported here, is the first model-independent evidence that the intruder configuration in the light Au isotopes is strongly deformed.

The present, model-independent, result provides a critical test of models of particle-core coupling. In particular, it can be used to test⁶⁴⁾ interacting boson model descriptions of the Hg⁶⁵⁾ and Pt⁶⁶⁾ cores in this region.

5. Conclusion

The isotope shifts and hyperfine structure of the D_1 -line of neutron-deficient gold isotopes have been measured by application of resonance ionization mass spectroscopy in order to study short-lived isotopes.

The signs of the magnetic moments of $^{188,186,185,189m}\text{Au}$ were determined. Except for ^{187}Au , the values of μ_I obtained in this work agree with the values cited in the literature. The reason for the discrepancy in ^{187}Au is unknown.

Applying the standard two-parameter approach, the ground-state deformation parameters of the gold isotopes with $185 \leq A \leq 189$ and the ^{189m}Au isomer were deduced from the experimental isotope shifts. A shape transition is shown to occur in the light gold isotopes very similar to the one observed for the light mercury isotopes. The ground-state proton configuration of ^{185}Au and ^{186}Au is interpreted as the strongly deformed $\pi 1h_{9/2}$ intruder state. The onset of strong deformation occurs two neutron numbers earlier in gold ($N = 107$) as compared to the neighbouring mercury ($N = 105$) isotopes. In contrast to the Hg isotopes, no pronounced odd-even staggering of the mean square charge radii (or the deformation parameters) is observed in the Au isotopic chain, neither in the weakly-deformed isotopes ($187 \leq A \leq 197$) nor in the strongly-deformed isotopes ($A = 186, 185$). Both facts can be ascribed to the differences in the pairing energies due to the unpaired proton in gold.

Recently, Machias-Marques and coworkers have investigated $^{183}\text{Au}^{67}$ by nuclear spectroscopy. From the low-energy nuclear level scheme of

^{183}Au , they suggest a very similar nuclear structure for ^{183}Au and ^{185}Au . Thus, ^{183}Au is expected to be strongly deformed also.

Due to the dramatically lowered production rate and the shorter halflives, the study of still more neutron-deficient Au isotopes by means of optical spectroscopy requires a method with increased detection efficiency. Encouraging tests have been performed in the meantime²⁴⁾. An increased efficiency was obtained by using a pulsed atomic beam instead of the continuous thermal atomic beam as applied in this work. A pulsed beam was achieved by pulsed laser desorption. A further gain can be expected from excitation to an autoionizing or Rydberg state instead of non-resonant photoionization in the third excitation step.

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Table 1

Properties of lasers used for resonance ionization spectroscopy of gold (SHG: second harmonic generation).

	Type/Dye	Wavelength	Pulse Energy	Pulse Duration	Bandwidth
L1	dye/C540A	535 nm	1 mJ	6 ns	< 200 MHz
	SHG	268 nm	25 μ J	4 ns	< 400 MHz
L2	dye/DPS	407 nm	150 μ J	6 ns	30 GHz
L3	Nd:YAG	532 nm	40 mJ	15 ns	15 GHz

Table 2

Values of the electronic factor F_{268} obtained by different approaches (DF = Dirac-Fock theory, SC = single configuration, MC = multi configuration).

F_{268} [GHz/fm ²]	Type of calculation	Reference
- 45.14	SCDF	A. Rosén et al. ³²⁾
- 43.07	MCDF	A. Rosén et al. ³²⁾
- 41.7	DF	S.A. Ahmad ⁶⁸⁾
- 59.1	semi-empirical	K. Wallmeroth ⁶⁹⁾

Table 3

Absolute transition wave numbers of the hyperfine components, centers of gravity, the deduced isotope shifts and hyperfine constants of the isotopes investigated in the D₁ line.

A	resonance [cm ⁻¹]	Position of cen- ter of gravity [cm ⁻¹]	$\delta\nu_{exp}^{197,A}$ [GHz]	A _{6s} [MHz]	A _{6p} [MHz]
197	37358.9940(12) 37358.7904(12)	37358.8584(28)	-	+3052(23)	*
190	37359.2779(23) 37359.1791(19)	37359.2379(23)	+11.39(16)	-1976(53)	*
189	37360.0132(32) 37359.0588(28) 37358.9512(30)	37359.2702(33)	+12.35(18)	+28632(128)	+3228(127)
188	37359.3612(50) 37359.2641(39)	37359.3222(50)	+13.91(23)	-1940(127)	*
187	37360.1772(32) 37359.1428(46) 37359.0236(44)	37359.3716(48)	+15.40(23)	+31032(168)	+3576(191)
186	37359.5796(69) 37359.4330(45) 37358.1633(53) 37358.0043(44)	37358.8863(28)	+ 0.84(17)	-12207(48)	-1317(48)
185	37360.5538(39) 37360.2696(48) 37358.0355(61) 37357.7525(62)	37358.9672(30)	+ 3.26(18)	+25176(56)	+2838(56)
189m	37363.1089(52) 37362.3727(66) 37356.5758(95) 37355.8584(102)	37359.2372(44) ^{a)} [37359.7199(44) ^{b)}	+11.36(22) +25.85(22) ^{b)}	+32625(42)	+3660(36)

* Due to the small magnetic moment, the hfs of the excited state could not be resolved.

a) Assuming a positive sign of the magnetic moment.

b) Assuming a negative sign of the magnetic moment.

Table 4

Nuclear half lives, spins and magnetic moments of Au isotopes with $A \leq 190$.

A	$T_{1/2}$	I^π	$\mu_I/\mu_N^{\text{this work}^*}$	μ_I/μ_N^{lit}
190	42.8m	1^-	$- 0.068(26)$	$- 0.063^{a,b}$
189	28.3m	$1/2^+$	$+ 0.494(14)$	-
188	8.8m	1^-	$- 0.067(28)$	$\pm 0.069(24)^c$
187	8.0m	$1/2^+$	$+ 0.535(15)$	$+ 0.72 (7)^c$
186	10.7m	3^-	$- 1.263(29)$	$\pm 1.07(13)^d$
185	4.2m	$5/2^-$	$+ 2.170(17)$	$\pm 2.22(14)^d$
189m	4.6m	$11/2^-$	$+ 6.186(20)$	$\pm 6.19(12)^d$

*) According to equation (4). The error accounts for the experimental error as well as the uncertainty in the hyperfine anomaly (for details see text).

^{a)} Ref. 70

^{b)} Ref. 22

^{c)} Ref. 25

^{d)} Ref. 48

Table 5

Isotope shifts and nuclear parameters λ , $\delta\langle r^2 \rangle$, $\delta\langle \beta^2 \rangle$ and $\langle \beta^2 \rangle^{1/2}$ of all gold isotopes investigated optically ($185 \leq A \leq 190$: this work and $191 \leq A \leq 197$: Ref. 22).

A	$\delta\nu^{\text{exp}}$ [GHz]	$\lambda_{197,A}$ [fm ²]	$\delta\langle r^2 \rangle$ [fm ²]	$\delta\langle \beta^2 \rangle$	$\langle \beta^2 \rangle^{1/2}$
197	0.00	0.00	0.000	0.0000	0.11
195	+ 3.05(22)	-0.072(6)	-0.076(6)	0.0025(5)	0.121
193	+ 6.29(11)	-0.148(4)	-0.157(4)	0.0046(3)	0.129
192	+ 8.32(15)	-0.195(5)	-0.208(5)	0.0047(4)	0.130
191	+ 9.67(12)	-0.227(5)	-0.242(5)	0.0063(4)	0.136
190	+11.39(16)	-0.267(6)	-0.285(6)	0.0071(6)	0.139
189	+12.35(18)	-0.290(7)	-0.309(7)	0.0096(6)	0.147
188	+13.91(23)	-0.327(8)	-0.347(9)	0.0108(8)	0.151
187	+15.40(23)	-0.362(9)	-0.385(9)	0.0121(8)	0.155
186	+ 0.84(17)	-0.025(8)	-0.014(8)	0.0482(7)	0.246
185	+ 3.26(18)	-0.081(8)	-0.075(9)	0.0475(8)	0.244
189m	+11.36(22)	-0.267(8)	-0.283(9)	0.0117(7)	0.154 ^{a)}
	[+25.85(22)]	-0.603(9)	-0.652(9)] ^{b)}	-	-

a) Assuming a positive sign of the magnetic moment.

b) Assuming a negative sign of the magnetic moment.

FIGURE CAPTIONS

- Fig. 1 Atomic level scheme of gold. The transitions used for RIMS are indicated by thick lines.
- Fig. 2 Experimental set-up for on-line resonance ionization mass spectroscopy (RIMS) of short-lived Au isotopes.
- Fig. 3 On-line RIMS spectrometer for the investigation of short-lived Au isotopes.
- Fig. 4 The oven and acceleration region of the RIMS spectrometer. The laser beams are directed perpendicularly to the plane of the drawing.
- Fig. 5 Simultaneously recorded spectra of (top to bottom): (i) the resonance fluorescence signal of the reference atomic beam (^{197}Au) (ii) the RIMS-spectrometer (^{186}Au ; analog data acquisition) (iii) the RIMS-spectrometer (^{186}Au ; digital data acquisition) (iv) absorption of molecular (^{127}I)₂ as a function of frequency of the laser used for the first excitation step.
- Fig. 6 Time-of-flight spectrum of ^{186}Au . ^{197}Au was added as a mass marker. The spectrum shown was recorded simultaneously to the spectra shown in Fig. 5.
- Fig. 7 Resonance ionization signals of the Au isotopes versus the frequency of the laser used for the first excitation step. The iodine absorption lines serve as frequency scale (top).
- Fig. 8 Changes of mean-square charge radii of Au (circles, right-hand scale: this work and from ref. 22) and Hg (squares, left-hand scale: Ref. 2).
- Fig. 9 Deformation parameters of the Hg (squares: Ref. 2) and Au (circles: this work and ref. 22) isotopes as calculated from isotope shift data.
- Fig. 10 Schematic model where an almost spherical ground state (dashed line) and a deformed intruder state (full line) cross. Fig. 10a shows the corresponding energies and Fig. 10b shows the corresponding isotopic shifts.

LASER SYSTEM AND FREQUENCY CALIBRATION

88 340

Fig. 2

88 341

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10