*Spins, Moments and Mean Square Charge Radii
of $^{104} - ^{127}\text{In}$ Determined by
Laser Spectroscopy⁺*

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Abstract: Hyperfine structures and isotope shifts of indium isotopes in the mass range 104 - 127 have been measured in the atomic transitions $5p\ ^2P_{1/2} - 6s\ ^2S_{1/2}$ (410 nm) and $5p\ ^2P_{3/2} - 6s\ ^2S_{1/2}$ (451 nm) by collinear fast-beam laser spectroscopy. Nuclear magnetic dipole and electric quadrupole moments have been determined for 37 ground and isomeric states. The magnetic moments in the sequence of the $\frac{1}{2}^-$ isomers are found to cross the Schmidt limit. Magnetic dipole and electric quadrupole moments of the odd-odd isotopes are compared to values obtained by additivity rules. The 8^- isomers exhibit a strong change in the coupling of the $h_{11/2}$ neutrons to the collective motion. The mean square charge radii show a parabolic behaviour with a maximum in the middle of the neutron shell at $N = 66$. This is interpreted by collective effects, which are considerably stronger than seen in the quadrupole moments or in the $B(E2)$ -values of neighbouring doubly-even nuclides.

⁺ This work comprises parts of the theses of U. Dinger and J. Eberz.

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List of Keywords

Nuclear Structure $^{104-127}\text{In}$; measured hfs, hyperfine constants $A(5p\ ^2P_{1/2})$, $A(5p\ ^2P_{3/2})$, $A(6s\ ^2S_{1/2})$, $B(5p\ ^2P_{3/2})$, spins, isotope shifts; deduced magnetic dipole moments, electric quadrupole moments, mean square charge radii, deformation β . Collinear fast-beam laser spectroscopy.

1. INTRODUCTION

More than 50 years ago, Schüller and Schmidt¹⁾ reported their finding of irregularities in the hyperfine structure (hfs) of atomic optical spectra, for instance in the case of ^{115}In and related them to the electric quadrupole moment of the nucleus. Since the last decade, owing to the Doppler-free spectroscopy with tunable cw dye lasers, these minute effects can be exploited for systematic studies of the nuclear structure even of short-lived nuclides produced in very small amounts^{2,3)}. In particular, on-line mass separators for the preparation of radioactive beams from fusion (GSI), spallation or fission (ISOLDE) reactions, combined with the sensitive method of collinear laser spectroscopy⁴⁾, allow the measurement of the hfs and isotope shift (IS) of isotopes far from stability.

Earlier measurements on $^{105-111}\text{In}$ were performed at the GSI on-line mass separator^{5,6,18)}. We report here results of the collinear laser spectroscopy on the neutron rich isotopes $^{111-127}\text{In}$ at the ISOLDE facility at CERN and an additional measurement on ^{104}In at the GSI on-line mass separator. The combined results are discussed and lead to an almost complete coverage of the isotopes between the magic neutron numbers $N = 50$ and $N = 82$, which will certainly contribute to a better understanding of the nuclear structure in this middle mass region.

Indium, with $Z = 49$, one proton below the strong magic number $Z = 50$, should exhibit only small deformation effects. This may reveal details of nuclear moments and radii, which are within the scope of a nearly spherical shell-model description. Furthermore, the ground and long lived isomeric states offer the possibility to follow different single-proton moments over long chains of neutron numbers. The mean square charge radii

and the nuclear moments extracted from the odd-odd isotopes can be compared with results on the cadmium isotopes, obtained by Doppler-limited laser spectroscopy^{7,8)} and on stable and radioactive tin isotopes at the proton shell closure at $Z = 50$ ^{9,10)}.

2. EXPERIMENTAL PROCEDURE

The experiments were performed

- a.) at the ISOLDE facility¹¹⁾ at CERN using mass-separated products of fission reactions induced by 600 MeV protons in a uranium carbide cloth target (15 g/cm^2 of uranium), irradiated with proton intensities up to $2.2 \text{ }\mu\text{A}$. The reaction products, diffusing out of the hot target container are surface-ionized in a tungsten tube heated to 2400°C . The ions are extracted to form a 60 keV beam, and after mass separation they are directed to the set-up for collinear fast-beam laser spectroscopy. The yields of the neutron-rich indium isotopes, determined by laser fluorescence spectroscopy and calibrated in a few cases with beam current measurements, are shown in Figure 1, together with the GSI yields, for the whole indium chain. The results for the neutron rich indium isotopes are comparable to former measurements of these yields by nuclear spectroscopy^{12,13)}.
- b.) At the GSI on-line mass separator¹⁴⁾ the neutron-deficient isotopes and in particular ^{104}In were produced via $(^{16}\text{O}, \text{pxn})$ fusion reactions with $^{92-100}\text{Mo}$ targets of about 30 mg/cm^2 isotopically enriched molybdenum foils placed in a plasma ion source of the FEBIAD-B2 type

with yielding between $3 \cdot 10^5$ and about $3 \cdot 10^7$ ions/sec (see Figure 1).

Here, the production rates and the separation efficiencies were measured by means of γ -spectroscopy¹⁵⁾ as well.

The collinear fast-beam set-ups, used at GSI⁵⁾ and at ISOLDE¹⁶⁾, are identical in principle. The mass-separated ion beam is merged with a laser beam using electrostatic deflection. This beam is neutralized in a sodium charge-exchange cell put at a variable potential for Doppler-tuning of the optical resonance with fixed laser frequency. The fluorescence light is detected with the photon-counting technique. A mini-computer is connected to the experiment by a CAMAC interface controlling the Doppler-tuning, the sequential measurement on different isotopes and the data taking.

The measurements were performed in the two transitions $5p \ ^2P_{1/2} \rightarrow 6s \ ^2S_{1/2}$ at 410 nm and $5p \ ^2P_{3/2} \rightarrow 6s \ ^2S_{1/2}$ at 451 nm by use of frequency stabilized cw dye lasers with the dyes stilbene 1 and stilbene 3, pumped by a UV argon ion laser. The access to both transitions is given by the simultaneous population of the atomic ground state doublet in the charge exchange process. The lifetime of the excited state is 7.2 ns¹⁷⁾, corresponding to a natural line width of 22 MHz. The experimental width of about 60 MHz contains the residual Doppler width from the ion source including a small additional energy spread from the charge-transfer process, the effects of beam divergence and some power broadening.

All spectra were measured in a multiscaling mode alternating between the radioactive and the stable reference isotope ^{115}In . Examples of the measured spectra are given in Fig. 2 for ^{117}In (together with the $I = \frac{1}{2}$ isomeric state of $^{117,121,125}\text{In}$) and in Fig. 3 for ^{122}In . The spectra of the $I = 1$ states in a few of the doubly-odd isotopes were incomplete and could not be included in the data analysis.

3. RESULTS

The peak positions of all observed hfs components were determined with an accuracy corresponding to typically 5-20 MHz, depending mainly on the statistics of the spectra and the systematic error of the voltage calibration which determines the frequency scale. These positions were fitted with the hfs formula describing them in terms of the nuclear spin I , the ground and excited state magnetic dipole interaction constants A_g and A_e , the quadrupole interaction constant B_g (in the case of the 451 nm transition) and the centre of gravity, which displays the IS. The resulting hfs constants and the IS are listed in Table 1, together with the spin values, either taken from this analysis or taken from the literature. Details of these spin measurements and assignments are given in section 3.1. For reasons of completeness we have included in Table 1 all data measured on indium isotopes by collinear fast-beam laser spectroscopy, in particular the data from GSI published earlier^{5,6,18}).

In ^{104}In we observed only the three strongest hfs components because of the low production. Therefore we used a fixed ratio of A_g to A_e to evaluate the hfs and the IS. A few resonances in the other spectra were displaced by accidental nonlinearities in the scanning voltage. Since the system of peak positions from idfferent measurements is highly overdetermined, such resonances could be identified and excluded from the data evaluation. Possible uncertainties of this procedure are accounted for by the errors in the Tables 1 and 2.

The nuclear magnetic dipole moments μ were evaluated from the hyperfine constants $A(6s\ ^2S_{1/2})$ using as reference the known value $\mu = 5.5408(2)$ n.m. (corrected for diamagnetism)¹⁹) together with accurately measured

A - factors for the stable ^{115}In ²⁰⁻²³). The errors do not account for possible effects of the hfs anomaly. This is justified, because the ratio between the A - factors of the ground and excited states is constant for all isotopes. The magnetic moments are given in column 3 of Table 2 and are displayed in Figure 4 for the odd-even and in Figure 5 for the odd-odd isotopes.

The spectroscopic quadrupole moments Q_s were deduced from the measured $B(5p\ ^2P_{3/2})$ factor by comparison to the value of ^{115}In , for which a Sternheimer corrected quadrupole moment of $Q_s = 0.81$ barn is used as discussed elsewhere⁵). Possible systematic uncertainties of this procedure are not included in the errors of the moments listed in Table 2, column 6 and displayed in Fig. 6.

3.1 NUCLEAR SPINS

The spins of all low-spin states ($I \leq 3$) follow directly from the consistent analysis of the hfs in the $^2S_{1/2}$, $^2P_{1/2}$ and $^2P_{3/2}$ states including their centres of gravity in the comparison of the two transitions (cf. King plot procedure described in section 3.4). Thus all odd-even low-spin isomers have $I = 1/2$ from the $\pi(p_{1/2})$ configuration, in accordance with nuclear spectroscopy results. For the ground states we adopt the general assumption of $I = 9/2$ from $\pi(g_{9/2})^{-1}$ which is supported by the corresponding magnetic moments (cf. section 3.2). The spins of the doubly-odd isotopes arise from a number of different configurations. In ^{104}In our analysis of the hfs, in combination with the semi-empirical coupling rules

for the moments (cf. section 3.3), yields $I = 5$ in agreement with a nuclear spectroscopy assignment²⁴). It would also be consistent with $I = 6$, but excludes $I = 3, 4$, which have been discussed in the literature^{25,26}). For $^{106,108,110}\text{In}$ we adopt the spin $I = 7$ as given in ref.^{5,6}) and the references therein. The spin of $^{108\text{m}}\text{In}$ ¹⁸) is directly determined to be $I = 2$. The spins $I = 4$ for ^{112}In [ref.²⁷)] and $I = 5$ for ^{114}In [ref.²⁸)], ^{116}In [ref.^{28,29})] and ^{118}In [ref.³⁰)] have been determined by ABMR. For the neutron-rich isotopes $^{120-126}\text{In}$ only spin assignments from nuclear spectroscopy are given in the literature. We adopt $I = 5$ for ^{120}In and ^{122}In in accordance with the semi-empirical analysis of the moments, while the earlier proposed values leave the choice between $I = 4$ and 5 for ^{120}In [ref.^{31,32})] and ^{122}In [ref.^{33,34})]. For $^{124,126}\text{In}$ Fogelberg and Carlé³⁴) assign $I = 3$ which is confirmed unambiguously by our hfs analysis. For the high-spin isomeric states of $^{116-126}\text{In}$ a spin assignment of $I = 7$ to $I = 9$ is consistent with our analysis. According to ref.³⁴) we choose $I = 8$ and make the evaluation of the hfs and the IS under this assumption.

3.2 MOMENTS OF THE ODD-EVEN INDIUM ISOTOPES

The magnetic dipole moments of the $I = 9/2$ ground states of the odd-even isotopes are nearly constant, $\mu \approx 5.5 \text{ nm}$, in the whole chain of $^{105-127}\text{In}$. This obviously reflects the stabilisation of the nearly closed proton shell, reducing the effect of neutron core polarisation. Among the many theoretical investigations of the moments in the indium region we refer to the recent ones by Heyde et al. and others³⁵⁻³⁹), using a hole plus

vibrating core model. Results of these calculations are listed in column 5 of Table 2 for most of the isotopes^{40,41}). They are based on the choice of $g_s = 0.5 g_{s,free}$ and $g_R = Z/A$ and reproduce well the ground state moments of the odd-even isotopes $^{107-123}\text{In}$ for which the calculations have been made.

The electric quadrupole moments of the $I = 9/2$ states are constant, $Q_s \approx 0.8$ barn, within the range $^{105-121}\text{In}$ and decrease gradually to 0.6 barn for ^{127}In . The hole plus vibrating core calculations for $^{107-123}\text{In}$ ⁴¹) yield an almost constant value $Q_s \approx 0.7$ barn. This will be discussed under the aspect of deformation in connection with the isotope shifts.

In contrast to the constant moments of the $I^\pi = 9/2^+$ ground states, the $I^\pi = 1/2^-$ isomeric states exhibit a surprising isotopic variation of the magnetic moments. They cross the $\pi(p_{1/2})$ Schmidt limit, $\mu_s = -0.263$ n.m., at $A = 117$ and finally reach $\mu = -0.433$ n.m. at $A = 125$, 1.7 times the Schmidt value. It is well known from the shell model description that the $p_{1/2}$ moments are insensitive to first-order core polarisation⁴²), which justifies the choice of $g_s = g_{s,free}$. With this choice the hole plus vibrating core model predicts a constant negative moment close to the Schmidt value, $\mu = -0.27$ n.m., independent of the neutron number. (The assumption $g_s = 0.5 g_{s,free}$ would lead to a small positive moment $\mu = 0.20$ n.m.). The observed trend would imply a substantial change in the admixture of the $[|p_{3/2} \otimes |2^+\rangle]_{I=1/2}$ configuration which has a negative magnetic moment of $\mu = -0.85$ n.m. for $g_R = Z/A$. However, such a variation in core excitation should be valid for the $I^\pi = 9/2^+$ states, too, and would result in substantial changes in μ . Another explanation could be connected with a change in deformation of the isomeric $1/2^-$ state. In this context we refer to an angular correlation measurement on a $3/2^-$ state of ^{117}In ⁴³), yielding $\mu_I = 0.102(59)$ n.m., far away from the

Schmidt value of $\mu_s = 3.8$ n.m., which is interpreted by assuming a rotational $3/2^-$ state built on the [301] $1/2^-$ Nilsson state. Within this picture the deformation dependence of the $1/2^-$ moment can be calculated by using formula [26] of ref.⁴⁴⁾, which gives no significant changes for β values between -0.3 and +0.3. Only for high-lying $1/2^-$ states a mixing of deformed Nilsson wavefunctions could reproduce a deformation dependent variation of the magnetic moment for β between 0.20 and 0.15⁴¹⁾. Such a change in deformation cannot be excluded by the analysis of the isotope shifts as discussed later on.

Still, the unusual magnetic moments of the $I = 1/2$ isomeric states represent an unresolved puzzle and may require a reconsideration of the overall nuclear structure of these isotopes.

3.3. MOMENTS OF THE DOUBLY ODD INDIUM ISOTOPES

The ground and isomeric states of the odd-odd isotopes are built from the $\pi(g_{9/2})^{-1}$ proton hole state found in the adjacent odd-even In isotopes and several neutron states in the adjacent isotones of Cd and Sn, namely $\nu(d_{5/2})$, $\nu(g_{7/2})$, $\nu(s_{1/2})$, $\nu(d_{3/2})$ and $\nu(h_{11/2})$.

The well-known additivity rule for magnetic moments is able to predict the magnetic moments of odd-odd nuclei from the moments of the neighbouring isotones and isotopes with angular moments and g - factors j_p , g_p and j_n , g_n , according to the vector coupling relation⁴⁵⁾

$$\mu_I = \frac{I}{2} \left[g_p + g_n + (g_p - g_n) \cdot \frac{j_p(j_p+1) - j_n(j_n+1)}{I(I+1)} \right] \quad (1)$$

The resulting 'empirical' moments are listed in column 4 of Table 2. Wherever possible, we have used average values from the neighbouring isotopes and the isotones in Sn and Cd. In a few cases, we had to use the moments of other nuclides with the same configuration. The configurations involved are discussed in ref.^{5,6,46-52)} for $^{106-114}\text{In}$ and in ref.³⁴⁾ for $^{116-126}\text{In}$. The lightest doubly-odd isotopes contain an unpaired $d_{5/2}$ neutron yielding $I = 5$ (or 6) for ^{104}In , $I = 7$ for $^{106,108,110}\text{In}$ and $I = 2$ for ^{108m}In . Their magnetic moments agree within 3-5 % with the semi-empirical moments according to (1). A neutron configuration $s_{1/2}$ is involved in ^{112}In with $I = 4$ and $^{114-122}\text{In}$ with $I = 5$. The ^{115}Sn neutron moment gives a value which is very close to the magnetic moment of ^{114}In . The other moments are reproduced within less than 12 %. The $I = 3$ states in $^{124,126}\text{In}$ involve a $d_{3/2}$ neutron, and the experimental moments are about 10 % below the semi-empirical ones based on ^{121}Sn . The comparison of the experimental and semi-empirical nuclear moments is shown in Fig. 5.

A particularly interesting situation is found in the sequence of the $I = 8$ isomers in $^{116-126}\text{In}$ where a $h_{11/2}$ neutron couples to the $g_{9/2}$ proton hole. The experimental moments increase gradually from $\mu = 3.2$ n.m. for ^{116}In to $\mu = 4.1$ n.m. for ^{126}In , whereas the semi-empirical values using the neutron moments of $^{117-125}\text{Sn}$ remain constant at $\mu = 3.0$ n.m.. For ^{116}In the neutron moment of the isotone cadmium leads to a better agreement with the experimental value. However, the corresponding moments of the more neutron-rich Cd isotopes are unknown. Therefore, it cannot be excluded that the observed variation with neutron number reflects a change in the core polarization of the neutron moment which should be visible in

Cd ($Z = 48$) rather than in Sn ($Z = 50$). On the other hand, an analogous change in the spectroscopic quadrupole moments for the $I = 8$ isomeric states has to be associated with rotational alignment, as discussed below. The additivity rule for magnetic moments is just the simplest case of a general tensor coupling scheme which is given e.g. by Bohr and Mottelson⁵³). Its specialisation for the spectroscopic quadrupole moments Q_s has been discussed repeatedly^{54,55,56}) and can be represented as follows¹

$$Q_s = q_p Q_s(j_p) + q_n Q_s(j_n) \quad (2)$$

with the spectroscopic quadrupole moments $Q_s(j_p), Q_s(j_n)$ of the single-particle proton or neutron states with angular momenta j_p and j_n , and

$$q_i = (-1)^{j_p+j_n+I} \cdot (2I+1) \left\{ \begin{matrix} j_p & j_n & I \\ a & b & j_i \end{matrix} \right\} \frac{\begin{pmatrix} I & I & 2 \\ I & -I & 0 \end{pmatrix}}{\begin{pmatrix} j_i & j_i & 2 \\ j_i & -j_i & 0 \end{pmatrix}}$$

with $i = p$ or n and

$$a; b = I; 2 \text{ for } j_i = j_p,$$

$$a; b = 2; I \text{ for } j_i = j_n.$$

Calculations using this quadrupole coupling rule are based on the same configurations as for the magnetic moments and the results are given in Table 2, column 7. Except for $I = 8$, they show very good agreement with the experimental quadrupole moments. It should be noted that this agreement is extremely sensitive to the spin assignments and the choice of the

¹ This formula is equivalent to the one given by Blin Stoye⁴⁵).

involved single-particle states j_p and j_n . Therefore, we have used it together with the coupling rule for magnetic moments to assign a few spins which remained ambiguous from the pure hfs analysis: In ^{104}In the tentative spin assignments $I = 3, 4, 5, 6$ and the neutron configurations $d_{5/2}$ and $g_{7/2}$ favour the choice $I = 5$ (or 6) with a configuration $[\pi(1g_{9/2})^{-1} \nu(d_{5/2})]_{I=5}$, which gives $Q_{s, \text{emp.}}$ and $\mu_{\text{emp.}}$ in agreement with the experimental data.

For the $I = 4$ and $I = 5$ isomeric states in the mass range 112-122 good agreement is achieved with the configuration $[\pi(1g_{9/2})^{-1} \nu(1s_{1/2})]_{4,5}$ (see values in Table 2), rather than the configuration $[\pi(1g_{9/2})^{-1} \nu(2d_{3/2})]_{4,5}$, which misfits quadrupole coupling rule. For $^{124,126}\text{In}$ the configuration $[\pi(1g_{9/2})^{-1} \nu(2d_{3/2})]_{I=3}$ with the spin $I = 3$ again reproduces the experimental quadrupole moment.

Only the quadrupole moments of the $I = 8$ isomers with a configuration $[\pi(1g_{9/2}) \nu(1h_{11/2})]_{I=8}$ show rather poor agreement with the experimental results, similarly to the magnetic moments. A singular agreement for Q_s is obtained for $^{112}\text{In}^{54}$, with a mean neutron contribution from ^{111}Cd and ^{113}Sn . For the heavier isotopes $^{116-126}\text{In}$ we have to calculate the empirical moments by using the experimental Sn values except for ^{116}In , where a mean value from ^{115}Cd and ^{117}Sn is available. Again, the discrepancy between experimental and semi-empirical values may be sought in the underestimation of core-polarization effects by using the Sn moments. Still, the semi-empirical quadrupole moments reproduce the smooth change from small negative to positive values, which is more pronounced in the experimental results. The variation cannot be associated with a change in deformation, since the very small isomeric shifts (see section 3.4) indicate a deformation independent of the spin states. The obvious explanation is a change in the projection of the intrinsic quadrupole moment Q_0 on the

spin axis as first observed for the $\nu(i_{13/2})$ Hg isomers⁵⁷). In the $h_{11/2}$ neutron shell similar effects have been discussed for the light Cd isotopes⁵⁸) indicating a transition from rotation aligned to strong coupling when the $h_{11/2}$ shell is filled^{59,60}). These effects are correspondingly expected for indium. Assuming that the quadrupole coupling relation remains valid, we can use (2) to extract semi-empirical quadrupole moments for the $h_{11/2}$ neutron state from the experimental quadrupole moments of the odd-odd isotopes. In Fig. 6 we compare them with the $h_{11/2}$ moments in the neighbouring elements. Rotational alignment should occur for the nearly empty $h_{11/2}$ shell at a deformation of about $\beta \approx 0.2$ ⁶⁰). The general projection formula for quadrupole moments reads

$$Q_s = \frac{3 \sum [d_{\alpha=j, \Omega}^j(\pi/2)]^2 - I(I+1)}{(I+1)(2I+3)} Q_0 . \quad (3)$$

For rotational alignment the average spin component Ω is minimum, corresponding to a negative projection factor $Q_s = -0.3 Q_0$, whereas the strong coupling limit $\Omega = I$, or

$$Q_s = \frac{I(2I-1)}{(I+1)(2I+3)} Q_0 \quad (4)$$

gives a positive projection $Q_s = 0.6 Q_0$ for the $h_{11/2}$ configuration. Provided that Q_0 remains positive, this leads to a transition from negative to positive Q_s as the neutron shell is filled. This trend is reproduced by our semi-empirical moments and agrees qualitatively with the Coriolis coupling calculations performed by Ekström⁵⁸).

The asymptotic approach to the strong-coupling limit gives an intrinsic quadrupole moment of $Q_0 \sim 1.2$ barn. It is remarkable that the quadrupole moments of all other spin states exhibit the same intrinsic moment by use

of the strong coupling formula (4). This supports the procedure to extract a deformation parameter $\langle \beta_2 \rangle$ from

$$\langle \beta_2 \rangle = Q_0 \frac{\sqrt{5\pi}}{4 Z r_0^2 A^{2/3}} \quad (5)$$

with $r_0 = 1.2$ fm and Q_0 calculated from Q_s with (4) in the strong coupling limit. This deformation parameter will be compared with the deformation observed in isotope shifts (cf. section 3.4).

3.4 CHANGE OF THE MEAN SQUARE NUCLEAR CHARGE RADIUS

The observed IS (Table 1) is the sum of the normal mass shift (NMS), the specific mass shift (SMS) and the field shift depending on the change of the mean square nuclear charge radius $\delta \langle r^2 \rangle^{A,A'}$ between the isotopes A and A'^{61}). Disregarding higher-order contributions in $\langle r^{2n} \rangle$ of less than 4 %⁶²), we can write

$$IS^{A,A'} = NMS^{A,A'} + SMS^{A,A'} + F \delta \langle r^2 \rangle^{A,A'} \quad (6)$$

The electronic factor F has been determined by a number of different procedures. Aufmuth⁶³) obtained the non-relativistic electron densities from Hartree-Fock (HF) calculations and included the relativistic and finite nuclear size effects according to Bodmer⁶⁴) or Blundell et al.⁶⁵) with almost identical results. The mass dependence of F⁶⁵) along the investigated indium chain is less than 1 % and can be neglected. Relativistic Dirac-Fock (DF) calculations by Fricke⁶⁶) give quantitatively the same result as the corrected non-relativistic calculations. The semi-empiri-

cal Goudsmit-Fermi-Segré formula for the $5s^2 6s$ configuration gives a value 1.5 times the HF and DF results. This discrepancy has to be related to a unusual screening in the $5s^2 6s$ configuration which leads to the large screening factor $\beta = 4.8$ for the $5p \rightarrow 6s$ transition⁶⁷⁾.

Here, the experimental isotope shifts have been analyzed with the Dirac-Fock electronic factor $F = 2.070(10)$ GHz/fm² including a 5 % calibration uncertainty in $\delta\langle r^2 \rangle$. The specific mass shift cannot be calculated with a reasonable accuracy. Therefore, the SMS is calibrated with an independent value of $\delta\langle r^2 \rangle^{113,115} = 0.128(8)$ fm². This independent value is an average of $\delta\langle r^2 \rangle$ for the isotonic pairs in Sn¹⁰), $\delta\langle r^2 \rangle^{114,116}\text{Sn} = 0.136$ fm² determined from K_α x ray shifts, and in Cd⁸), $\delta\langle r^2 \rangle^{112,114}\text{Cd} = 0.121$ fm² taken from the analysis of the optical data. This choice is extensively discussed in ref.⁵⁾. One obtains from this procedure for the specific mass shift in the 410 nm transition $\text{SME}^{A,A'} = (-1.10 \pm 0.20) \cdot \text{NME}^{A,A'}$ and in the $\lambda = 451$ nm transition $\text{SME}^{A,A'} = (-1.17 \pm 0.20) \cdot \text{NME}^{A,A'}$. A King plot yields the experimental ratio of the field shift factors $F(410 \text{ nm})/F(451 \text{ nm}) = 0.996(37)$, while the DF calculations result in a ratio of 1.0.

The $\delta\langle r^2 \rangle$ values are compiled in Table 2. In the first bracket we quote only the experimental errors. In the second bracket we include the uncertainty due to the errors of F and SME as given above.

The change of the mean square charge radius of the In isotopes is shown in Figure 7. The isomer shifts, which are almost zero within the limits of our errors are omitted for reasons of clarity. The data cover the neutron numbers from $N = 55$ to $N = 78$ between the major shell closures $N = 50$ and $N = 82$ and show a smooth variation with N except for the regular odd-even staggering. This smooth curve can be fitted with a polynom of second order, as has been suggested by Talmi⁶⁸⁾ for elements with a closed proton

shell and in particular for the $1f_{7/2}$ neutron shell by Wohlfahrt et al⁶⁹⁾. This polynomial is symmetric around midshell ($N = 66$). Except for the linear and a quadratic term in $(N-66)$, the parabolic fit shown in Figure 7 contains an odd-even term⁷⁰⁾ similar to the one of Talmi⁶⁸⁾ and Zamick⁷¹⁾, written as

$$\begin{aligned}\delta\langle r^2 \rangle^{66,N} &= \delta\langle r^2 \rangle_{\text{sph.}} + \delta\langle r^2 \rangle_{\text{quad.}} \\ &= a(N - 66) + b(N - 66)^2 + 1/2 c(1 - (-1)^N) \quad . \quad (7)\end{aligned}$$

The fit parameters are $a = 0.060(1) \text{ fm}^2$, $b = -1.47(13) \cdot 10^{-3} \text{ fm}^2$ and $c = -0.015(4) \text{ fm}^2$. Such a parabolic feature has been discussed for the neighbouring chains of $\text{Sn}^{10)}$ and $\text{Cd}^8)$ isotopes. The curvature is less pronounced at $Z = 50$ and stronger in Cd with two protons less than the closed shell. The linear term coincides within 10 % with $a = 0.055 \text{ fm}^2$ from the spherical droplet model⁷²⁾. The quadratic term in $\delta\langle r^2 \rangle$ can be explained as a quadrupole contribution in a core polarization model⁶⁸⁾, including the well-known odd-even staggering and has been compared with experiment in the cases of $\text{Ca}^{73)}$ and $\text{Pb}^{74)}$. This quadrupole contribution in $\delta\langle r^2 \rangle$ is a function of the occupation number n in the major shell j given in ref.⁶⁸⁾ to

$$\delta\langle r^2 \rangle_{\text{quad.}} \approx f \left[n(2j+1-n) - \frac{1 - (-1)^n}{2} (j+1/2) \right] \quad (8)$$

where the factor f describes the reduced matrix element of the quadrupole operator. The bilinear term is proportional to the number of particles times the number of holes in the shell and the second term accounts for

the odd-even staggering. Both are completely reproduced in our parabolic fit. The equivalence of (7) and (8) becomes evident when (7) is rewritten with reference to $N = 50$ and $N = 82$,

$$\delta \langle r^2 \rangle_{50, N} = a(N - 50) + b(N - 50)(N - 82) + 1/2 c (1 - (-1)^N) \quad (9)$$

With the generalized occupation number $n = N - 50$ for the configurations between $N = 50$ and $N = 82$, the bilinear and odd-even terms coincide with (7). This means that the quadrupole contributions become zero at shell closure. The valence space of the major shell is symmetrical in particles and holes and gives a maximum contribution at midshell. We want to extend the interpretation of this core polarization model to a direct geometrical picture as given by the 'two-parameter' formula,

$$\delta \langle r^2 \rangle_{A, A'} = \delta \langle r^2 \rangle_{\text{sph.}}^{A, A'} + \langle r^2 \rangle_{\text{sph.}}^{\bar{A}} \left[\frac{5}{4\pi} \delta(\Sigma \beta_i^2) \right], \quad \bar{A} = (A + A')/2. \quad (10)$$

which also contains a nearly linear term in N , namely the spherical contribution, $\delta \langle r^2 \rangle_{\text{sph.}}^{A, A'}$ and a deformation term which contains all contributions of dynamic and static deviations from sphericity. Therefore, we identify the linear and quadratic term in (7) with the spherical and deformation terms of (10) where $\langle r^2 \rangle_{\text{sph.}}^{\bar{A}}$ and $\delta \langle r^2 \rangle_{\text{sph.}}^{A, A'}$ are usually taken from the droplet model⁷²⁾ and the term $\Sigma \beta_i^2$ describes all surface correlation effects which reduce in many cases to the quadrupole term.

3.5 DEFORMATION OF THE IN ISOTOPES

Since the linear term in the parabolic fit (7) agrees within 10 % with the spherical droplet model, we can analyse our data on this basis and set $\Sigma\langle\beta_1^2\rangle = 0$ for $N = 50$ and $N = 82$ in accordance with the core polarization model. The deformation values extracted from the experimental data are then given by

$$\Sigma\langle\beta_1^2\rangle^N = [5/(4\pi)\langle r^2\rangle_{\text{sph.}}^N]^{-1} [-\delta\langle r^2\rangle_{\text{exp.}}^{66,N} + a(N-66) + b(66-50)(66-82)] \quad (11)$$

and are shown in Fig. 8. These values are compared with $\langle\beta_2\rangle$ from the intrinsic quadrupole moments discussed in chapter 3.3. The static deformation exhausts only part of the total deformation and has a rather constant value decreasing in one step to ^{104}In and more gradually towards ^{127}In . Otherwise, $\langle\beta\rangle$ and $\langle\Sigma\beta_1^2\rangle^{1/2}$ differ in size and trend. It is evident that the dynamical plus static deformation $(\Sigma\langle\beta_1^2\rangle)^{1/2}$ always exceeds $\langle\beta\rangle$, and close to the magic numbers the collective zero point motion may not be restricted to the quadrupole mode only. A considerable dynamic octupole contribution has been discussed for Ca^{73}) and in a more general form by Reinhard and Drechsel⁷⁵⁾.

Another explanation is based on a extra variation of the surface thickness. A variable skin thickness has been used by Friedrich and Voegler⁷⁶⁾ for interpreting electron scattering experiments. However, their skin-thickness parameter also includes the radial average of any possible multipole deformation which we have accounted for by the expression $\Sigma\langle\beta_1^2\rangle$. The effects of deformation on skin-thickness are included in a

semi-empirical model² by Wesolowski⁷⁷) on the basis of parametrized deformations given by Jaenecke⁷⁸). The results of this are shown in Figure 7. For ¹¹⁵In Jaenecke gives a $\langle\beta\rangle \sim 0.12$ in agreement with our value from Q_s . All the difference to $(\Sigma\langle\beta_i^2\rangle)^{1/2}$ in Figure 8 is phrased as a change in surface thickness in ref.⁷⁷). The real nature of the difference between isotope shift and static quadrupole deformation cannot be elucidated without more detailed investigations.

4. SUMMARY AND CONCLUSION

The nuclear spin I , the magnetic dipole moment μ , the electric quadrupole moment Q_s and the change in mean square charge radius $\delta\langle r^2 \rangle$ could be determined in 37 ground and isomeric states of the indium isotopes.

Prominent features and results are :

- (i) The ground states of the odd-A isotopes are described by a $g_{9/2}$ shell-model proton state in ¹⁰⁵⁻¹²⁷In. *Indium* is now the longest chain for which the nuclear moments of isotopes with essentially identical shell model proton states have been measured.
- (ii) The magnetic moments of the $I = 1/2$ isomeric states cross the Schmidt value in going from ¹¹³In to ¹²⁵In. Several attempts to understand this behaviour have not yet been conclusive.

² E. Wesolowski has corrected his equations [16] and [17] of his work⁷⁷) according to $\Delta N = 1/N \dots$ [16] and $\dots + 1/A^{1/3} (\delta_p + \delta_n)$ [17].

- (iii) Spins of low spin states ($I \leq 3$) of odd-odd In isomers were determined unambiguously via a King-plot procedure. They are confirmed by the additivity relations for magnetic dipole and electric quadrupole moments in the framework of a single-particle description. These relations have also been used for the spin assignments $I > 3$.
- (iv) High spin $I = 8$ isomers, built from the $g_{9/2}$ proton and the $h_{11/2}$ neutron configuration, show a behaviour in moments and charge radii indicating a change from rotation aligned to strong coupling.
- (v) $\delta\langle r^2 \rangle$ exhibits a parabolic curvature which peaks around midshell at $N = 66$ between the major shell closures $N = 50$ and $N = 82$. This is interpreted as an effect of surface correlations which are substantially stronger than the deformation evaluated from the quadrupole moments.

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TABLE CAPTIONS

Table 1 Nuclear spins, hfs constants and isotope shifts evaluated from the measurements in the 410 nm ($5p\ ^2P_{1/2} \rightarrow 6s\ ^2S_{1/2}$) and 451 nm ($5p\ ^2P_{3/2} \rightarrow 6s\ ^2S_{1/2}$) lines of In I. A different spin assignment for ^{104}In would also lead to slightly different A and B factors.

Table 2 Nuclear spins, magnetic dipole moments, electric quadrupole moments and differences in mean square charge radii of the measured In isotopes (For ^{104}In see Table 1).

Table 1

Mass A	Spin I	Hyperfine constants				Isotope shift	
		5p $^2P_{1/2}$	5p $^2P_{3/2}$		6s $^2S_{1/2}$	IS ^{115,A} / MHz	
		A / MHz	A / MHz	B / MHz	A / MHz	410 nm	451 nm
104	(5) ^j		174.2(1.0)	362.(58.)	1214.0(6.0)		-1686.(34.)
105	9/2 ^j		250.6(1.2) ^a	460.(28.) ^a	1726.0(1.3) ^a		-1465.(29.) ^a
106	7 ^a		136.8(1.3) ^a	540.(34.) ^a	961.3(1.9) ^a		-1359.(24.) ^a
107	9/2 ^j		243.1(1.4) ^b	448.(29.) ^b	1698.7(2.3) ^b		-1150.(21.) ^b
108	7 ^c	1209.0(5.)	127.6(0.4) ^c	558.(4.) ^c	891.9(0.6) ^c	-1011.(22.)	-1019.(10.) ^c
108	2 ^c	4576.0(22.)	484.2(1.6) ^c	259.(8.) ^c	3377.0(4.0) ^c	-988.(36.)	-1002.(10.) ^c
109	9/2 ^b		241.7(0.8) ^b	467.(15.) ^b	1684.3(1.2) ^b		-819.(14.) ^b
110	7 ^b		132.7(0.9) ^b	555.(12.) ^b	921.5(1.6) ^b		-722.(17.) ^b
111	9/2 ^d	2268.9(1.9)	239.3(1.0) ^b	446.(12.) ^b	1673.7(2.0) ^b	-537.(8.)	-517.(20.) ^b
112	4 ^l	2457.2(3.0)	259.6(0.4)	396.(6.)	1805.6(2.0)		-437.(2.8)
113	9/2 ^d	2277.0860(4) ^d	241.6409(4) ^e	443.414(4) ^e	1681.8(0.8) ^f	-258.2(3.0) ^f	-255.4(0.5) ^g
114	5 ^m	1729.0(2.0)	183.5(0.4)	410.(6.)	1277.3(0.7)	-176.5(4.9)	-175.6(2.3)
115	9/2 ^d	2281.9501(4) ^d	242.1647(3) ^e	449.545(3) ^e	1685.3(0.6) ^f	0.0	0.0
115	1/2 ^h	-903.5(1.1) ^h	-95.97(1) ^h		666.4(14.2)		29.0(6.4)
116	5 ^m	1573.7(0.4)	168.3(0.5)	445.(6.)	1159(4)	97.3(3.2)	94.2(2.8)
116	8 ^k	744.6(0.4)	80.1(0.3)	172.(5.)	550(2)	88.7(5.9)	85.1(2.5)
117	9/2 ^j	2279.2(1.0)	241.4(0.5)	460.(6.)	1679.4(1.2)	241.6(8.2)	234.0(6.1)
117	1/2 ⁱ	-932.996(12) ⁱ	-99.005(10) ⁱ		-747.1(21.1)		250.4(12.)
118	5 ⁿ	1568.9(1.6)	167.1(0.3)	442.(4.)	1158(3)	313.2(3.8)	312.8(4.1)
118	8 ⁿ	770.1(0.4)	82.5(0.2)	245.(5.)	568(2)	307.7(3.2)	302.3(3.1)
119	9/2 ⁿ	2270.6(1.2)	241.7(0.3)	474.(4.)	1677.5(2.4)	439.5(7.8)	441.6(6.0)
119	1/2 ⁿ		-124.8(4.3)		-863.2(8.8)		441.9(5.4)

120	5 ^j	1591.7(0.8)	168.9(0.8)	450.(9.)	1176(1)	506.2(3.6)	499.1(5.4)
120	8 ^k	854.9(0.5)	91(2)	294.(5.)	631.7(7)	481.3(3.3)	488.1(4.2)
121	9/2 ⁿ	2266.0(1.8)	240.8(0.3)	452.(6.)	1673.4(0.8)	613.9(5.8)	610.0(4.8)
121	1/2 ⁿ		-139.0(3.5)		-971.5(7.7)		604.4(6.1)
122	5 ^j	1600.1(1.3)	170.1(0.9)	447.(11.)	1182.0(1.5)	664.4(7.5)	662.3(7.8)
122	8 ^k	875.5(0.7)	93.0(0.3)	329.(12.)	647(1)	654.8(6.6)	661.3(6.9)
123	9/2 ^j	2264.6(1.3)	240.4(0.3)	420.(5.)	1670.1(1.6)	772.9(8.0)	764.5(6.0)
123	1/2 ^j		-160.3(5.2)		-1095.2(12.)		750.3(8.1)
124	3 ^j	2493.2(2.9)	264.5(2.0)	341.(38.)	1844(5)	830.2(14.)	812.0(11.)
124	8 ^k	904.0(1.5)	96.3(0.4)	369.(5.)	665(2)	802.5(11.)	811.3(6.2)
125	9/2 ^j	2265.9(1.4)	240.5(1.0)	394.(20.)	1673.6(2.0)	907.6(7.8)	894.9(11.)
125	1/2 ^j		-172.0(4.4)		-1184.9(10.)		880.3(10.)
126	3 ^j	2497.5(7.5)	264.0(5.7)	274.(32.)	1842(5)	970.5(22.)	943.0(11.)
126	8 ^k	943.3(1.7)	100.1(1.6)	379.(7.)	694.8(7)	962.0(8.5)	948.0(8.)
127	9/2 ^j		240.8(0.7)	327.(16.)	1679.6(1.7)		1000.6(13.)

a Reference 6)

b Reference 5)

c Reference 18)

d Reference 19)

e Reference 21)

f Reference 22,23)

g Reference 79)

h Reference 80)

i Reference 81)

j this work

k assignment according to 34)

l Reference 27)

m Reference 28)

n Reference 30)

Table 2

Mass A	Spin I	Magnetic Moments			Quadrupole Moments			$\delta\langle r^2 \rangle^{115,A}$	
		in n.m.			in barn			in fm ²	
		$\mu(\text{exp.})$	$\mu(\text{emp})$	$\mu(\text{theo.})$	$Q_s(\text{exp.})$	$Q_s(\text{emp.})$	$Q_s(\text{theo.})$		
104	(5)	4.435(22)	4.45		0.659(106)	0.73		-0.842(15)	(55)
105	9/2	5.675(5) ^a			0.829(50) ^a			-0.733(14)	(48) ^a
106	7	4.916(7) ^a	4.83	4.42 ^d	0.972(61) ^a	1.24		-0.678(12)	(43) ^a
107	9/2	5.585(8) ^b		5.34 ^e	0.807(52) ^b		0.68 ^e	-0.575(10)	(37) ^b
108	7	4.561(3) ^c	4.73	5.40 ^d	1.005(07) ^c	1.15	0.60 ^d	-0.509(5)	(32) ^c
108	2	4.935(5) ^c	5.12		0.467(14) ^c	0.53		-0.501(5)	(32) ^c
109	9/2	5.538(4) ^b		5.31 ^e	0.841(27) ^b		0.63 ^e	-0.410(7)	(27) ^b
110	7	4.713(8) ^b	4.71	4.88 ^d	1.000(22) ^b	1.15		-0.361(8)	(24) ^b
111	9/2	5.503(7) ^b		5.36 ^e	0.804(22) ^b		0.67 ^e	-0.262(5)	(18) ^b
112	4	5.277(5)	5.89		0.714(10)	0.75		-0.218(6)	(14)
112	8	3.080(32) ^l	2.99		-0.093(6) ^f	-0.09			
113	9/2	5.5289(2) ^h		5.35 ^e	0.799 ^j		0.70 ^e	-0.1280(3)	(8)
113	1/2	-0.21074(2) ^h		-0.27 ^e					
114	5	4.653(5) ^k	4.62	4.45 ^g	0.739(12)	0.80		-0.087(2)	(6)
115	9/2	5.5408(2) ^h			0.810 ⁱ		0.68 ^e	0.0	
115	1/2	-0.24398(5) ^h		-0.27 ^e				0.014(3)	(3)
116	5	4.235(15)	4.53	4.55 ^g	0.802(12)	0.82		0.048(1)	(4)
116	8	3.215(11)	2.99	3.29 ^g	0.310(9)	-0.04		0.043(3)	(4)
117	9/2	5.519(4)		5.35 ^e	0.829(10)		0.69 ^e	0.119(4)	(8)
117	1/2	-0.25174(3) ^h		-0.27 ^e				0.125(6)	(10)
118	5	4.231(9)	4.47		0.796(8)	0.84		0.157(2)	(10)
118	8	3.321(11)	2.99		0.441(7)	0.15		0.153(2)	(11)

119	9/2	5.515(10)		5.35 ^e	0.854(7)		0.68 ^e	0.220(4)	(16)
119	1/2	-0.319(5)		-0.27 ^e				0.222(3)	(15)
120	5	4.295(5)	4.47		0.810(17)	0.83		0.252(2)	(18)
120	8	3.692(4)	2.99		0.530(10)	0.18		0.243(6)	(18)
121	9/2	5.502(5)		5.35 ^e	0.814(11)		0.68 ^e	0.306(3)	(22)
121	1/2	-0.355(4)		-0.27 ^e				0.305(3)	(22)
122	5	4.318(5)	4.47		0.806(20)	0.79		0.332(4)	(25)
122	8	3.781(6)	2.99		0.592(21)	0.26		0.330(5)	(25)
123	9/2	5.491(7)		5.35 ^e	0.757(9)		0.65 ^e	0.385(3)	(29)
123	1/2	-0.400(4)		-0.27 ^e				0.379(4)	(27)
124	3	4.043(11)	4.51		0.614(68)	0.57		0.412(6)	(30)
124	8	3.888(9)	3.01		0.664(9)	0.27		0.405(8)	(30)
125	9/2	5.502(9)			0.710(36)			0.452(5)	(35)
125	1/2	-0.433(4)						0.446(5)	(33)
126	3	4.034(11)	4.53		0.494(49)	0.51		0.480(7)	(36)
126	8	4.061(4)	3.01		0.683(12)			0.480(5)	(36)
127	9/2	5.522(8)			0.589(29)			0.508(7)	(38)

^a Reference ⁶)

^b Reference ⁵)

^c Reference ¹⁸)

^d Reference ⁴⁰)

^e Reference ⁴¹)

^f Reference ⁵⁴)

^g Reference ⁸²)

^h Reference ¹⁹)

ⁱ Reference ⁸³)

^j Reference ²¹) and recalculated with the listed $Q(^{115}\text{In})$

^k compare $\mu = 4.658(14)$ n.m. in Reference ⁸⁴)

^l Reference ⁸⁵)

FIGURE CAPTIONS

Figure 1 Production and separation yield of indium isotopes resulting from fusion reactions of ^{16}O beams with energies of 6 - 9 MeV/u on molybdenum targets at GSI and from 600 MeV proton - induced fission reactions on an uranium carbide target at ISOLDE.

Figure 2 Observed fluorescence signal as a function of frequency, recorded at mass number 117, in the 451 nm transition. The spectrum shows the dominating hfs lines of the $I = 9/2$ ground state and the weak signals of the $I = 1/2$ isomer in between these strong lines. The hfs of the $^{121,125}\text{In}$ ($I=1/2$) isomers is given in the same frequency scale to demonstrate the increasing magnetic hfs splitting. Diagrams of the relevant atomic levels of indium are given as inset.

Figure 3 Observed fluorescence signal of ^{122}In as a function of the frequency in the 451 nm transition. The hfs components of the different spin states are marked by arrows according to the nuclear spins $I = 1, 5$ and 8 .

Figure 4 Nuclear moments of the odd In isotopes

- (1) the quadrupole moments for $I = 9/2$ (theory from 41)),
- (2) the magnetic moments for $I = 9/2$ (theory from 41)) and
- (3) for $I = 1/2$. The Schmidt limit is shown as a dotted line.

Figure 5 Nuclear moments of the even In isotopes. Full symbols : experiment; open symbols : semi-empirical values according to the additivity rules (1) and (2).

Figure 6 The electric quadrupole moments of the $1h_{11/2}$ neutron states determined with the help of the quadrupole additivity rule of the $I^\pi = 8^-$ In isomers (full symbols) in comparison to other experimental results of this neutron configuration (open symbols) in this mass region (Cd : references ^{7,8,19}), Sn : references ^{9,19}), Sb : references ⁵⁶), Cs : reference ⁸⁶), Ba : reference ¹⁶)).

Figure 7 Change of the nuclear mean square charge radii $\delta\langle r^2 \rangle$ relative to ^{115}In ($N = 66$). The solid line corresponds to the prediction of the spherical droplet model⁷²), whereas the dashed line follows the results of Wesolowski's formula⁷⁷). The dotted line represents the result of the fit ansatz given by relation (7).

Figure 8 Deformation parameter β according to the relation (11), describing collective contributions [full symbols : experiment; open symbols : fit ansatz], in comparison to static deformation, deduced from quadrupole moments, given from relation (4) and (5).

figure 1

figure 2

figure 3

figure 4

figure 5

figure 6

figure 7

figure 8