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NUCLEAR SPINS AND MAGNETIC MOMENTS OF SOME CESIUM ISOTOPES

C. Ekström *)

Department of Physics, Chalmers University of Technology and
University of Gothenburg, Gothenburg, Sweden.

S. Ingelman and G. Wannberg

Institute of Physics, University of Uppsala, Uppsala, Sweden.

M. Skarestad +)

E.P. Division, CERN, Geneva, Switzerland

and

The ISOLDE Collaboration, CERN, Geneva, Switzerland.

ABSTRACT

Using an atomic-beam magnetic resonance apparatus connected on-line with the ISOLDE isotope separator, CERN, hyperfine structure measurements have been performed in the $^2S_{1/2}$ electronic ground state of some cesium isotopes. An on-line oven system which efficiently converts a mass separated ion-beam of alkali isotopes to an atomic-beam is described in some detail.

Experimentally determined nuclear spins of $^{120}, ^{121}, ^{121m}, ^{122}, ^{122m}, ^{123}, ^{124}, ^{126}, ^{128}, ^{130}, ^{130m}, ^{135m}$ Cs, the isomer of 121 Cs being discovered in this work, and magnetic moments of $^{121}, ^{122}, ^{123}, ^{124}, ^{126}, ^{128}, ^{130}, ^{130m}$ Cs are reported and discussed in terms of different nuclear models. The experimental data indicate deformed nuclear shapes of the lightest cesium isotopes.

NUCLEAR MOMENTS (static) $^{120}, ^{121}, ^{121m}, ^{122}, ^{122m}, ^{123}, ^{124}, ^{126}, ^{128}, ^{130m}, ^{135m}$ Cs; measured J. $^{121}, ^{122}, ^{123}, ^{124}, ^{126}, ^{128}, ^{130}, ^{130m}$ Cs; measured a; deduced μ . Atomic-beam magnetic resonance.

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*) Present address : E.P. Division, CERN, CH-1211 Geneva 23, Switzerland.

+) On leave from Department of Chemistry, University of Oslo, N-1000 OSLO 3, Norway.

1. INTRODUCTION

The importance of systematic investigations of nuclear spins and moments as a test of different models for nuclear structure is well recognized. The experimental situation, however, becomes increasingly complicated as one moves away from the line of beta-stability, because of shorter half-lives, lower production yields and of the large number of reaction products. These complications are to a large extent overcome in on-line experiments using a fast intermediate isotope separation step. The atomic-beam magnetic resonance (ABMR) apparatus connected on-line with the ISOLDE isotope separator at CERN has proven to be a useful tool in hyperfine structure investigations of short-lived nuclides far from beta-stability. We here report briefly on the on-line operation of the system, and on the measurements of nuclear spins and magnetic moments of some cesium isotopes. In an earlier paper ¹⁾ we described the atomic-beam experiments at ISOLDE on some moderately short-lived gold isotopes using off-line techniques.

2. EXPERIMENTAL METHOD

2.1 General procedure

In the on-line ABMR experiments, the ion-beam from the isotope separator is focused by an electrostatic quadrupole doublet to a small spot at the oven position of the atomic-beam apparatus, from where it is continuously evaporated in the form of free atoms. A sixpole magnet acts as a state selector on the atomic-beam; atoms with positive m_J -values are focused into the central region, while atoms with negative m_J -values are defocused. By inducing transitions from a state with positive m_J -value to one with negative m_J -value with an external r.f.-field, the atoms are defocused by a fourpole analysing magnet and reach the collector. Otherwise, the atoms are focused and hit the cooled

central obstacle in the analysing magnet, where they are adsorbed. The activity passing through the apparatus is collected on discs fed from a supply and counted in an on-line detector system. A mini-computer handles the data acquisition and controls most of the experimental routines, such as changing the r.f. frequencies and transporting the collector discs within the collector-detector system. A technical description of the atomic-beam apparatus will be published in a forthcoming paper ²⁾. We therefore restrict ourselves to details pertinent to the experiments on the cesium isotopes.

2.2 Beam production

The isotopes studied in this work were produced by spallation reactions in a liquid lanthanum target bombarded with 600 MeV protons from the CERN synchro-cyclotron. Among the volatile reaction products, cesium is selectively ionized by surface ionization and subsequently mass separated in the ISOLDE on-line isotope separator ^{3,4)}. The experimental yields of cesium isotopes from a molten lanthanum target as measured at the collector side of the separator are given in fig. 1. The peak yield of 7 nA represents an improvement of a factor 500 as compared to the data before the reconstruction of the synchro-cyclotron and the ISOLDE facility. This improvement is of course of vital importance for the atomic-beam experiments, requiring typically 10^6 - 10^7 atoms/sec.

The atomic-beam oven is in the case of on-line operation simply a metal foil heated by resistance heating. It is mounted at a 45° angle to the incoming ion-beam as well as to the optical axis of the atomic-beam apparatus. This arrangement is described in ref. ²⁾. The experiments on the alkali elements, however, require a particular attention as to the choice of oven-foil material. The following conditions should be fulfilled :

- i) low surface work function,
- ii) thermochemical stability at temperatures above 1000° C,
- iii) low sensitivity to induced heterogeneity,
- iv) ease of manufacturing.

The first requirement appears because of the necessity to convert the incoming ion-beam to an atomic-beam at the foil. According to the Saha-Langmuir formula, the neutralization efficiency of a surface may be written :

$$\xi = \frac{f_o}{f_p} = 1 - \{1 + C \exp(W - \phi)/kT\}^{-1} \quad (1)$$

where f_o = flux of atoms leaving the surface, f_p = flux of incoming ions, C = statistical constant, W = first ionization potential of the atom, ϕ = electron work function of the surface, k = Boltzmanns constant and T = the absolute temperature. For the alkali elements, the constant C takes the value 2. The alkali elements potassium, rubidium and cesium have ionization potential $W = 4.34, 4.18$ and $3.89 \text{ eV}^{5)}$, respectively.

Oven foils of different refractory metals such as Nb, Mo, Ta, W, Re and Pt, having work functions $\phi > 4 \text{ eV}$, have been tested and found to give a low atom to ion ratio of cesium in accordance with the expectations. We have found that an oven foil of tantalum covered by a thin layer of yttrium satisfactorily meets the requirements above :

- i) Polycrystalline yttrium metal has a work function $\phi \approx 3.2 \text{ eV}^{6)}$. This value, however, has been measured under pure conditions (clean surface, high vacuum). In our oven section, where the pressure is in the range $10^{-6} - 10^{-5}$ torr, this condition is probably not fulfilled. Heterogeneity induced by O_2 or N_2 is likely to exist, but it is difficult to predict to which extent it will influence the work function of the surface $^{7)}$. In any case, we note that also the oxide of yttrium has a low work function,

$\phi \approx 3.1 \text{ eV}^6)$.

- ii) The melting point of yttrium is $1509^\circ \text{ C}^5)$. The maximum temperature at which the foil can be operated is 1400° C . Above this temperature the evaporation loss of yttrium becomes too high ($> 25 \text{ mg/cm}^2 \cdot \text{hour}^8)$).
- iii) Yttrium is a stable metal which can be stored at room temperature in air. The corrosion rate is about $1 \text{ mg/cm} \cdot \text{day}^9)$.
- iv) The foil is easily prepared by melting some 20 mg yttrium on a $50 \text{ }\mu\text{m}$ Ta-backing in vacuum. The amount corresponds to about 100 mg/cm^2 . The Ta-backing, which does not alloy with yttrium, gives the foil the necessary mechanical stability at high temperatures.

In order to determine the foil temperatures needed for a fast release of alkali atoms, a separate study was carried out using ^{84}Rb ($T_{1/2} = 33 \text{ d}$) implanted in Y/Ta foil samples. The amount of ^{84}Rb in a sample after implantation was measured with a NaI-detector. The sample was then placed in a high vacuum unit and heated to a certain temperature for a certain period of time. After the heating period, the sample activity was measured again. This cycle was repeated 3 times at 3 different temperatures. The results, given in fig. 2, will be discussed below.

The incoming 60 keV alkali ions penetrate the surface at a maximum range of typically some $0.05 \text{ }\mu\text{m}^{10)}$. The initial ion trapping is followed by release processes which are thermally activated. Two separate processes are of importance, i.e. bulk diffusion of the product to the surface and evaporation of the product from the surface. The relative importance of the processes depends on the activation energies in the two cases. The surface desorption step is commonly described by the equation :

$$\tau = \tau^0 e^{Q/RT} \quad (2)$$

where τ^0 is the time of oscillation of the absorbed atom perpendicular to the surface, Q is the desorption energy, R the gas constant and T the absolute temperature. For the alkali elements τ^0 and Q have been measured to be $\approx 10^{-13}$ s and ≈ 54 kcal/mol, respectively ¹¹⁾. This means that for rubidium, the lingering time τ at 800° C takes the value $\approx 8 \cdot 10^{-7}$ s and at 1200° C $\approx 8 \cdot 10^{-8}$ s. These values are far below the time constants found in fig. 2, indicating that the bulk diffusion step is the time consuming release mechanism. Also, the non-exponential form of the release curves support this explanations (ref. ³⁾ p. 123).

The half-lives of alkali nuclides available for atomic-beam measurements are generally above 20 s. The nuclides with shorter half-lives found on the extreme wings of the yield curves are generally produced in too low yields to allow atomic-beam experiments. This means that a foil temperature of about 1000° C should be sufficient to ensure no significant decay loss on the foil. However, in a few cases extremely short-lived nuclides may be produced in high yield, like e.g. ^{219}Fr ($T_{1/2} = 20$ ms) from a high temperature uranium carbide target. In order to judge the prospects of such rare but interesting cases, we have made a rough extrapolation of the delay (in terms of the time for 50% release) as a function of temperature. It is seen in fig. 3 that half-lives below the 100 ms level can be handled by pushing the temperature to the limit of 1400° C.

The on-line oven system described above has shown to be very efficient when studying short-lived activities. It has been used in this investigation of cesium isotopes, except in the experiments on $^{135\text{m}}\text{Cs}$ (53 min) where the conventional off-line oven proved to be superior.

2.3 Detection

The activity passing through the atomic-beam apparatus was

collected on aluminium foils and subsequently measured. Thin (1 mm) plastic scintillators, mounted on PM-tubes, were used for the detection of the β^+ -decaying isotopes, i.e. the main part of the isotopes studied. The isomer ^{135m}Cs , decaying by two γ -transitions (841 and 786 keV) to the ground state, was measured with Ge(Li) and NaI detectors.

The signal to background ratio obtained in the experiments using the on-line oven system was of the order 20 : 1 in a typical spin measurement. It was reduced to about 5 : 1 in the high field measurements where a smaller number of hyperfine states contributed to the signal.

2.4 Measurements and results

The experiments were performed in the $6s\ ^2S_{1/2}$ electronic ground state of cesium having the splitting factor $g_J = 2.0025410(24)^{12}$. The hyperfine levels of a $J = \frac{1}{2}$ atom are given in the (F, m_F) -representation by the Breit-Rabi formula :

$$W(F, m_F) = - \frac{h\Delta\nu}{2(2I+1)} - g'_I \mu_B B m_F \pm \frac{h\Delta\nu}{2} \sqrt{1 + \frac{4m_F}{2I+1} x + x^2} \quad (3)$$

where $x = (g'_I + g_J) (\mu_B B/h) (1/\Delta\nu)$. The positive sign refers to the hyperfine level $F = I + \frac{1}{2}$ and the negative sign to the level $F = I - \frac{1}{2}$. The hyperfine structure separation $\Delta\nu$ is related to the dipole hyperfine constant a by :

$$\Delta\nu = a(I + \frac{1}{2}). \quad (4)$$

The energy level diagram for an $I = 1$ atom is shown in fig. 4, assuming a positive value of a .

In weak external magnetic fields B , the resonance frequency for allowed transitions between substates belonging to the same hyperfine level is given by the expression :

$$\nu = g_J \frac{\mu_B B}{h} \frac{1}{2I+1} \quad (5)$$

neglecting the small term in g_I' . In the case $I = 1$, the single-quantum transition ($F = 3/2, m_F = -1/2$) $\rightarrow$ ($F = 3/2, m_F = -3/2$) is indicated in fig. 4 by an arrow. Normally this transition requires moderate r.f. power to be saturated. By increasing the r.f. power, the double-quantum ($3/2, 1/2$) $\rightarrow$ ($3/2, -3/2$) and triple-quantum ($3/2, 3/2$) $\rightarrow$ ($3/2, -3/2$) transitions may also be induced. In the weak-field region, these multiple-quantum transitions appear at the same frequency as that of the single-quantum transition. It is thus of importance to apply sufficient r.f. power in order to get strong resonance signals, particularly in the case of high spin values where the hyperfine levels are split into a large number of magnetic sub-states.

The spin measurements in cesium were made at 2 or 3 different settings of the external magnetic field in the range 80-290 μ T. The results obtained are given in table 1. One may note the previously unknown isomer in ^{121}Cs , observed in the spin-separated samples. The $I = 3/2$ and $I = 9/2$ states showed to have similar half-lives, $T_{1/2} \approx 2$ min, and to be produced in about equal amounts. It was, however, not possible to determine whether the $3/2$ or $9/2$ state corresponds to the ground state. A careful search was made without success for the high spin isomer in ^{120}Cs reported by Genevey-Rivier et al ¹³).

By increasing the external magnetic field and observing the deviations from the linear Zeeman-effect, it is possible to determine the hyperfine structure separation $\Delta\nu$ and the dipole hyperfine constant a . These measurements were performed in the isotopes ^{121}Cs ($I = 3/2$), ^{123}Cs ($I = 1/2$), $^{122}, ^{124}, ^{126}, ^{128}, ^{130}\text{Cs}$ ($I = 1$) and $^{130\text{m}}\text{Cs}$ ($I = 5$). In all isotopes except ^{121}Cs and $^{130\text{m}}\text{Cs}$, both the single- and double-quantum transitions were identified in an external magnetic field of 2.25 mT. The identification of the single-quantum transitions in ^{121}Cs and $^{130\text{m}}\text{Cs}$

was made on the basis of the low r.f.-power needed for saturation. No resonance signals corresponding to higher order transitions were observed at these power strengths. The single-quantum transitions were subsequently followed in the cesium isotopes above up in fields; the strongest field used was 23.2 mT. The resonance curves obtained for the isotopes ^{132}Cs (21 sec) and ^{130}Cs (30 min) at 15 mT are given in fig. 5a and 5b, respectively. The curves show the same line shape as the potassium calibration line at this field, a slight broadening towards lower frequencies, and line widths FWHM of about 80 kHz.

In order to increase the accuracy of the hfs separation in ^{132}Cs , we decided to try a measurement in weak external field of the $\Delta F = 1$ transitions $(^3/2, -1/2) \leftrightarrow (^1/2, 1/2)$, $(^3/2, 1/2) \leftrightarrow (^1/2, -1/2)$ and $(^3/2, 3/2) \leftrightarrow (^1/2, 1/2)$; the frequencies of the first two transitions being degenerate and field independent to second order. This resonance line is thus expected to be narrow, FWHM of the order 10 kHz, with the r.f. geometry used. The r.f. generator to be used in such an experiment therefore should have good resolution (5 kHz or better), as well as good longtime stability and a useful output power level to overcome inevitable matching losses. Preferably, it should also be programmable in order to retain the automated measuring facilities. A system operating in the region around 620 MHz and satisfying the requirements outlined above was constructed. The solution, illustrated schematically in fig. 6, was shown to perform satisfactorily on all accounts. The results from the frequency scan in a field of about 30 μT is shown in fig. 7.

In table 2 are collected the results from the hfs measurements in the cesium isotopes. The uncertainty of the calibration and resonance frequencies is taken to be a quarter of the line widths. In case of field drifts during the experiment, the error has been increased correspondingly. The residuals, χ^2 and the hfs constants obtained in a least-squares fit of the experi-

mentally observed resonances to the Breit-Rabi formula, eq. 3, assuming either a positive or a negative sign of the nuclear g-factors, are also given in table 2.

Performing a confidence test of the sign assignments to the g-factors, the assumption of a positive moment in the isotopes $^{123}, ^{124}, ^{126}, ^{128}, ^{130}\text{Cs}$ proved to be valid at a high level of confidence. In ^{122}Cs and $^{130\text{m}}\text{Cs}$, however, the magnitude of the magnetic moment showed to be too small to have a decisive influence (a positive sign is slightly preferred) upon the goodness of the fit for either choice of sign. In ^{121}Cs , the fit favours the choice of a positive sign of the magnetic moment. However, the measurements were not made in fields sufficiently strong to ascertain definitively whether it is positive or negative. The resulting hfs separations and dipole hyperfine constants are given in table 3. The errors quoted are one standard deviation. The present data on the isotope ^{130}Cs represent an improvement of a factor 30 in accuracy compared to the results obtained by Nierenberg et al. ¹⁴⁾. From their data, the sign of the moment could not be determined.

The magnetic moments of the cesium isotopes are easily calculated from the dipole constants by a direct comparison with the known values in the stable isotope ^{133}Cs .

$$\mu_I = \mu_{I133} \frac{a_{133} I_{133}}{a_{133} I_{133}} (1 + A_{\Delta}^{133}) \quad (7)$$

where $\mu_{I133} = 2.582065(9) \text{ n.m. (diam. corr.) }^{15)}$,
 $a_{133} = 2298.157943 \text{ MHz }^{16)}$,
 $I_{133} = 7/2^{15)}$.

A large uncertainty is, however, introduced by the unknown hyperfine anomaly A_{Δ}^{133} . We give in table 3 the magnetic moments calculated under the assumption of $A_{\Delta}^{133} = \pm 1\%$. The hyperfine anomaly may, however, in certain cases exceed this value; and in

the isotope ^{122}Cs , having a very small magnetic moment, it probably would be more appropriate to give an absolute error (cf. section 3 in ref. ¹⁷)).

The variation of the magnetic moments of the isotopes $^{121-130}\text{Cs}$ with mass number is shown in fig. 8.

3. DISCUSSION

3.1 General considerations

A general idea about the nuclear properties to be expected in the region around the neutron-deficient cesium isotopes may be obtained by inspecting the partial nuclear chart shown in fig. 9. In the region enclosed by $50 = (N, Z) = 82$, the stable and identified radioactive nuclides are found in the corner $Z > 50$ and $N < 82$. Close to these shell closures, the spherical shell model ¹⁸⁾ is expected to give a good description of the nuclear properties. At the center of the region enclosed by $50 = (N, Z) = 82$, strongly deformed nuclear shapes have been suggested to appear ^{19, 20)}. The iso-deformation curves for prolate shapes, as calculated by Arseniev ²¹⁾ are incorporated in fig. 9. Between these regions of extreme nuclear shapes, we have a transition region. Here, we may expect a competition between vibrational and rotational structures, and even within the same nucleus one may observe states of both spherical and deformed shapes, the latter often of triaxial character ^{22, 23)}. Two distinct types of band structure may be observed in a nucleus with moderate deformation, if the Fermi surface is located close to the lower or upper part of levels originating from a high-spin shell model state ²⁴⁾. In a prolate nucleus, decoupled bands appear for particle states and rotational bands for hole states. The levels originating from low-spin shell model states are in the transition region often strongly mixed, making the interpretations of nuclear spins, moments and level structure very complicated.

3.2 Discussion of nuclear spins and moments in the cesium region

The shell model states $g_{7/2}$, $d_{5/2}$, $h_{11/2}$, $s_{1/2}$ and $d_{3/2}$ are available as odd-proton as well as odd-neutron states in the region $50 \leq (N, Z) \leq 82$. For obvious reasons, the main part of odd-proton ground states are characterized either by $g_{7/2}$ or $d_{5/2}$. Similarly, in odd-neutron nuclei we find, close to $N = 82$, mainly $s_{1/2}$ or $d_{3/2}$ ground states. The low-lying level structure of nuclei with $N > 77$ has been discussed previously in connection with our spin-measurements in isotopes of the elements promethium-gadolinium ²⁵⁾. To this may be added the spin $I = 19/2$ of ^{135}mCs which may be interpreted as a three-quasiparticle state, in which the $h_{11/2}$ neutron state has to be involved.

A large part of the nuclei in the region $50 < (N, Z) < 82$ which are experimentally accessible may be regarded as transitional. The first experimental results on band structure associated with the rotation-aligned coupling scheme ²⁴⁾ were obtained in this region in a number of lanthanum isotopes ²⁶⁾. Since the Fermi surface in lanthanum is located at the lower part of the levels originating from the $h_{11/2}$ shell model state, the observed decoupled bands based on the $11/2$ -isomeric states clearly indicate prolate-type deformation. Similar decoupled bands have later been observed in isotopes of iodine, cesium, praseodymium and promethium ^{27-30, 32)}. In odd-A isotopes of antimony and iodine, rotational bands built on the $9/2^+$ isomeric states have been identified ^{31, 32)}. This fact again points at prolate-type shapes, since here the Fermi surface is situated above the levels originating from the $g_{9/2}$ shell model state. The Fermi surface in odd-neutron nuclei close to $N = 82$ is located at the upper part of the levels from the $h_{11/2}$ shell. Rotational-like bands have here been observed in a large number of nuclei indicating prolate-type shapes ³³⁻³⁷⁾. The same conclusion may be drawn from the decoupled bands identified in the light barium isotopes with $N = 65$ and $N = 67$, occupying the low-spin levels from the $h_{11/2}$ shell ³⁸⁾.

Recent theoretical calculations incorporating asymmetric nuclear shapes reproduce satisfactorily the band structures of high-spin unique-parity states in the transition region ^{22,23}). These results are consistent with those obtained from an investigation ³⁹) of level schemes and transition probabilities in doubly-even nuclei, revealing spherical shapes near the shell closures at $Z = 50$ and $N = 82$, asymmetric shapes ($20^\circ < \gamma < 30^\circ$) and moderate values of the deformation parameter β in a transition region, and, further away from the shell closures, a transition to more symmetric shapes and to stronger β -deformations.

The results above do not, however, necessarily apply to the low-spin states in the transitional and deformed regions. Theoretical potential energy surfaces generally show two minima close in energy, one at prolate and the other at oblate deformation, the barrier in the γ -direction being very low.

Since it seems possible to get a consistent picture of the low-spin states at the center of the region $50 < (N, Z) < 82$ by assuming a prolate deformation, we will attempt an interpretation of the light cesium isotopes in terms of the strong-coupling model, keeping in mind that many of the properties are as well reproduced by the intermediate coupling version of the unified model ^{40,41}).

Single-particle energy levels as functions of the quadrupole deformation ϵ have been calculated within the Nilsson model, employing several sets of shell parameters, e.g. the parameters valid in the strongly deformed rare-earth region, the parameters obtained by an extrapolation from the actinides and the rare-earths to the centre of the region $50 < (n Z) < 82$, and the "modified" parameters suggested by Ragnarsson and Nilsson ⁴²). The Nilsson diagrams obtained using the "extrapolated" shell parameters $\kappa_p = 0.0662$, $\mu_p = 0.540$ and $\kappa_n = 0.0637$, $\mu_n = 0.450$ are shown in fig. 10. In the "rare-earth" diagram for odd protons,

the energy difference between the levels $g_{7/2}$ and $d_{5/2}$ is larger and the orbitals $[420^{1/2}]$ and $[422^{3/2}]$ do not intersect for ϵ -values smaller than 0.3. For the odd neutrons, the $h_{11/2}$ state is located between the states $s_{1/2}$ and $d_{3/2}$. Using the "modified" parameters, we find that the level order between the proton levels $g_{7/2}$ and $d_{5/2}$ is reversed, and that the $h_{11/2}$ neutron state is located above the $s_{1/2}$ and $d_{3/2}$ states. The "extrapolated" diagrams shown in fig. 12 thus represent medium cases to the "rare-earth" and "modified" diagrams.

The nuclear ground state spins of the odd-A cesium isotopes $^{123}, ^{125}, ^{127}, ^{129}\text{Cs}$ have been measured with the result $I = 1/2$ in all cases. Positive parity is suggested by spectroscopic works. These results are accounted for by the Nilsson orbital $[420^{1/2}]$ which, in the level diagram shown in fig. 10 is occupied by the 55th proton of cesium in a wide range of positive deformation values. The experimental magnetic moments of these isotopes are well reproduced by the theoretical moment of the level $[420^{1/2}]$, assuming $g_s = 0.6 g_s^{\text{free}}$, $g_1 = 1$, $g_R = 0.45$ and the shell parameters from the rare-earth region. The moments obtained using the extrapolated parameters are slightly too small, $\Delta\mu \approx 0.2$ n.m., while the "modified" values are considerably smaller, $\Delta\mu \approx 0.5 - 1.0$ n.m.

The variation of the theoretical magnetic moments of the proton orbitals $[420^{1/2}]$ and $[422^{3/2}]$ as functions of deformation, shell parameters and g_s -factor is shown in fig. 11. The curves denoted by A, B and C are calculated with the "rare-earth", "extrapolated" and "modified" shell parameters, respectively. The solid curves, denoted by μ_2 are calculated with $g_s = 0.6 g_s^{\text{free}}$, while the dashed curves, μ_1 , use the free g_s -value. The experimental magnetic moments are plotted at the calculated ²¹⁾ equilibrium deformation positions.

In a recent spectroscopic work on the decay of ^{127}Ba , Beyer et al ⁴³⁾ propose the strongly fed $3/2^+$ excited state in ^{127}Cs to be a rotational member of the ground state band. Furthermore, the low-lying states with $I^\pi = 5/2^+, 3/2^+, 7/2^+$ and $11/2^-$ are shown to have the same sign of the deformation. These states may consequently be given the assignments $[423^{5/2}]$, $[411^{3/2}]$ or $[422^{3/2}]$, $[404^{7/2}]$ and $11/2^- - [550^{1/2}]$, respectively. A similar interpretation of the low-lying states in ^{137}Pr has recently been attempted by Klewe-Nebenius et al ²⁹⁾. We may also mention our earlier spin measurements in the odd-Z elements lanthanum and praseodymium ^{44, 45)}. The $3/2^+$ ground states in ^{131}La and ^{135}Pr may be assigned $[411^{3/2}]$, and the $5/2^+$ ground state in ^{133}Pr $[413^{5/2}]$.

In the isotope ^{121}Cs we observe two isomers of similar half-lives having the nuclear spins $I = 3/2$ and $I = 9/2$. Assuming a nuclear deformation $\epsilon \approx 0.25$, the spin values may be interpreted as arising from the orbitals $[422^{3/2}]$ and $[404^{9/2}]$, the latter one originating from the $g_{9/2}$ shell and raising steeply with increasing deformation. The magnetic moment of the $I = 3/2$ state in ^{121}Cs is in good agreement with the predictions of the orbital $[422^{3/2}]$, (cf. fig. 11). Further evidence for deformed nuclear shapes in the light cesium isotopes is given by the nuclear ground state spin of ^{119}Cs , $I = 9/2$, measured by the optical pumping group at ISOLDE ⁴⁶⁾.

The doubly-odd cesium isotopes in the mass range $A = 122-130$, all have a nuclear ground state spin and parity $I^\pi = 1^+$. The magnetic moments, on the other hand, show a drastic variation in magnitude (cf. fig. 8). The large difference between the magnetic moments of ^{122}Cs and ^{124}Cs , may be explained by assuming the proton orbitals $[422^{3/2}]$ and $[420^{1/2}]$, respectively, coupled to a $[411^{1/2}]$ neutron. This interpretation is consistent with the assumption that the neighbouring nuclei ^{121}Cs and ^{123}Cs are

characterized by $[422^{3/2}]$ and $[420^{1/2}]$, respectively. The further increase in magnitude for the heavier cesium isotopes is, however, not accounted for by the predictions of the Nilsson model. It seems that these nuclei have to be treated as transitional, with an increasing influence of the $1^+(p d_{5/2} n d_{3/2})$ shell model configuration, having a nuclear magnetic moment of about 2 n.m.

We have previously measured ^{44, 45)} the nuclear spins in the $N = 75$ isotones ^{133}Ce and ^{135}Nd with the result $I = 9/2$. In the strong-coupling limit they may be interpreted as arising from the Nilsson orbital $[514^{9/2}]$. The $9/2^-$ states in ^{131}Ba , ^{133}Ce and ^{135}Nd form the band heads of the perturbed rotation bands discussed above. The nuclear spin $I = 5$ of the isomeric state in ^{130}Cs may be explained by this neutron state coupled to the $I = 1/2$ proton state of ^{129}Cs . Assuming a positive sign of the experimental magnetic moment $\mu_I = 0.631(10)$ n.m., we obtain a qualitative agreement with the prediction of the configuration above. The magnetic moment of ^{129}Cs $I = 1/2$ is 1.482(9) n.m. ⁴⁷⁾, and of ^{131}Ba $I = 9/2$, $\mu_I = -0.8$ n.m. (calculated).

Returning again to the light cesium isotopes, the high-spin $I = 8$ isomer in ^{122}Cs may be explained by coupling the proton orbital $[404^{9/2}]$, appearing in ^{121}Cs , with the neutron orbital $[523^{7/2}]$. This configuration implies a negative parity of the state.

The doubly-odd isotope ^{120}Cs with a nuclear spin $I = 2$ may be given the same nuclear configuration as ^{122}Cs , namely $p[422^{3/2}] n[411^{1/2}]$, this time, however, coupled according to the rules of Gallagher and Moszkowski ⁴⁸⁾.

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ADDENDUM

In a recent paper (Bull. Am. Phys. Soc. 22 (1977) 595), Garg et al. report on in-beam studies of $^{121,123}\text{Cs}$. Of particular interest is the rotational band structure preliminary interpreted to be built on the $9/2^+$ state. The observed band structure supports our interpretation of the state as $[404^{9/2}]$.

REFERENCES

- 1) C. Ekström, I. Lindgren, S. Ingelman, M. Olsmats and G. Wannberg, Phys. Lett. 60B, (1976) 146.
- 2) C. Ekström, S. Ingelman and G. Wannberg, subm. to Nucl. Instr.
- 3) The ISOLDE Isotope Separator On-Line Facility at CERN, eds. A. Kjelberg and G. Rudstam, CERN Report 70-3, 1970.
- 4) H.L. Ravn, L.C. Carraz, J. Denimal, E. Kugler, M. Skarestad, S. Sundell and L. Westgaard, Nucl. Instr. 139, (1976) 267.
- 5) Handbook of Chemistry and Physics, 55th Ed. (The Chemical Rubber Co., Cleveland, Ohio, 1975) p. E67.
- 6) Atomic Sources and Detectors, eds. W.J. Vernon and L.S. Howard (Academic Press, New York, 1967) p. 21.
- 7) M. Karminsky in Atomic and Ionic Impact Phenomena on Metal Surfaces (Springer-Verlag, Berlin, 1965) p. 8.
- 8) Selected Values of the Thermodynamic Properties of the Elements, eds. R. Hultgren, P.D. Desai, D.T. Hawkins, M. Gleiser, K.K. Kelly and D.D. Wagman (American Society for Metals, Ohio, 1973) p. 559.
- 9) The Rare-Earths, eds. F.H. Spedding and A.H. Daane (R.E. Krieger Publishing Co. Inc., New York, 1971) p. 166.
- 10) F. Brown, G.C. Ball, D.A. Channing, L.M. Howe, J.P.S. Pringle and J.L. Whitton, Nucl. Instr. 38, (1965) 249.
- 11) Absorption and Desorption Phenomena, ed. F. Ricca (Academic Press, New York, 1972) p. 169.
- 12) K.D. Böklen, W. Dankwort, E. Pitz and S. Penselin, Z. Physik 200, (1967) 467.
- 13) J. Genevey-Rivier, A. Charvet, G. Marguier, C. Richard-Serre, J. D'Auria, A. Huck, G. Klotz, A. Knipper and G. Walter, submitted to Nucl. Phys.
- 14) W.A. Nierenberg, H.A. Shugart, J.B. Silsbee and R.J. Sunderland, Phys. Rev. 112, (1958) 186.
- 15) V.S. Shirley and C.M. Lederer, Table of Nuclear Moments, Hyperfine Interactions Studied in Nuclear Reactions and Decay (Vol. II), invited papers, eds. E. Karlsson and R. Wäppling (Almqvist and Wiksell International, Stockholm-New York, 1975).

- 16) J. Terrien, Metrologia 4, (1968) 41.
- 17) C. Ekström, G. Wannberg and Y.S. Shishodia, Hyperfine Interactions 1, (1976) 437.
- 18) A. de-Shalit and I. Talmi, Nuclear Shell Theory (Academic Press, New York, 1963).
- 19) R.K. Sheline, T. Sikkeland and R.M. Chanada, Phys. Rev. Lett. 7, (1961) 446..
- 20) E. Marshalek, L. Person and R.K. Sheline, Rev. Mod. Phys. 35, (1963) 108.
- 21) D.A. Arseniev, A. Sobiczewski and V.G. Soloviev, Nucl. Phys. A139, (1969) 269.
- 22) J. Meyer-ter-Vehn, Nucl. Phys. A249, 111, (1975) 141.
- 23) H. Toki and A. Faessler, Nucl. Phys. A253, (1975) 231 and Z. Physik A276, (1976) 35.
- 24) F.S. Stephens, Rev. Mod. Phys. 47, (1975) 43.
- 25) C. Ekström, S. Ingelman, M. Olsmats and B. Wannberg, Physica Scripta 6, (1972) 181.
- 26) F.S. Stephens, R.M. Diamond, J.R. Leight, T. Kammuri and K. Nakai, Phys. Rev. Lett. 29, (1972) 438.
- 27) U. Garg, T.P. Sjoreen and D.B. Fossan, Bull. Am. Phys. Soc. 21 (1976) 635 and 1003.
- 28) K. Wisshak, H. Klewe-Nebenius, D. Habs, H. Faust, G. Nowicki and H. Rebel, Nucl. Phys. A247, (1975) 59.
- 29) H. Klewe-Nebenius, D. Habs, K. Wisshak, H. Faust, G. Nowicki, S. Göring, H. Revel, G. Schatz and M. Schwall, Nucl. Phys. A240, (1975) 137.
- 30) D. Habs, G. Nowicki, H. Klewe-Nebenius, K. Wisshak, J. Buschmann, H. Tebel and G. Schatz, Proc. Int. Conf. on Nuclear Physics, Munich 1973, eds. J. de Boer and H.J. Mang (North-Holland, American Elsevier, 1973) p. 183.
- 31) A.K. Gaigalas, T.E. Schroy, G. Schatz and D.B. Fossan, Phys. Rev. Lett. 35, (1975) 555.
- 32) D.M. Gordon, M. Gai, A.K. Gaigalas, R.E. Shroy and D.B. Fossan, Phys. Lett. 67B (1977) 161.
- 33) I. Rezanka, A. Kerek, A. Luukko and C.J. Herrlander, Nucl. Phys. A141, (1970) 130.

- 34) J. Gizon, A. Gizon, M.R. Maier, R.M. Diamond and F.S. Stephens, Nucl. Phys. A222, (1974) 557.
- 35) J. Gizon, A. Gizon and D.J. Horen, Nucl. Phys. A252, (1975) 509.
- 36) J. Gizon, A. Gizon and J. Meyer-ter-Vehn, Nucl. Phys. A277, (1977) 464.
- 37) G.P. Nowicki, J. Buschmann, A. Hanser, H. Rebel, H. Faust, D. Habs, H. Klewe-Nevenius and K. Wisshak, Nucl. Phys. A249, (1975) 76.
- 38) J. Conrad, R. Repnow and J.P. Wurm, Proc. Int. Conf. on Reactions Between Complex Nuclei, Nashville, 1974, p. 153.
- 39) D. Habs, H. Klewe-Nevenius, K. Wisshak, R. Löhken, G. Nowicki and H. Rebel, Z. Physik 267, (1974) 149.
- 40) A. Bohr and B.R. Mottelson, K. Dan. Vidensk. Selsk. Mat.-Fys. Medd. 27, No 16 (1953).
- 41) D.C. Choudhury, K. Dan. Vidensk. Selsk. Mat.-Fys. Medd. 28, No 4 (1954).
- 42) I. Ragnarsson and S.G. Nilsson, Proc. of Colloquium on Intermediate Nuclei, Institut de Physique Nucléaire d'Orsay, 1971, p. 112.
- 43) G. Beyer, R. Arlt, E. Herrmann, A. Jasinski, O. Knotek, G. Musiol, H.G. Ortlepp, H.V. Siebert and J. Tyrroff, Nucl. Phys. A260, (1976) 269.
- 44) S. Ingelman, C. Ekström, M. Olsmats and B. Wannberg, Physica Scripta 7, (1973) 24.
- 45) C. Ekström, S. Ingelman, M. Olsmats, B. Wannberg, G. Andersson and A. Rosén, Nucl. Phys. A196, (1972) 178.
- 46) H. Fischer, private communication.
- 47) J.M. Khan, N. Braslau and G.O. Brink, Bull. Am. Phys. Soc. 7, (1962) 476.
- 48) C.J. Gallagher Jr and S.A. Moszkowski, Phys. Rev. 111, (1958) 1282.
- 49) S. Ullrich and E.W. Otten, Nucl. Phys. A248, (1975) 173.

Table 1

Summary of results from the spin measurements
in the cesium isotopes

Mass number	Half-life	Measured nuclear spin
A	$T_{1/2}$	I
120	58 sec	2
121	2 min	$3/2$
121	2 min	$9/2$
122	21 sec	1
122m	4.2 min	8
123	5.8 min	$1/2$
124	30.8 sec	1
126	1.6 min	1
128	3.8 min	1
130m	3.7 min	5
135m	53 min	$19/2$

Table 2

Experimentally observed $\Delta F=1$ transitions in weak fields and $\Delta F=0$ transitions in strong external fields, together with results from the fitting procedure.

Iso- tope	Frequency of calibration transition in ^{39}K (MHz)	$\nu_B B/h$ (MHz)	Observed resonance frequency (MHz)	$g_I > 0$		$g_I < 0$	
				Residual (MHz)	χ^2 Hfs constant (MHz)	Residual (MHz)	χ^2 Hfs constant (MHz)
^{121}Cs	11.085 (7) 24.136 (7) 50.427 (7)	20.693(12) 41.969(11) 77.775 (9)	10.455 (7) 21.418 (7) 40.368 (7)	-0.001 -0.001 0.000		-0.007 -0.009 0.003	
^{122}Cs	0.225(12) 0.225(12) 36.531(17) 108.470(30) 200.110(40) 386.890(50)	0.449(24) 0.449(24) 59.828(23) 137.966(27) 209.626(28) 326.432(29)	619.861 (3) 620.454(15) 45.378 (7) 122.482(15) 210.990(20) 384.810(45)	0.000 -0.006 -0.004 0.002 -0.003 -0.004		0.000 -0.006 -0.009 -0.007 -0.013 -0.013	
^{123}Cs	108.488(18) 200.301(25)	137.982(16) 209.760(17)	140.260(15) 214.970(25)	-0.001 0.001	0.087 0.004	0.013 0.047	-413.240(2) -9313 (52)
^{124}Cs	36.530(17) 108.495(19) 200.190(26) 386.927(30)	59.826(23) 137.988(17) 209.682(18) 326.453(17)	40.945 (7) 97.622(13) 152.884(20) 249.900(25)	-0.001 0.003 -0.002 0.000		-0.025 -0.032 -0.028 0.032	
^{126}Cs	36.538 (7) 108.485(18) 200.313(30) 386.920(30)	59.837(10) 137.979(16) 209.768(21) 326.449(17)	40.810 (7) 96.842(10) 151.125(20) 245.360(35)	-0.002 0.001 -0.009 0.007	0.043 2099.0 (16)	0.028 -0.034 -0.028 0.073	-2109.5(16)
^{128}Cs	36.540 (7) 108.479(18) 200.150(29) 386.960(40)	59.840(10) 137.974(16) 209.654(20) 326.472(23)	40.624 (8) 95.840(15) 148.710(20) 239.567(23)	-0.004 -0.003 -0.002 0.004	0.201 2427.2 (26)	-0.038 -0.053 -0.039 0.053	-2466.4(26)
^{130}Cs	200.270(40) 386.975(40)	209.738(28) 326.481(23)	145.735(22) 232.057(21)	0.003 -0.001		0.071 0.024	-3078.3(36) -4679.8(83)
^{130m}Cs	11.083 (7) 24.134 (7) 50.429 (7)	20.690(12) 41.966(11) 77.778 (9)	3.832 (7) 7.917 (7) 15.145 (7)	0.000 0.000 0.000	391.1 (26)	-0.002 -0.003 0.001	-395.0(26)

a) $(^3/2, ^1/2) \leftrightarrow (^3/2, ^1/2)$, $(^3/2, ^1/2) \leftrightarrow (^1/2, ^1/2)$.

b) $(^3/2, ^3/2) \leftrightarrow (^1/2, ^1/2)$.

The remaining frequencies correspond to $\Delta F=0$ single-quantum transitions.

Table 3

Hyperfine structure (hfs) data and magnetic moments
evaluated from the experimentally observed resonance frequencies

Mass number A	Nuclear spin I	Hfs separation $\Delta\nu$ MHz	Dipole constant a MHz	Magnetic moment μ_I n.m.*)
121	3/2	± 3260 (58)	± 1630 (29)	± 0.785 (16)
122	1	± 619.860 (3)	± 413.240 (2)	± 0.133 (2)
123	1/2	8655 (45)	8655 (45)	1.389 (16)
124	1	3148.5 (24)	2099.0 (16)	0.674 (7)
126	1	3640.8 (39)	2427.2 (26)	0.779 (8)
128	1	4564.7 (53)	3043.1 (35)	0.977 (10)
130	1	6851 (12)	4567.3 (79)	1.466 (15)
130m	5	± 2162 (25)	± 393.1 (45)	± 0.631 (10)

*) A hyperfine anomaly $A_{\Delta}^{133} = \pm 1\%$ is assumed.

FIGURE CAPTIONS

Fig. 1 : Experimental yields of cesium isotopes from a 140 g/cm² lanthanum target irradiated by a 0.7 μ A proton beam. Dots and squares indicate measurements using Faraday cup and beta counting, respectively. Our spin measurements are marked by crosses at the bottom of the figure, and previously known spins are marked by circles.

Fig. 2 : Release of rubidium from an Y/Ta foil. The curves show the remaining activity in the foil relative to the initial activity as a function of heating time.

Fig. 3 : Delay time (in terms of the time for 50% release) as a function of the inverse of the absolute temperature. The corresponding temperatures in $^{\circ}$ C are indicated at the top. Note that the activation energy for diffusion of rubidium in yttrium is given by the slope of the line. The value of approximately 50 kcal/mol is typical for diffusion processes.

Fig. 4 : Energy level diagram of a spin $I = 1$ cesium isotope in the $^2S_{1/2}$ electronic ground state as a function of external magnetic field. A positive value of a is assumed. The single-quantum transition followed in the hyperfine structure measurements in $^{122}, ^{124}, ^{126}, ^{128}, ^{130}\text{Cs}$ is indicated by an arrow.

Fig. 5 a and b : Resonance curves of the single-quantum transition $(^3/2, -^1/2) \leftrightarrow (^3/2, -^3/2)$ in ^{122}Cs and ^{130}Cs , respectively, recorded in an external magnetic field of 15.0 mT.

Fig. 6 : Block diagram of the r.f.-system used in the search for the $\Delta F = 1$ transitions in ^{122}Cs . A stable crystal-oscillator derived signal at 145.000 MHz is mixed in a doubly-balanced hot carrier diode ring mixer with the ≈ 10 MHz variable output from a programmable low-frequency synthesizer. The upper sideband component at 155 MHz is filtered out by a 5-pole bandpass filter, amplified 40 dB in a broadband amplifier and fed into a times-4 varactor multiplier. This yields an output power of about 2 W maximum into 50 Ω , at an efficiency of 25%, while suppressing the driving frequency and its other harmonics more than 26 dB referred to the output. The resolution of the output frequency is equal to the resolution of the low-frequency synthesizer times four, i.e. in this case 4 kHz. The primary source of drift was the 145 MHz source, which drifted about ± 2 ppm/h, but this could easily be corrected for by monitoring the 145 MHz signal with a frequency counter.

Fig. 7 : Results from the frequency scan for the $\Delta F = 1$ transitions in the isotope ^{122}Cs at an external field of about 30 μT . The FWHM of the "field independent" resonance line to the left is about 12 kHz.

Fig. 8 : Experimentally determined nuclear ground state magnetic moments of the cesium isotopes in the mass range 121-130. Positive signs have been chosen for the moments of ^{121}Cs , ^{122}Cs and ^{130}mCs . The two lines connect the ground state moments of the odd-A and doubly-odd isotopes, respectively. Because of the uncertainty as to position of the $3/2$ and $9/2$ states in ^{121}Cs , and of the difference in spin value compared to the heavier odd-A isotopes, the line between the moments of ^{121}Cs and ^{123}Cs is dashed. The magnetic moments of the $I = 3/2$ state in ^{121}Cs and of the $I = 1/2$

ground states in $^{123,125,127,129}\text{Cs}$ are in agreement with the Nilsson model predictions of the orbitals $[422^{3/2}]$ and $[420^{1/2}]$, respectively. The large difference between the moments of ^{122}Cs and ^{124}Cs may be explained by the configurations $1^+\{p[422^{3/2}] n[411^{1/2}]\}$ and $1^+\{p[420^{1/2}] n[411^{1/2}]\}$, respectively. We note, however, that both configurations violate the Gallagher-Moszkowski coupling rule of parallel intrinsic spins ⁴⁸). The moments of the heavier doubly-odd isotopes, being located in a transition region, are difficult to interpret in terms of simple configuration assignments. The shell-model configuration $1^+(p_{5/2} n_{3/2})$, with a magnetic moment of about 2 n.m. probably has an increasing influence as the shell closure at $N = 82$ is approached.

Fig. 9 : Portion of the nuclear chart showing stable and identified radioactive nuclides in the region $50 \leq (N, Z) \leq 82$. The cesium isotopes investigated in this work are indicated; nuclear spin measurements by a ring and hyperfine structure by the symbol $\blacksquare$. The isodeformation curves for prolate deformations obtained in the Nilsson-model calculations of Arseniev et al. [20] are also shown. From these it is clear that the lightest cesium isotopes extend into regions with expected strong nuclear deformation. Ullrich and Otten [48] have made a systematic survey of deformation parameters from different experimental sources; isotope shifts, BE2-values and quadrupole moments, of iodine, xenon, cesium and barium isotopes in the corner $Z \geq 50, N \leq 82$. The theoretical deformation values shown in the figure are in qualitative agreement with the experimental data.

Fig. 10 : Nilsson diagrams for odd-proton and odd-neutron levels, calculated with the "extrapolated" shell parameters $\kappa_p = 0.0662$, $\mu_p = 0.540$ and $\kappa_n = 0.0637$, $\mu_n = 0.450$, and hexadecapole deformation parameter $\epsilon_4 = 0$. Full lines represent levels with positive parity, dashed lines negative parity. The odd-proton levels $[420^{1/2}]$, $[422^{3/2}]$ and $[404^{9/2}]$, relevant to the discussion of the light cesium ($Z = 55$) isotopes, are drawn with heavy lines. Similarly, the odd-neutron level $[411^{1/2}]$, occupied by the 67th neutron for strong nuclear deformations, is emphasized.

Fig. 11 : Nuclear magnetic moments of the odd-proton orbitals $[420^{1/2}]$ and $[422^{3/2}]$ as functions of deformation parameter ϵ , g_s -factor ($g_s = g_s^{\text{free}}$ and $g_s = 0.6 g_s^{\text{free}}$ indicated by μ_1 and μ_2 , respectively) and shell parameters ("rare-earth" parameters $\kappa = 0.0641$ and $\mu = 0.597$, "extrapolated" parameters $\kappa = 0.0662$ and $\mu = 0.540$, and "modified" parameters $\kappa = 0.0680$ and $\mu = 0.450$, denoted by A, B and C, respectively). The experimental magnetic moments are plotted at the theoretical ²¹⁾ equilibrium deformation positions.

Fig. 1

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Fig. 2

Fig. 3

Fig. 4

Fig. 5a

Fig. 5b

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11