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**MEASUREMENT OF THE ANTIPROTON MAGNETIC MOMENT AND A
DETERMINATION OF THE SPIN-ORBIT TERM
FOR THE ANTIPROTON-NUCLEUS INTERACTION**

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(Presented by A. Kreissl)

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MEASUREMENT OF THE ANTIPROTON MAGNETIC MOMENT AND A DETERMINATION OF THE SPIN-ORBIT TERM FOR THE ANTIPROTON-NUCLEUS INTERACTION

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ABSTRACT

The measurement of the fine-structure splitting of antiprotonic X-ray transitions in heavy nuclei allows a detailed study of the particle properties and the \bar{p} -nucleus interaction.

From the splitting of the $\bar{p}^{208}\text{Pb}$ 11 \rightarrow 10 transition, the magnetic moment $\mu_{\bar{p}}$ of the antiproton was determined to an accuracy of 3×10^{-3} .

In $\bar{p}^{174}\text{Yb}$, the splitting of the last observable transition 9 \rightarrow 8 contains the information on a possible spin-orbit term of the \bar{p} -nucleus interaction. The effect of this term can be investigated for the first time.

1. INTRODUCTION

In this study of the X-ray spectra of antiprotonic atoms, the two important subjects are i) particle properties and ii) the investigation of the strong \bar{p} -nucleus interaction (SI).

In the first case, a measurement of the antiproton magnetic moment $\mu_{\bar{p}}$ is presented, allowing a test of the CPT theorem for the strong interaction. At the same time the contribution of binding effects to the magnetic moment can be analysed. In the second case, the possible existence of a spin-orbit term of the \bar{p} -nucleus interaction is investigated.

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In both instances the results are extracted from the resolved fine-structure (FS) splitting of antiprotonic X-ray transitions in heavy nuclei. The magnetic moment is deduced from those transitions that are influenced only by the electromagnetic interaction, whilst the last observable transition of each spectrum (nucleus) contains the information on the spin-orbit (LS) term of the strong \bar{p} -nucleus interaction.

The data were taken in the frame of the CERN experiments PS176 and PS186 at LEAR.

2. EXPERIMENTAL SET-UP

The experimental set-up, consisting of a trigger telescope, the target, and up to five semiconductor detectors, is shown in Fig. 1.

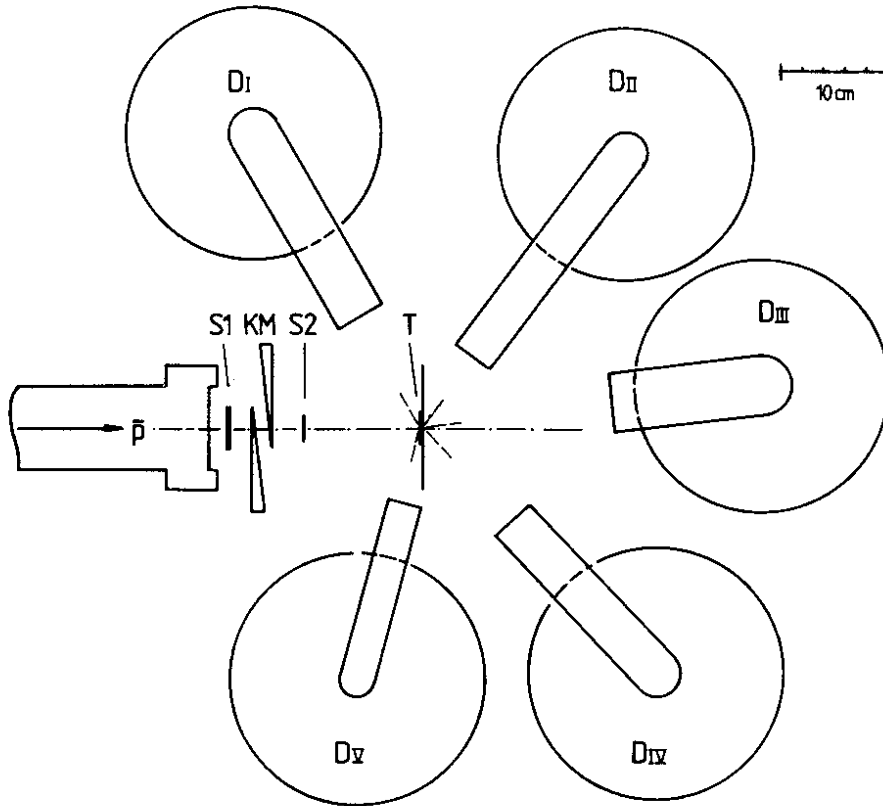


Fig. 1 Schema of the experimental apparatus

An incoming antiproton is defined by the coincidence signal of the two scintillation counters S1 and S2, and before S2 it is slowed down with the wedge moderator KM. It stops in the target T, and the resulting characteristic antiprotonic X-rays are detected with Ge semiconductor detectors, covering ranges from 10–430 up to 10–1290 keV.

Data were taken at initial antiproton momenta of 200 MeV/c (August 1984) and 300 MeV/c (May 1985).

3. THE ANTIPROTONIC ENERGY LEVELS

The energies of the antiprotonic levels are obtained from the solution of the Dirac equation, and the Hamiltonian operator for the \bar{p} -nucleus system can be written as

$$H^* = H^{em} + H^{SI} \quad , \quad (1)$$

where H^{em} and H^{SI} describe the electromagnetic interaction and the strong \bar{p} -nucleus interaction, respectively.

The operator H^{em} consists of the kinetic energy T of the antiproton, the Coulomb potential V_{Coul} , the term V_{VP1} for the first-order vacuum polarization, and a term V_κ for the contribution of the anomalous magnetic moment κ of the antiproton. Furthermore there are correction terms \tilde{V}_{corr} , depending on the measured nucleus, which are treated as perturbations, so that we have [1]

$$H^{em} = T + V_{Coul} + V_{VP1} + V_\kappa + \tilde{V}_{corr} \quad (2)$$

The second operator H^{SI} is

$$H^{SI} = \sum_i \rho(|r-r_i|) \cdot u(r) \quad , \quad (3)$$

where $\rho(r)$ stands for the nucleon distribution of a nucleus, and $u(r) = v(r) + iw(r)$ is a complex NN potential, describing the antiproton interaction with the nucleons in the nucleus. This operator is only relevant for the energy levels of the last observable transition, which are affected by the strong interaction.

The eigenvalues E^{em} of H^{em} are real, whilst the strong interaction causes an energy shift ΔE^{SI} and a broadening Γ^{SI} of an influenced energy level, so that the eigenvalues of H^* are

$$E^* = E^{em} + \Delta E^{SI} + (i/2)\Gamma^{SI} \quad . \quad (4)$$

4. The \bar{p} MAGNETIC MOMENT

According to the CPT theorem, the magnetic moments of the proton and the antiproton are expected to have the same value but opposite sign. Under this condition it is

$$\mu_{\bar{p}} = -(1 + \kappa)\mu_N \quad (\mu_N: \text{nuclear magneton}) \quad , \quad (5)$$

where $\kappa \approx 1.793$ is the anomalous magnetic moment of the antiproton due to the extended structure of the particle.

The method of antiprotonic atoms is appropriate for testing the CPT theorem. In the region of purely electromagnetic interactions $H^* = H^{em}$, and the FS splitting of an energy level (neglecting small corrections) is [2]

$$\Delta E_{nl} = [1 + 2\kappa(m/m_{\bar{p}})] (mc^2/2) \{ [Z\alpha]^4 / [n^3 \ell(\ell + 1)] \} \quad . \quad (6)$$

Here m is the reduced mass of the \bar{p} -nucleus system. By measuring the energy splitting of the allowed transitions a, b, and c between two energy levels, as shown in Fig. 2a, κ can be determined directly. The intensity ratio of these transitions is given by the relation

$$I_a : I_b : I_c = j(2j + 3) : 1 : [j(2j + 1) - 1] \quad , \quad (7)$$

from which one can see the dominance of the two components a and c with increasing total angular momentum j .

As the important criterion for the selection of a transition to be measured, the energy splitting of these components has to be larger than the detector resolution for the transition energy.

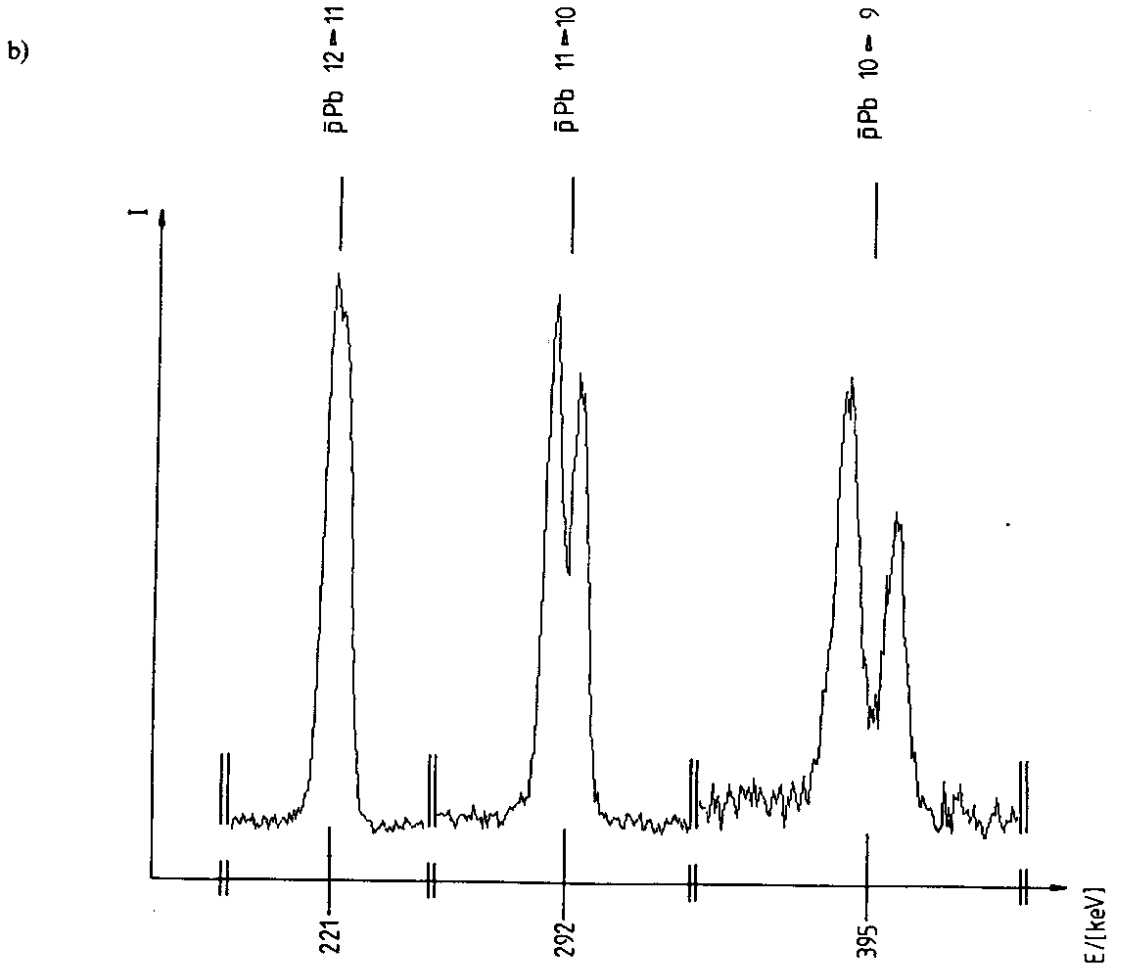
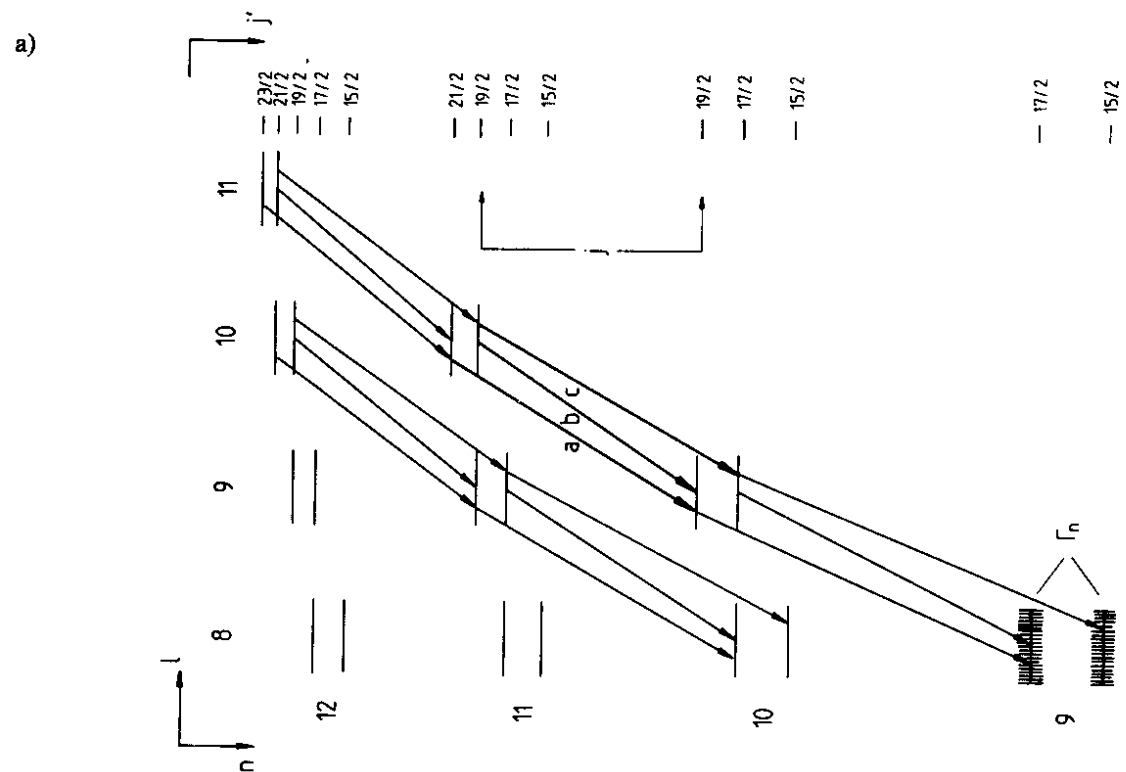


Fig. 2 Level scheme for the $\mu_{\bar{p}}$ measurement (nucleus: ^{208}Pb)

Following Eq. (6), this can be achieved using a nucleus with high Z and vanishing nuclear spin (no hyperfine structure) and a transition to the lowest level n . Furthermore, the selected line must be free from disturbing X-rays or γ -rays. These conditions are fulfilled for the transition $11 \rightarrow 10$ in $\bar{p}^{208}\text{Pb}$ [$E_{\text{theor}} = 292 \text{ keV}$; $\Delta E_{\text{theor}}(a-c) = 1195.4 \text{ eV}$].

Figure 2b shows a part of a spectrum with the clearly resolved transition $11 \rightarrow 10$. The experimental result for the FS splitting from all measured spectra is $\Delta E_{\text{exp}}(a-c) = 1199.4 \pm 5.6 \text{ eV}$, from which the magnetic moment of the antiproton is determined to be

$$\mu_{\bar{p}} = (-2.8007 \pm 0.0091) \mu_N \quad (\text{Exp. PS176})$$

Compared with the best previous measurement [3], this means a reduction of the uncertainty by a factor of ≈ 2 , and the obtained value agrees with the one for the magnetic moment of the proton [4],

$$\mu_p = (2.7928456 \pm 0.0000011) \mu_N \quad (\text{proton})$$

within the error. The new world average value for $\mu_{\bar{p}}$ is now

$$\mu_{\bar{p}} = (2.7998 \pm 0.0082) \mu_N \quad , \quad (\text{new av.})$$

which corresponds to an accuracy of 3×10^{-3} .

Finally, it should be mentioned that with semiconductor detectors and more statistics, one could reach an accuracy of at least $\approx 10^{-3}$, which would make it possible to increase the sensitivity to binding effects [5]. In this case, however, a careful study and a reduction of the systematic error would be necessary. An alternative to semiconductor detectors would be a crystal spectrometer.

5. THE SPIN-ORBIT TERM FOR THE \bar{p} -NUCLEUS INTERACTION

We now consider spin-orbit effects induced by the strong \bar{p} -nucleus interaction and described by H^{SI} . The operator H^{SI} can be constructed from the elementary NN potential $u(r)$ by a folding with the nucleon distribution $\rho(r)$. Therefore one can write

$$H^{\text{SI}} = U(r) = V(r) + iW(r) \quad , \quad (8)$$

where $V(r)$ consists generally of a central potential V_c , a spin-orbit potential V_{LS} , a tensor term V_T and a spin-spin V_σ . For $W(r)$ one normally chooses a phenomenological central potential W_c (Woods-Saxon potential), and up to now there has been no experimental evidence that further imaginary parts such as a spin-orbit term are needed. By measuring the energy shifts and Lorentz widths of the two resolved fine-structure components a and c separately (Fig. 3a), we hoped to obtain information on the contribution of such a term.

The conditions for a nucleus, whose antiprotonic X-ray spectrum should show a FS splitting of the last observable transition, are the same as before. In addition, there should be no tensor and spin-spin term to simplify the experimental and theoretical situation; thus ^{174}Yb , as an even-even nucleus with its last observable transition $\bar{p}^{174}\text{Yb } 9 \rightarrow 8$ [$E_{\text{theor}} = 402 \text{ keV}$; $\Delta E_{\text{theor}}^{\text{em}}(a-c) = 2350 \text{ eV}$], fulfils these conditions.

The measured spectrum is shown in Fig. 3b. In addition to the pure electromagnetic splitting ΔE^{em} , we observed for the first time a contribution from the strong interaction, which amounts to

$$\Delta E^{\text{SI}} = \epsilon_a + \epsilon_c = 58 \pm 25 \text{ eV} \quad ,$$

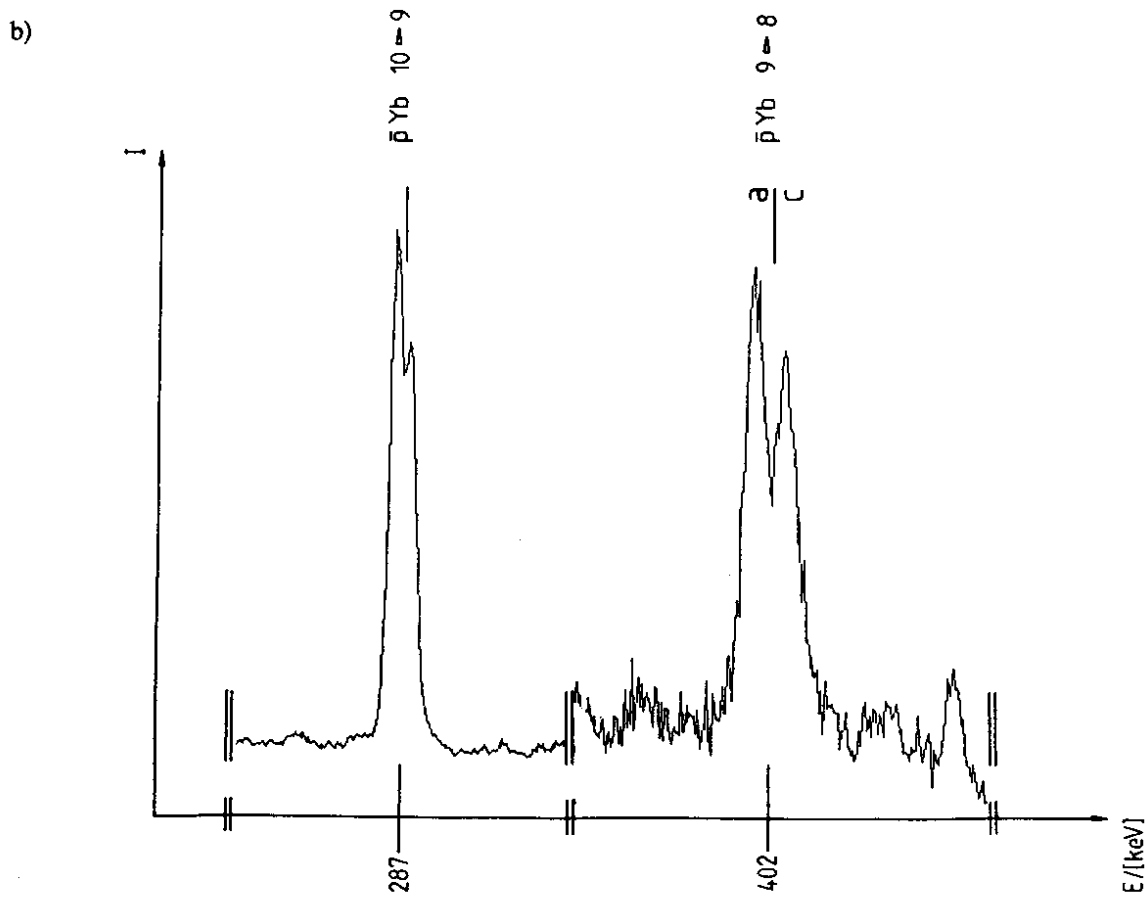
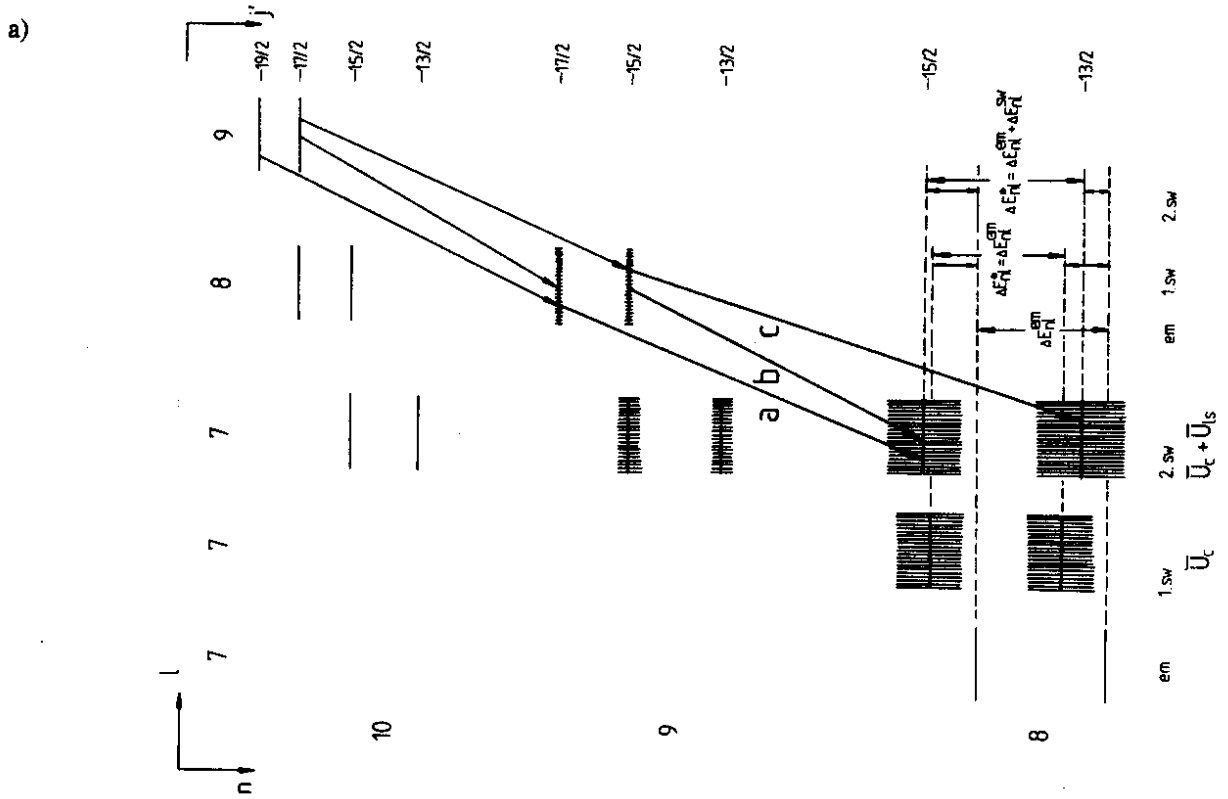


Fig 3 Level scheme for the LS effect (nucleus: ^{174}Yb)

where ϵ_a and ϵ_c describe the energy shifts of the transition components a and c. Also the Lorentz widths differ by

$$\Delta\Gamma^{SI} = -(\Gamma_a - \Gamma_c) = 195 \pm 58 \text{ eV} \quad ,$$

with an average width $\Gamma_{ac} = 1119 \pm 41 \text{ eV}$. These results observed in the transition $9 \rightarrow 8$ are essentially due to the different effect of the strong interaction on the two FS levels of the $n = 8$ state.

For the interpretation of the results, one has to take into account that the central part, $U_c = V_c + iW_c$, of H^{SI} acts differently on the two electromagnetic wave functions of the level $n = 8$, because there is a different overlap of these wave functions with the nucleus. This fact will already cause different shifts and widths of the two components a and c of the $9 \rightarrow 8$ transition. After the separation of this 'trivial' LS effect, the influence of a spin-orbit term of the strong interaction, having the form $U_{LS} = (V_{LS} + iW_{LS})LS$ can be investigated. The analysis of this effect is in progress.

Further measurements with different nuclei (e.g. ^{138}Ba) would be helpful for improving the statistics and for studying the systematics.

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