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A SUMMARY OF RECENT ANTIPROTONIC ATOM EXPERIMENTS

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ABSTRACT

The outcome of the measurements on antiprotonic atoms performed in recent years is summarized. The experiments, done at the low-energy antiproton ring (LEAR), mainly studied the strong interaction of antiprotons with nucleons. The principle goals of the investigations were the measurement of level energies and widths in antiprotonic atoms with the aim of getting information on the overall antiproton-nucleus and antiproton-nucleon interactions in general, and the study of the spin and isospin dependence of that force. Moreover, the magnetic moment of the antiproton was determined with a factor of 2 higher precision than previously known. Furthermore, the antiproton absorption was studied in detail. The analysis of the strong-interaction effects in terms of an antiproton-nucleon potential is in progress.

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1. INTRODUCTION

The use of exotic atoms is an experimental method for the test of quantum electrodynamics, the study of hadron-nucleon interactions at low energy, and the investigation of nuclei. It is also applied in the determination of the static properties of particles with high precision.

When the low-energy antiproton ring (LEAR) came into operation it was the hope of the experimenters that this well-proven technique could again be used to investigate these aspects, namely in this case the antiproton-nucleon interaction, and also to determine accurately the mass and magnetic moment of the antiproton. The eventual use of the antiproton was also envisaged as a probe for the nucleus.

Given the limited length of this paper, the entire outcome of the experimental programme concerning antiprotonic atom studies at LEAR cannot be reviewed here. However, the most recent results are summarized.

2. OBJECTIVES OF THE INVESTIGATIONS

The spectroscopy of exotic atoms is an experimental technique, which, when applied to antiprotons, focuses on the study of $\bar{p}N$ interaction and the measurement of antiproton particle properties. One of the pillars of the arguments for building LEAR was the possible existence of states (baryonium) between antiprotons and nucleons bound by strong interaction. Antiprotonic atoms would provide a means to check the existence of such objects by determining whether the interaction is attractive or repulsive at threshold and illuminating the role of annihilation. In antiprotonic hydrogen this could be studied free of nuclear effects; however, under difficult experimental conditions. In heavier atoms the binding of the nucleons in the nucleus has complicated the interpretation of data, yet the experimental set-up seemed to be less sophisticated. However, the objectives of the antiprotonic atom studies went far beyond that. They can be summarized as below.

2.1 Antiprotonic hydrogen

- a) Determination of the s-wave scattering length.
- b) Search for states bound by strong interaction.

- c) Study of antiproton-proton annihilation.
- d) Study of the antiproton atomic cascade for various target densities.
- e) Determination of s-wave and p-wave annihilation.

2.2 Heavier antiprotonic atoms (strong interaction)

- a) Study of antiproton-nucleus interaction (Z , A , and ℓ dependence).
- b) Study of isospin dependence (isotope effects).
- c) Study of spin-orbit dependence (fine-structure effects).
- d) Study of antiproton annihilation mechanisms.
- e) Measurement of neutron distributions at the nuclear surface.
- f) Search for long-range quantum chromodynamics contributions.

2.3 Heavier antiprotonic atoms (electromagnetic interaction)

- a) Determination of the magnetic moment of the antiproton.
- b) Study of the antiproton interaction with the electron cloud.
- c) Study of antiproton polarizability.

The results of some of these studies were reviewed recently¹⁻³). In the following we shall choose a few of the most recent results amongst the list of subjects given above.

3. ANTIPROTONIC HYDROGEN

The determination of energies, widths, and intensities of Lyman X-ray transitions in antiprotonic hydrogen was the goal of three experiments at LEAR applying different experimental approaches. These transitions were expected to be of low intensity owing to the Stark effect which, in dense hydrogen targets, mixes atomic s-states with higher angular momentum states. The admixture of s-states leads to antiproton-proton annihilation high up in the cascade, preventing the antiproton from reaching low-lying levels and hence suppressing the intensity of the Lyman lines which are needed for the determination of the antiproton-proton s-wave scattering length. This triggered the measurement of the intensity of X-ray transitions to the 1s and to the 2p states as a function of

target density in order to determine the amount of s-wave annihilations in higher levels. Apart from that, there is a general interest in knowing the ratio of s-wave to p-wave annihilation in hydrogen in order to impose limits on annihilation channels by applying selection rules.

In experiment PS171 shift and broadening of the $1s$ state were determined from the X-rays measured in drift chambers surrounding the gaseous target at ambient pressure and temperature⁴⁾. Because of the large solid angle covered by the detector, coincidence measurements could be performed between X-rays and neutral annihilation as well as charged annihilation products detected in chambers placed around the cylindrical target inside a magnetic field⁵⁾.

In experiment PS174 a cryogenic target was used, which allowed the target density to be varied by changing the temperature of the hydrogen gas. The X-rays were measured⁶⁾ with a Si(Li) solid-state detector providing a high resolution but covering only a small solid angle. Recently⁷⁾, the sensitivity of this experiment was considerably increased by adding a gaseous scintillation detector⁸⁾, which covered a large solid angle. Figure 1 shows the spectrum of the Lyman region (a smooth background subtracted) with a clear signature of the Lyman- α line and the series limit. The upper part shows the X-rays for 700 Torr and the lower one for 190 Torr hydrogen gas pressure. The increase of the intensity of the $2p \rightarrow 1s$ transition with respect to the series limit for decreasing target pressure is clearly seen and demonstrates distinctly the influence of the Stark mixture.

In experiment PS175 a new experimental technique (cyclotron trap) was applied⁹⁾ in order to slow down antiprotons in a thin gaseous target. Antiprotons were radially injected into a chamber, filled with hydrogen gas at low pressure, and placed in between the coils of a superconductor. Exposed to continuous energy loss the antiprotons spiralled to the centre of the chamber, where they were captured into atomic states. The emitted X-rays were detected with solid-state detectors located off the magnetic field axis. This method allowed the use of a very low density target providing the possibility of almost turning off the Stark effect. Figure 2 displays the X-ray

spectrum between 6 and 14 keV for a target pressure of only 30 mbar, showing also a fit to the $2p \rightarrow 1s$ transition and to the series limit of the Lyman series¹⁰⁾.

The results of the three experiments^{4-8,10)} for the shift ϵ (measured minus electromagnetic energy) and width of the ground state of antiprotonic hydrogen are shown in Fig. 3, which differ not very much from theoretical predictions¹¹⁻¹⁵⁾ also shown there. Hence one can conclude that the basic predictions of the potential models are reproduced; however, more precise data are needed in order to distinguish between the different approaches. From the measurement of shift and width in antiprotonic atoms the ratio ρ of the real to the imaginary part of the antiproton-nucleon scattering amplitude at rest can be determined. It is a remarkable feature that the antiprotonic atom measurements point to negative values around unity for this quantity that differ from the values determined from Coulomb interference measurements at low energies.

In future experiments one should try to determine the strong-interaction effects in the $1s$ states more precisely and should aim at the measurement of the effects in the singlet and triplet state separately. Also an attempt should be made to measure the energies and widths of the $2p$ states to gain information on the p -wave scattering volume. This could certainly provide new input for the ρ -parameter problem.

4. HEAVIER ANTIPROTONIC ATOMS

Heavier nuclei were investigated in experiments PS174, PS175, PS176, and PS186. The goals were manifold. We shall discuss a few aspects in the following subsections.

4.1 Strong antiproton-nucleus interaction

4.1.1 General studies

The strong antiproton-nucleus interaction is detectable as in the case of antiprotonic hydrogen through the shift and broadening of atomic levels. When the overlap of the antiproton wave function with the nucleus becomes sufficiently large the antiproton is absorbed before it can undergo an electromagnetic transition to a lower state. This leads to the situation that the antiproton atomic cascade, which is started after atomic

capture, is abruptly stopped from a certain level onwards. The last X-ray transition to this level contains essentially all the information about the strong antiproton-nucleus interaction. Its energy is shifted with respect to the electromagnetic value, it is broadened with respect to the electromagnetic transition width, and it is attenuated in intensity because absorption of the antiprotons takes place already in the last but one observable level.

Owing to the level binding energy increasing as Z^2 the antiproton is absorbed mainly in the 2p state in helium, while in thorium this happens already in the 9k state. This feature allows the study of strong-interaction effects in different angular momentum states¹⁶⁻²³).

4.1.2 E2-resonance effect

In particular cases the shifts and widths of 'hidden' levels can be determined indirectly when an atomic transition is energetically degenerated with the E2 excitation from the nuclear ground state. Then through 'inner conversion' the nucleus is excited, leading to an abnormal attenuation of an atomic X-ray transition. This effect was observed (in experiment PS186) in molybdenum isotopes¹⁹) and recently also in ^{148}Nd ²¹).

4.1.3 Isotope effects

Antiprotons may be absorbed by protons or by neutrons in the nucleus. This allows the investigation of the isospin dependence of the antiproton-nuclear force by comparing strong-interaction effects in isotopes of the same element. Large isotope effects were found in the oxygen^{17,18}) and the nickel isotopes²²), while in the helium²³) and lithium²⁰) isotopes they are very small.

4.1.4 Spin-orbit effect

As for the nucleon-nucleon interaction we expect the spin-orbit force to play an important part also in the $N\bar{N}$ system. This can be investigated by measuring the shift and broadening separately in atomic fine-structure levels as pointed out some time ago²⁵). First evidence for such spin-orbit effects was

found in ^{174}Yb ^{3,24}). The difference in the shift is 58(25) eV and in the width 195(58) eV for the two fine-structure levels²⁴).

It is not possible to discuss the outcome of all the experiments in detail here. Therefore, the results of the strong-interaction measurements are summarized only in the plot of Fig. 4. In order to present the data in a clear way the shifts ϵ and the widths Γ were divided by a scaling factor ϵ^* and Γ^* as defined in Fig. 4. The scaling factors represent to a certain extent the overlap of the antiproton wave-function with the nucleus. The such normalized values in Fig. 4 scatter around value of 1 eV for strong interaction effects in the 2p up to the 7i level and for nuclear masses from A=3 to 138. This regularity is remarkable.

4.2 Magnetic moment of the antiproton

The magnetic moment of the antiproton was determined from the size of the fine-structure splitting of the $11 \rightarrow 10$ transition not perturbed by strong interaction in ^{208}Pb with the accuracy improved by a factor of 2 with respect to the previous world average. The new value is -2.8007(91) nuclear magnetons²⁴), which agrees within the errors with the corresponding value for the proton.

4.3 Antiprotonic cascade

The intense low-energy antiproton beams made it possible to use thin targets. Especially in the cyclotron trap (experiment PS175) antiprotons were stopped in gaseous targets of pressures as low as 20 mbar. This led to the observation of a new effect. When antiprotons are captured in a highly excited atomic state they de-excite by Auger transitions (ejection of an electron from the cloud). Stepwise de-excitation should lead in dilute gases to a complete ionization of the atom since electrons cannot be refilled sufficiently fast as, for instance, in a liquid or solid target. As soon as all electrons are stripped off, the de-excitation proceeds exclusively through X-ray transitions where all of them must have the same intensity. This was observed in experiment PS175²⁶). As long as the de-excitation energy is smaller than the electron binding energy, electrons cannot be ejected and the energy gained is released as

an X-ray. However, when the antiproton transition energy exceeds the electron binding energy of a shell the electron can be ejected and therefore the following X-ray transitions are less intense. This is very nicely seen in Fig. 5, which shows the attenuation of the antiprotonic X-ray transitions in argon as soon as the binding energy of the 1s electrons is exceeded (from the transition 17 → 16 onwards).

4.4 Antiproton absorption

Antiproton absorption in nuclei was studied in experiment PS176 and PS186 through the investigation of residual nuclear gamma spectra and the spectroscopy of neutral and charged particles. Most of the data are still under evaluation; however, first results of the analysis of spectra of residual nuclei indicate that up to 30 nucleons might be emitted after antiproton annihilation²⁷⁾.

5. THEORETICAL CALCULATIONS

A number of authors calculated strong-interaction effects in antiprotonic atoms²⁸⁻³⁶⁾ using different antinucleon-nucleon potentials and folding in nuclear effects. We are not yet in a position to distinguish between the models, as we still need a complete analysis of the data. However, the recent measurements of the strong-interaction effects in antiprotonic hydrogen allow determination of the antiproton-proton scattering length which differs not very much from theoretical predictions. Bounds on the antiproton-neutron scattering length can probably be deduced from measurements of isotope effects. A strong spin-orbit dependence in the antiproton-nucleon interaction was predicted by theory. While polarization measurements are not yet conclusive, the first experimental indication for L-S dependence comes from antiprotonic atoms.

6. CONCLUSIONS

The study of the antiproton-nucleon interaction in antiprotonic atoms is a field of high activity. After the first experiments at LEAR a large amount of information is available. Only a fraction of it could be discussed here. From future experiments we expect still higher precision and more

information on details of the antiproton-nucleon interaction, such as isospin and spin-orbit effects. It might also be that hyperfine-interaction effects become measurable which would allow the study of spin-spin effects. Moreover, the antiproton absorption will be studied in further detail with the goal of obtaining more information, for instance, on the strange-particle creation in antiproton annihilation in nuclei and on multibody annihilation.

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Figure Captions

- Fig. 1 : X-ray spectrum of the Lyman region (a smooth background subtracted) measured with a gas scintillation detector for 700 Torr and for 190 Torr hydrogen gas⁷). (Courtesy of C. Batty and W.J.C. Okx.)
- Fig. 2 : X-ray spectrum of antiprotonic hydrogen between 6 and 14 keV for a target pressure of only 30 mbar⁷). The fit to the $2p \rightarrow 1s$ transition and to the series limit of the Lyman series is also shown. (Courtesy of L.M. Simons.)
- Fig. 3 : Experimental and theoretical values for the shift ϵ and width Γ of the $1s$ state in antiprotonic hydrogen.
- Fig. 4 : Normalized experimental shifts ϵ and widths Γ for various levels in antiprotonic atoms as a function of nuclear mass A .
- Fig. 5 : X-ray spectrum of antiprotonic argon showing the attenuation of the transitions as soon as the binding energy of the $1s$ electrons is exceeded (from the transition $17 \rightarrow 16$ onwards). (Courtesy of L.M. Simons.)

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5