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INVESTIGATION OF THE HADRONIC INTERACTION BY MEANS OF ANTIPROTONIC X-RAY SPECTROSCOPY*

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With the advent of high intensity antiproton beams at LEAR ultimate resolution spectroscopy of antiprotonic X-rays became feasible. We describe an experiment that uses the cyclotron trap to produce a high intensity antiprotonic X-ray source. The Kα radiation of antiprotonic atoms is measured with a CCD detector system, while the Lα radiation is analysed with ultimate resolution and high precision by specially optimized doubly focussing crystal spectrometers using two dimensional position sensitive CCD detectors. MC simulations of the experiments, scheduled for 1994, show that new information about the hadronic interaction and a crucial check of our basic understanding can be expected.

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1. Introduction

One of the most challenging fields of fundamental physics is the investigation of the hadronic interaction in the nucleon–antinucleon system. In the classical domain of nucleon–nucleon interaction, collision and reaction experiments have revealed a large bulk of information about the hadronic interaction. On the other hand, the advent of antiparticle beams enabled the investigation of two additional phenomena: the nucleon–antinucleon annihilation and the formation of electrodynamically bound nucleon–antinucleon systems [1, 2]. This latter case permits the use of spectroscopic methods to study the hadronic interaction at threshold which is not accessible by any

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other technique [3]. Of special interest is here the investigation of the lightest nucleon–antiproton system as it allows a crucial check of our theoretical insight in the hadronic interaction [4].

So far only spin-averaged measurements have been performed, where the basic limitation is set by the experimental resolution (Refs [1–10] in [4]). To overcome these restrictions we have set up an experiment with ultimate resolution [4]. It uses the low energy antiproton beam of LEAR which is captured in the cyclotron trap to yield a high intensity antiprotonic X-ray source. The Kα radiation is measured with a special CCD detector, while simultaneously, the Lα radiation is analysed by Bragg crystal spectrometers. For a systematical investigation we will study the antiprotonic Kα and Lα transitions in the H and He isotopes.

2. The experiment

The experimental setup is shown in Fig. 1. The low energy $\bar{p}$ beam of LEAR with a momentum of 105 MeV/c is injected tangentially into the gas chamber of the cyclotron trap [5, 6]. This is a superconducting split coil magnet with a mean field of 4.2 T. Due to collisions with the residual gas the antiprotons lose energy and spiral down to the center of the trap. There, in a volume of a few cm^3, the antiprotons are captured in high-lying bound atomic states with quantum number n between 30 and 40. By a proper choice of the gas pressure (20 to 30 mbar) the radiative deexcitations can be favoured so that up to 80% of the bound antiprotons run down the atomic cascade predominantly populating the circular transitions. Therefore in the $n = 3$ shell mainly the D states are populated decaying via Lα transitions to the $n = 2$ P states. Due to the long range part of the hadronic interaction these levels, and even more the $n = 1$ S states, are shifted and broadened. In this part of the cascade the annihilation channel becomes more and more dominant. Due to the multiplet splitting of the atomic levels a high resolution measurement of the connecting transitions allows to determine the corresponding states of the hadrons uniquely.

In this way the center of the cyclotron trap provides an intense source of antiprotonic X rays.

The Kα transitions, which are expected to be rather broad (several hundred eV) [7], are measured by a special CCD-detector system which is introduced close to the center of the cyclotron trap. It is capable to reject the background rather efficiently and yields an energy resolution of the order of 150 eV. The Lα transitions, in which a multiplet splitting of the order of 100 meV is expected [7], are analysed by means of the two doubly focussing crystal spectrometers I and II. They are arranged in a symmetrical way so that the independent systems can be operated simultaneously.

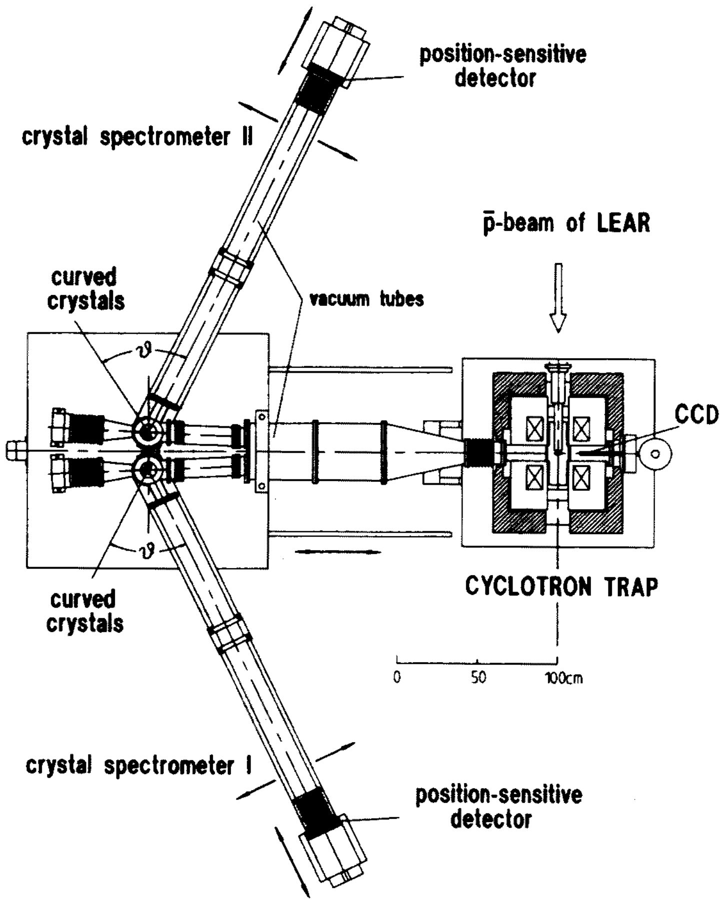

Fig. 1. Schematic view of the experimental setup.

Photons with energy E hitting onto a crystal are reflected only within a narrow angular range around the Bragg angle ϑ. Using the dynamical theory the angular width $\Delta\vartheta$ can be estimated [8]. For the typical $L\alpha$ transitions in the $\bar{p}p$ system $E = 1.7$ keV. Using a (100) quartz crystal we obtain $\vartheta = 57°$ and $\Delta\vartheta = 24$ arcsec corresponding to an energy resolution of 130 meV. With a radius of curvature of 3 m this yields a distance of 0.3 mm in a detector located on the Rowland circle. It fits nicely to the spatial resolution of a CCD detector. As the X ray image in the detector plane is curved, a two-dimensional position sensitive detector allows to correct this effect, maintaining the initial resolution. With the conventional cylindrically bent crystals the image height is more than twice the crystal diameter. By means of a new developed technique it become possible to curve the crystals spherically. Thus the image height is drastically reduced allowing for a small size detector with an accordingly reduced background noise. In this place a special CCD detector system will be installed that has been developed by the MPE, Munich [9, 10]. It uses the principle of sideward depletion and is more than 90% efficient in the interesting energy range. The overall efficiency, including the solid angle and using quartz crystals with 10 cm diameter, is estimated to be around 10^{-6} which can be doubled by the operation of the twin spectrometer system.

The first experiment on-line at the LEAR $\bar{p}$ beam is scheduled in the second half of 1994. So far only MC simulations based on current theoretical predictions are available.

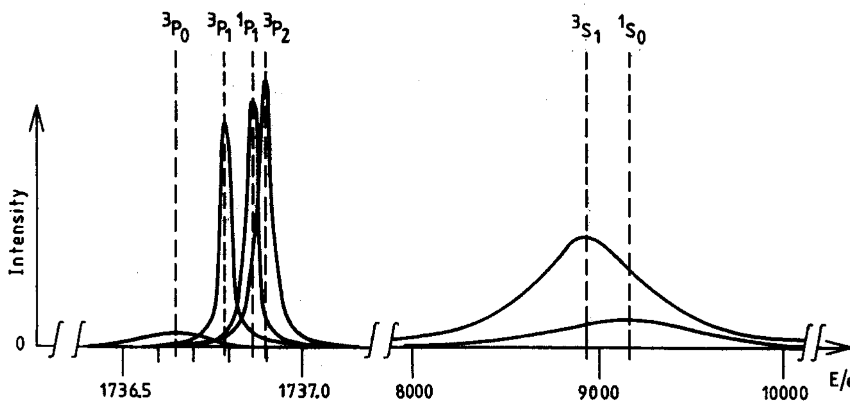

Fig. 2. The Lα and Kα spectrum of $\bar{p}p$ the system based on the theoretical predictions of [7]. The hyperfine states are labelled according to their quantum numbers. The different energy scale for Lα and Kα should be noted.

In Fig. 2 is shown the Lα and Kα spectrum of the $\bar{p}p$ system based on the predictions of [7]. Of special interest is the resolved measurement of the $^3P_0$ state as it yields direct information about the isoscalar tensor term of the hadronic interaction, whereas the average of the other close-lying P states gives indication about the existence of poles below the threshold. Correspondingly the study of $n = 1$, $^3S_1$ and $^1S_0$ hyperfine levels, which can be resolved analytically in the present experiment will give information about the spin–spin interaction at threshold. The improvement in accuracy that can be achieved with the present apparatus is shown in Fig. 3 for the Lα transitions in the $\bar{p}p$ system. With the help of MC simulation we estimated the results of an experiment with $2 \cdot 10^{11}$ antiprotons corresponding to a beam time of 3 weeks as main user at the LEAR facility. The uncertainties of the widths and of the energy shifts of the $^3P_0$ level and the average of the $^3P_2$, $^3P_1$ and $^1P_1$ levels are given in the upper and lower part of the figure, respectively. They are compared to previous experimental results on

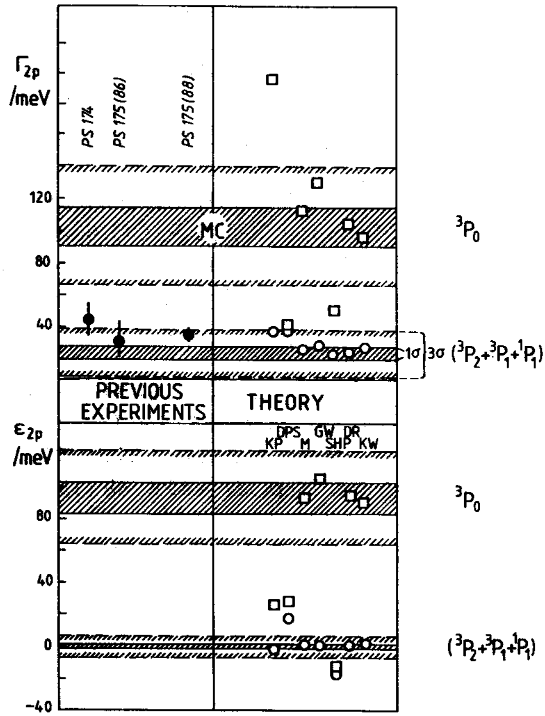

Fig. 3. Comparison of the estimated precision of the present experiment, using a MC simulation with $2 \cdot 10^{11}$ antiprotons, with previous experimental results (left side) and theoretical predictions (right side). In the upper (lower) part the situation for the line width (energy shift) is shown for the Lα transitions in $\bar{p}p$. The hatched areas denote the standard deviation 1σ, the corresponding fringe lines give the 3σ limit. Open squares denote the theoretical predictions for the $^3P_0$ level, the open circles indicate the average of the $^3P_2$, $^3P_1$ and $^1P_1$ levels. It is obvious that the present experiment will provide a crucial test for the theoretical understanding. The symbols have the following meaning: PS174 [3 in [4]], PS175(86) [8 in [4]], PS175(88) [11], KP [32 in [4]], DPS [20 in [4]], M [15 in [4]], GW [16 in [4]], SPH [19 in [4]], DR [11–14 in [4]], KW [12].

the left side and to several prominent theoretical predictions on the right side. Present experimental results, as are indicated in Fig. 3 for $p\bar{p}$, are even more rare for the other H isotopes and ^{3}He. To enable a systematic study of the antiproton–proton and antiproton–neutron interaction, it is foreseen to measure all relevant parameters in these isotopes as well.

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