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THE ANTIPROTONIC X-RAY SPECTRUM OF LIQUID HELIUM^{x)}

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ABSTRACT

The X-ray spectrum of liquid $\bar{p}$ -He has been measured. The energies and relative intensities of the X-ray transitions feeding the 3d and 2p levels were determined. The analysis of the L series yielded a strong interaction shift ϵ and width Γ for the 2p level of $\epsilon_{2p} = (-50 \pm 18)$ eV and $\Gamma_{2p} = (90 \pm 70)$ eV.

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Recently, considerable attention has been paid to the antiproton-nucleon interaction. Particularly the low-energy and threshold behaviour of the $\bar{p}N$ interaction has gained great interest. The interaction of antiprotons with matter at rest can be studied by means of antiprotonic atoms. This has been done for complex nuclei and isotope effects have been used to disentangle $\bar{p}n$ and $\bar{p}p$ effective interactions [1]. Only in very light nuclei has the antiproton a chance to reach low-lying atomic states, such as 2p and 1s, before it is absorbed. In that respect, helium is of particular interest, since the optical potential for the $\bar{p}$ interaction can be tested for these states. In addition, the atomic cascade in liquid helium shows the influence of the Stark mixing of atomic levels and that of the external Auger effect, which play a dominant role in the cascade of hadronic hydrogen. Experimentally, it is a challenge to measure the $\bar{p}$ -He spectrum owing to its low energetic X-ray transitions. We succeeded in measuring the X-ray spectrum and present the data on strong interaction effects and on the atomic cascade.

The experiment has been performed at the k_{18} beam of the CERN PS. Antiprotons of 820 MeV/c were extracted from an internal target and brought to rest in a liquid ^4He target. The antiprotons were identified by a telescope consisting of scintillation and Čerenkov counters. A total of 35×10^6 antiprotons were stopped. The X-rays were detected with two small Si(Li) detectors placed perpendicular to the beam. The liquid helium target consisted of a thin-walled (200 μm) mylar cylinder of 12 cm length and 12 cm diameter. At each side facing an X-ray detector, thin mylar windows of 25 μm thickness and 25 mm diameter were introduced. The target was wrapped in 100 layers of 4 μm thick aluminized mylar. The windows were covered by only four layers. This container was hanging in a cylindrical vacuum tank made of 2 mm titanium and with 200 μm thick mylar covers at beam entrance and exit. Again mylar windows of the same dimensions as above were introduced at the site of the X-ray detectors.

The Si(Li) detectors had a surface of 80 mm² and 200 mm² and a thickness of 5 mm. The resolution of the smaller detector was 200 eV FWHM at 5.6 keV. Only

this one was used to measure the shapes of the X-ray lines. A more detailed description of the experimental set-up is given elsewhere [2]. A similar set-up was used for the measurement of the X-ray spectrum of π^- - ^4He [3].

The calibration of the detectors was done regularly with radioactive sources in random coincidence with different telescope triggers. The stability of the system was frequently controlled by a test pulse coupled directly into the pre-amplifier of the Si(Li) detectors. X-rays from the target were detected in coincidence with the trigger of a stopped antiproton. The coincidence window was 400 nsec wide. The pulse height and time of arrival of each detector signal were recorded event by event (Fig. 1). Thus a two-dimensional spectrum was generated. In the off-line evaluation the coincidence condition was constricted in such a way that the best peak-to-background ratio was obtained. For example, the time resolution at 11 keV was 10 nsec (FWHM). There were no delayed X-rays from $\bar{p}$ -He. Such an "off-line timed" spectrum is shown in Fig. 2. A small accidental background as deduced from the delayed spectrum was subtracted.

The spectrum shows clearly the L ($n \rightarrow 2$) and M ($n \rightarrow 3$) series up to their series limits with high resolution and efficiency, even at low energy. The K_{α} line, which should be around 60 keV, was not seen. The background is low and smooth. The background lines ($\bar{p}$ -C) from the mylar container are very weak.

The shapes of the peaks were analysed, allowing for asymmetries on both sides of the lines. All peaks turned out to be symmetric. Since the fine structure splitting in $\bar{p}$ -He is very small, it was neglected. The spectrum was fitted with Gaussians for the M series, Lorentzians folded with Gaussians for the L series, and linear or quadratic shapes for the background. The resolution was taken from the calibration spectra and kept fixed for the determination of the Lorentzian. In addition, the background was fitted separately, excluding regions of peaks. The influence on the fit results of fit regions, of the shape and magnitude of the background, and of changes in the resolution polynomial were investigated in great detail and accounted for in the error.

Table 1 shows the results of the fits. In column 2 the calculated energies of the transitions, including all significant electromagnetic contributions, are displayed. The fitted energies with their errors are shown in column 3.

A particular procedure was applied to correct the measured intensities for absorption and the detector efficiency. The mylar container was cut up and placed back in the original experimental set-up. With different radioactive sources the response of the detector system was measured at several points inside the target. These data were fitted by an analytic response function, taking into account absorption and detection efficiency of the Si(Li) detector. Then the absorption in helium was calculated, integrating over the entire target and weighing each target point with its response and the stopping distribution of the antiprotons. Thus the final intensity correction was obtained. The sources covered the energy range from 4.5 keV to 60 keV and were calibrated in their intensities to 3%, thus allowing the determination of the absolute detector efficiency (Fig. 3). Additionally, another method was used to determine the shape of the efficiency curve. From the intensity ratio K_α/K_β of the X-rays of the source, the slope of the efficiency function at that energy was determined. The sources were selected in such a way that the K_β line of the lower energetic source overlapped with the energy of the K_α line of the higher energetic source. Thus, an efficiency function could be constructed from the slopes, which was independent of absolute intensity measurements. Both methods gave, within the errors, the same shape of the efficiency function. The corrected intensities of the observed transitions are listed in column 4 of Table 1. They are normalized to the $4 \rightarrow 3$ transition. The errors given are the total errors.

For the determination of the strong-interaction shift ($\epsilon = E^{\text{exp}} - E^{\text{th}}$) and width Γ of the 2p level all members of the L series were used. In the fits their energy spacings were kept fixed and their Lorentzian widths were varied commonly. The results are

$$\epsilon_{2p} = (-50 \pm 18) \text{ eV}$$

$$\Gamma_{2p} = (90 \pm 70) \text{ eV}$$

$$Y_{3 \rightarrow 2} = (77 \pm 22) \% .$$

The yield $Y_{3 \rightarrow 2}$ is the intensity of the $3 \rightarrow 2$ transition normalized to a 100% population of the 3d level. The absolute yield of the $3 \rightarrow 2$ transition is about 1% per stopped $\bar{p}$.

The $\bar{p}$ -He spectrum shows that many members of a series with $\Delta n > 1$ are present and their relative intensities (Table 1, column 4) underline that they participate strongly in the de-excitation process. This indicates that the cascade proceeds to a considerable amount via non-circular ($\ell < n - 1$) levels. Cascade calculations, including radiative transitions, internal Auger effect, and strong absorption, reproduce the intensity ratios very well, if one assumes an initial distribution more central than usual. A similar initial distribution was found for the π^- cascade in liquid hydrogen [4]. However, such a central cascade may also be produced by the Stark effect, if the $\bar{p}$ -He atom is exposed to strong electric fields, as may happen during collisions with neighbouring atoms. Such density-dependent effects have been observed [3,5] in π^- -He, where the intensity ratio of $K_\alpha/K_\beta < 1$ in the liquid phase. Owing to these effects, the de-excitation from the 4f level may take place also by radiationless transitions. The unknown contribution of these processes does not allow the derivation of the strong interaction width of the 3d level by intensity balance [6].

The results obtained from the lines of the L series show, however, that strong interaction effects of the 2p level can be observed. The strong interaction shift in the 2p level turns out to be repulsive. Optical potential calculations using the previously established parameters [1] give, for the 2p level,

$$\epsilon_{2p}^{th} = -8 \text{ eV} \quad \text{and} \quad \Gamma_{2p}^{th} = 28 \text{ eV} .$$

One notices that the measured energy shift ϵ_{2p} is not well reproduced by such calculations whereas the width is not sufficiently determined in order to make a meaningful comparison. The observed X-ray intensity ratios indicate a rather central cascade. This may be due to an initial capture predominantly into atomic levels with low angular momentum. The Stark effect, which is very strong in liquid hydrogen, would also explain such a cascade qualitatively.

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Table 1

Experimental results from $\bar{p}$ -He

Transition	E^{th}	E^{exp}	I^{rel}
1	2	3	4
4 $\rightarrow$ 3	3.887	3.945 ± 0.055	100.0 ± 11.0
5 $\rightarrow$ 3	5.6884	5.676 ± 0.028	44.0 ± 5.0
6 $\rightarrow$ 3	6.660	6.663 ± 0.035	17.2 ± 3.5
7 $\rightarrow$ 3	7.249	7.295 ± 0.045	9.7 ± 3.1
8 $\rightarrow$ 3	7.623	7.769 ± 0.075	7.3 ± 3.0
3 $\rightarrow$ 2	11.129	11.071 ± 0.008	135.0 ± 24.0
4 $\rightarrow$ 2	14.970	14.956 ± 0.026	26.0 ± 6.1
5 $\rightarrow$ 2	16.766	16.723 ± 0.037	17.7 ± 4.9
6 $\rightarrow$ 2	17.742	17.772 ± 0.033	22.6 ± 5.7

Figure captions

- Fig. 1 : Scatter plot of the X-ray events of $\bar{p}$ -He. Each point indicates the energy and arrival time of an event.
- Fig. 2 : Timed X-ray spectrum of $\bar{p}$ -He.
- Fig. 3 : Detection efficiency for 80 mm² detector including absorption in helium and mylar. The maximum is normalized to 10.

$\bar{p}$ -He

Fig. 1

Fig. 2

Fig. 3