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Abstract

HELIUMTRAP (PS205) investigates the recently discovered anomalously long-lived states of antiprotons in various helium media. An overview is given of experiments stopping antiprotons in several phases of helium performed at LEAR in the last two years.

1. INTRODUCTION

In an experiment at the National Laboratory for High Energy Physics in Japan (KEK) it has recently been discovered that about 3 % of antiprotons stopped in liquid helium do not annihilate immediately with mean lifetime $\tau \leq 10^{-12}$ s due to nuclear absorption as it was commonly believed (and as the remaining 97 % do). On the contrary, those $\bar{p}$'s survive for times in the order of several μ s[1], about 6 orders of magnitudes longer than expected. This very exciting result was the start of a series of measurements carried out at LEAR in 1991 and 1992, where the low-energy and high-rate antiproton beam allows the measurement of $\bar{p}$ lifetimes even in low density gas targets.

A possible explanation for the long lifetimes of $\bar{p}$ in He can be based on an atomic

model of Condo [2], which was proposed in 1964 to explain the anomalously large free-decay fractions of negative mesons in liquid helium. Later on Russel [3] extended this model and also predicted the metastability of $\bar{p}$ in He. According to this model, some fraction of stopped negative mesons or hadrons X^- occupy metastable circular orbits of large principal quantum number in a neutral exotic He atom $X^-e^-He^{++}$. In the case of $\bar{p}$, the metastable atom $\bar{p}e^-He^{++}$ has a very unusual structure and possesses some of the attributes of both atoms and molecules, e.g., it could be called an *exotic helium atom* since one e^- is replaced by a $\bar{p}$, or an *exotic hydrogen atom*, since $\bar{p}He^+$ is an extended pseudo-proton, or an *exotic diatomic molecule*, where one nucleus has a charge of +2 and the other "nucleus" has a charge of -1. More details on the structure of those "atomcules" can be found in another publication [4].

The observed $\bar{p}$ -annihilation time spectrum (spectral shape, lifetime components, delayed fraction, ...) should in principle be related to

1. the level lifetimes $\tau(n, \ell)$,
2. the population of metastable states $P(n, \ell)$, and
3. the destruction of metastable states $(n, \ell) \rightarrow (n', \ell')$ through collisions etc.

Although the level lifetimes have been calculated [3,5], no full explanation of the observed time spectrum in liquid helium has been reached yet. The time spectrum is expected to depend on the density and the phase of helium media. It may also depend on the presence of foreign atoms/molecules, which are expected to change the energy spectrum $w(E)$ and thus the population $P(n, \ell)$ of $\bar{p}$ at the formation stage, and/or to cause collisional deexcitation. So, in the PS205 HELIUMTRAP we started systematic studies of delayed $\bar{p}$ annihilation in various helium media besides liquid helium.

Section 2 gives details on the experimental method used, and sections 3 and 4 present recent data on $\bar{p}$ annihilation in pure helium of different phases (gaseous, liquid, and solid) and in helium gas with admixtures of other gases.

2. EXPERIMENT AND ANALYSIS

Up to now HELIUMTRAP had two run periods, in two different areas of the LEAR experimental hall with different beam momenta: first in M1 at 105 MeV/c in 1991, and then in C1 at 200 MeV/c in 1992. The first run in 1991 used only a room temperature gas target to study pure helium gas as well as helium gas with admixtures of impurities. Results of this period are being reported [4], and a detailed description of the experiment will be published elsewhere [6].

In 1992, we started a series of measurements using various target systems. The longer antiproton range at 200 MeV/c permitted us to use a thicker entrance window into the gas vessel, which in turn allowed pressures up to 20 bar to be attained. We also investigated the effect in low temperature gases as well as in liquid and solid He.

2.1 Experimental setup

The basic setup is shown in Fig. 1. The beam line vacuum ends with a 100 μm thick Be window. After an air gap of 15 cm, a 1 mm thick plastic scintillator (beam counter B) of 10 mm diameter was placed. An additional ring-shaped counter (A), which served as a veto counter as well as a monitor of the incoming beam halo, was placed about 1 cm upstream of B.

The framework which supported the target and the detectors for charged annihilation products (pions) was placed just after these beam counters. We used two different counter systems: One is a hodoscope array (not shown in Fig. 1) to measure the $\bar{p}$ stopping position. The other comprises 4 sets of telescope counters T_A , T_B , T_C and T_D . The counters of one side consist of one inner scintillator T1 and three outer scintillators T2a, T2b and T2c. The telescope array covered a solid angle of π and was divided into 12 elements to reduce the probability of two or more pions hitting the same telescope. This was necessary to reduce the background which is caused by $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay from pions stopped in the walls of the target chamber. This background has a lifetime of 2.2 μsec , which lies within the time scale we are interested in (cf. Fig. 2 b). In order to reduce this background, it is very effective to tag multi-pion-hit at the telescope counters.

Figure 1: Setup used in 1992 in C1 area (top view). For details see text. The B and A counters have been drawn in an enlarged scale.

2.2 Targets

In the center of Fig. 1 the vessel for high-pressure room temperature gas is shown. It is a cylindrical stainless steel container of 19.7 cm inner diameter and 5 mm wall thickness. The entrance window for $\bar{p}$ (15 mm diameter, 0.5 mm thick stainless steel foil) was mounted on a nozzle of 5.5 cm inner diameter welded perpendicular to the cylinder axis. A degrader of 0.5 mm thick Kapton foils was necessary to stop the $\bar{p}$ in the center of the target at a helium pressure of 5 bar. The vessel used HELICOFLEX seals for the two flanges in order to reduce contaminations from rubber O-rings and to stand for baking at about 150 $^{\circ}\text{C}$. The chamber was simultaneously pumped and baked for at least 6 hours before being filled with the high quality (impurity content <1 ppm) helium gas used in these experiments. For adding other gases, a gas handling system consisting of 3/8 inch stainless steel pipes was used. The pipes were also baked at the same condition.

The gas samples were maintained at a constant temperature by a helium-flow cryostat (Janis) specially designed for this purpose. This cryostat has a target chamber of 6 cm diameter and 18 cm length. There are two entrance windows of 50 μm Kapton and 2 cm diameter, one at the vacuum layer and one at the target chamber. An additional Kapton degrader of 2 mm thickness was necessary. It was placed outside the vacuum, which caused a fraction of the $\bar{p}$ to stop inside the flange of the target chamber window due to the small angle scattering.

Another cryostat was prepared by ourselves to make solid ^4He . It is necessary to achieve about 30 bar of pressure at 2 K to solidify helium. The target chamber was entirely made of a Cu-Be alloy with a very high yielding stress and was able to withstand more than 90 bar pressure. It was 12 mm in diameter and 1 cm long, and had an entrance window of 0.5 mm thickness. As with the low temperature gas cryostat, a small fraction of the $\bar{p}$ beam fell outside the entrance window and therefore stopped in the walls of the target vessel. Temperatures below 4.2 K were achieved by pumping on liquid He. This cryostat was also used for the liquid ^4He and ^3He measurements.

2.3 Electronics and Data Acquisition

In both runs the same electronic circuit was used. The trigger condition was as follows:

$$B * \bar{A} * \sum_{\alpha=(A,B,C,D)} \left(T1_{\alpha} * \sum_{\beta=\{a,b,c\}} T2_{\alpha\beta} \right) * \overline{\text{Computer Veto}} * \overline{\text{Pre-pileup}}.$$

$T1_{\alpha}$ is the inner scintillator of side α , and $T2_{\alpha\beta}$ are the outer ones. The hodoscopes were only used to monitor the stopping position of $\bar{p}$. The start time of a long-range time-to-digital converter (TDC LeGroy 4208) was determined by the B counter, and the stop time by the telescope counters. The arrival times of pions in the outer annihilation counter array T2 were digitized by TDCs connected to each element $T2_{\alpha\beta}$ of the array. This enabled us to improve the time resolution for the coincidence of two telescopes using software cuts on this time information. The time range we used in the both experiments was 50 μsec .

Electronic confusion can arise if particles unrelated to an antiproton which has started a TDC precede or follow in it a time interval of the same order as that during which its own delayed annihilation is expected. The electronic logic was therefore arranged so that a beam antiproton which started the TDC but was preceded by another beam antiproton

by less than $50 \mu\text{s}$ was rejected as a candidate for delayed annihilation. This is known as pre-pileup rejection. Rejection of "post-pileup" events (in which particles are detected in the B counter within an interval of $50 \mu\text{s}$ after a given TDC start) was done by recording the time of B-counter hits following the one which caused to start the TDC. This was easily achieved by using the multiple-stop recording capability of the 4208 TDC. The presence of more than one stop signal in the B counter TDC indicated that more than one $\bar{p}$ had arrived within the $50 \mu\text{s}$ period and the event was accordingly discarded offline.

For each event, the TDC information as well as a hit pattern showing which of the telescope or hodoscope counters detected a particle, was recorded. The data were acquired

Figure 2: Time spectra of empty target: a) raw data, b) data after pile-up rejection, c) with additional $\geq 2\pi$ -tag and d) with $\geq 3\pi$ -tag.

by a CES-J11 (PDP-11 compatible Camac Auxiliary Controller) and were transferred to a VAX station using Direct Memory Access and then written to 8mm tape. The dead time of the CES-J11 was typically $32 \mu\text{sec}$ per event. However, we carried out pre- and post-pileup rejection for $50 \mu\text{sec}$ each. Due to this, our data acquisition system has $100 \mu\text{sec}$ of dead time per accepted event.

2.4 Analysis

To select coincidence hits in the telescope counters, we proceeded as follows: for all N_{hit} TDC's which contained a valid time information, the average hit time $\langle t \rangle$ as well as the dispersion Δ around $\langle t \rangle$ were calculated:

$$\langle t \rangle = \frac{\sum_{T_i=hit} T_i}{N_{hit}}, \quad \Delta = \sqrt{\frac{\sum_{T_i=hit} (T_i)^2}{N_{hit}} - \langle t \rangle^2}.$$

Coincident T counter hits were included in the analysis only when their dispersion value was smaller than 10 ns . This cut can be improved, if a drift and time jitter in the time zeros of the 12 TDCs is corrected. This has not yet been done for the new data of 1992, so they represent only preliminary results.

Fig. 2 shows the effect of pile-up rejection as well as ≥ 2 and $\geq 3 \pi$ tagging. In Fig. 2 a), the raw time spectrum recorded without $\bar{p}$ post pile-up rejection is shown. The large number of pile-up events is reduced drastically when the post pileup rejection is applied (cf. Fig. 2 b). The background caused by the $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay which can even still be seen in the Fig. 2 c) is strongly suppressed by the high-multiplicity tagging. Therefore, a multiplicity of at least two charged particles in the telescope counters was required for the final time spectra.

3. RESULTS OF $\bar{p}$ ANNIHILATION MEASUREMENTS IN PURE HELIUM

Systematic studies on $\bar{p}$ annihilation in pure ^4He have been made for four conditions: low temperature gas, high pressure room temperature gas, liquid and solid He at various pressures and temperatures. Fig. 3 shows typical results for each condition. The overall shape of the time spectra is similar: it is not single exponential, but has a growth-decay structure. To describe the spectra in a model-independent way, we use an "average lifetime" $T_{av}(> t_0)$ defined by

$$T_{av}(> t_0) = \frac{\int_{t_0}^{50\mu\text{s}} t \cdot n(t) dt}{\int_{t_0}^{50\mu\text{s}} n(t) dt} - t_0.$$

Values for T_{av} are also shown in Fig. 3. Comparison of the spectra shown in Fig. 3 reveals the following striking features:

- The longest lifetime observed (Fig. 3a) is in 10 K gas ($T_{av} = 3.8 \mu\text{s}$). Whether this is caused by the absence of impurities which are frozen out, or by the low temperature is not yet clear.

- There is a significant difference between low temperature gas and all other conditions: the spectrum of Fig. 3a which, as we saw, has the longest T_{av} , does not show the short lived component which is present in Figs 3b, c and d. It is especially surprising that Fig. 3a differs significantly from Fig. 3b (room temperature, 20 bar) when the density in these two cases is comparable. On the other hand, only small differences are seen between the spectra for liquid and solid He (Figs. 3c,d).
- The shape of all time spectra at $t > 10 \mu s$ seems to deviate from the exponential shape, i.e. the curve is bent downwards. This may indicate the existence of chain decay channels.

Figure 3: Comparison of $\bar{p}$ time spectra in pure ^4He under different conditions.

The present status of the analysis does not allow more than those qualitative conclusions. A more detailed analysis using multiexponential fits looking for a density dependence is in progress.

4. $\bar{p}$ ANNIHILATION TIME IN HELIUM GAS WITH ADMIXTURES

Fig. 4 shows time spectra of room temperature helium gas with admixtures of other noble gases. For each type of admixture, a series of different concentrations at different pressures has been measured. The detailed analysis is not yet finished, but a general feature of these data is that an admixture of the order of 10 % noble gas shortens the

Figure 4: Comparison of $\bar{p}$ time spectra in He gas with admixtures of noble gases.

$\bar{p}$ lifetime slightly without changing the overall shape of the spectra. This might be attributed to collisional processes.

The situation changes drastically, if molecular gases are added to He (cf. Fig. 5). At impurity concentrations of about 100 ppm H_2 or O_2 , a dramatic change in the lifetime spectrum begins to appear (noticeable effects are in fact present at concentrations as low as 20 ppm). This indicates much more violent reactions between the metastable $\bar{p}He^+$ atoms and molecules. For N_2 admixtures, the effect is less drastic, but still more pronounced than in the case of noble gases. The fact that the trapping fraction remains constant [4] suggests that the quenching effect is not caused by changes in the initial population of ℓ -levels, but due to collisions.

Figure 5: Comparison of $\bar{p}$ time spectra in He gas with admixtures of molecular gases.

5. CONCLUSIONS AND OUTLOOK

In this report only an overview of the available data could be given. In a short time since the discovery of the metastable $\bar{p}He^+$ atoms in liquid He, data of helium in gaseous, liquid and solid phases, as well as helium gas with admixtures of noble gases and molecular gases have been accumulated. The density dependence of the lifetime spectrum is small even between gaseous and solid He, suggesting that collisions with ordinary helium atoms influence our atomcules only weakly. This is in sharp contrast to our initial expectations. On the other hand, their violent destruction in the presence of foreign molecules (but not atoms) indicates a strong quenching process, which may or may not be collisional in origin. Further analysis of the substantial quantity of data that we have obtained should provide more detailed information on the density dependence of the $\bar{p}$ lifetime and allow some estimation of rates or cross sections of the processes responsible for the changes in the lifetime.

Future experiments are planned to study higher impurity concentrations than those used up to now. At high concentrations of suitable foreign atoms, the energy distribution of the $\bar{p}$ at capture should be changed, producing a corresponding change in the initial population of ℓ -values. Another line of approach is to examine the $\bar{p}$ energy levels of the atomcules directly, by exciting them with lasers to nearby levels which are not metastable. A new series of experiments along these lines is planned for 1993, using high power excimer-pumped dye lasers.

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REFERENCES

- 1 M. Iwasaki et al., Phys. Rev. Lett. 67 (1991) 1246.
- 2 G.T. Condo, Phys. Lett. 9 (1964) 65.
- 3 J.E. Russell, Phys. Rev. Lett. 23 (1969) 63; Phys. Rev. 188 (1969) 187; Phys. Rev. A1 (1970) 721, 735, 742.
- 4 T. Yamazaki et al., Nature, in press.
- 5 T. Yamazaki and K. Ohtsuki, Phys. Rev. A45 (1992) 7782.
- 6 S.N. Nakamura et al., to be published