Theoretical Study of Pion Spectra after Antiproton Annihilation at Rest in Nuclei

J. H. Kim and Hiroshi Toki

Department of Physics, Tokyo Metropolitan University, Tokyo 158

(Received June 23, 1984)

We study the role of the nuclear medium on the pion spectra after the antiproton annihilation at rest in nuclei. The nuclear medium acts as a scatterer and an absorber of outgoing pions and modifies the pion energy spectra. The pion spectra seem to be reproduced by assuming that half of the pions moving outward go out freely, while the other half moving inward to the nucleus are absorbed by nucleons according to the \(x\)-nucleus absorption cross sections. We propose a coincidence experiment to verify this picture.

Recently, the low energy high intensity antiproton beam became available from the low energy antiproton ring (LEAR) in CERN. This intense beam of antiprotons enables us to study the behavior of an antiproton in a nucleus in great detail. One interesting new aspect of antiproton induced reaction is the annihilation of an antiproton, which deposits a large amount of energy (~2 GeV) with small momentum in the nucleus. Therefore, we shall find an entirely different response of a nucleus from other means.

There is a large number of data on the antiproton-proton annihilation at rest. After the annihilation, the large energy is carried out by many pions of about 5 in average. The question we would like to ask here is what will happen to those pions then if this annihilation takes place in a nucleus.

Although we shall have many data of this kind from LEAR, such a data is already available in literature, where the pion energy spectra are presented. In Fig. 1, we compare the pion energy spectrum after the antiproton annihilation at rest in the emulsion with that of the antiproton-proton annihilation in the free space. We find the overall similarity between the two spectra except for the region of \(T_x = 100 \sim 200\) MeV. In this paper, we would like to study this difference under the assumption that the pions produced by the annihilation scatter with nucleons and disappear by absorption on the way out from the nucleus.

Since the antiproton-proton cross section is extremely large at low energy, the antiproton annihilates with a nucleon right at the nuclear surface. About half of the pions produced by the annihilation move out freely, while the other half move into the nucleus. Those moved into the nucleus will interact with nucleons. Let us see...
what will happen to the pions by using the $\pi + ^{12}$C reaction data at various energy.\textsuperscript{41} We see in Fig. 2 that the absorption cross section is strongly energy dependent and about $1/3$ of the total cross section, while the scattering cross section (inel. +el.+scx.) is only slightly energy dependent.

We shall use the available $\pi + ^{12}$C experimental data to estimate the amounts of absorption and scattering, although the emulsion consists of several nuclei; Ag, Br, O, C, H, where the abundance of C is the biggest except H(proton) among all. Our analysis goes as follows. We assume that half of the produced pions go out freely, while the other half makes interaction with nuclear medium. We take the ratio of each process to the total cross section of the $\pi + ^{12}$C reaction from Fig. 2, where the available data have been extrapolated as indicated by dotted lines. The elastic portion does not affect the pion energy spectrum. The absorption portion simply corresponds to the loss of pions. The single charge exchange process is combined with the inelastic process, which makes change of the energy spectra. Pions with high energy are brought down to the lower energy by inelastic quasi-free scattering.

The pion energy $E'$ after inelastic scattering (quasi-free) is calculated by using kinematics of a pion-nucleon system

$$E' = \frac{(M + E)(EM + m^2) + (E^2 - m^2) \times (M^2 - m^2 \sin^2 \theta)^{1/2} \cos \theta}{(M + E)^2 - (E^2 - m^2) \cos^2 \theta}.$$ 

Here $E$ is the incoming pion energy and $m, M$ are the pion and nucleon masses. $\theta$ is the average scattering angle of the pion in laboratory system, which is obtained by the weighted average of the scattering angle with the differential cross sections provided by pion-nucleon scattering.\textsuperscript{9}--\textsuperscript{10} Hence, $\theta$ is obtained as a function of the incoming pion energy $E$.

The calculated results are shown in Fig. 1 as the short dashed line. The high energy side loses its amount by the inelastic process of pions with nucleons and this inelastic process feeds the low energy side. The pion absorption process decreases the strength in the energy range of 100 $\sim$ 200 MeV. However, the above consideration does not provide a satisfactory result to reproduce the dip around 150 MeV. This disagreement might suggest many body effect on antiproton annihilation in nuclei due to the presence of many nearby nucleons in nuclei.

Before discussing such a possibility, we may find that the marked difference between the pion yields in the free space and in nuclei appears only in the energy range of 100 $\sim$ 300 MeV. This energy range corresponds to the delta isobar resonance and hence those pions have large chances to disappear due to pion absorption in nuclei. We might therefore like a simpler assumption that the antiproton annihilates slightly more inside of the target nucleus than the previous assumption. Then assume that the produced pions are in the range of pion absorption for those pions at the delta resonance energy when they move inwards of the nucleus. This implies that the antiproton annihilation takes place at $R = \sqrt{\sigma_{\text{tot}}(E_x=150 \text{MeV})/\pi}$ so that all the pions at $E_x=150$ MeV moving inwards are absorbed, while other pions at different energies moving inwards would be absorbed according to the probability proportional to the absorption cross section in Fig. 2. On the other hand, pions moving outwards would escape without appreciable interaction as assumed before. The inelastic process is simply neglected. The numerical results of such an assumption are provided in Fig. 1 as the long dashed line. The agreement is remarkable.

If this would be the picture of pions after

![Fig. 2. Pion-nucleus ($^{12}$C) cross sections in various components as a function of the pion energy in MeV.](https://academic.oup.com/ptp/article-abstract/72/5/1049/1926919)
antiproton annihilation in nuclei, it would be interesting to perform a coincidence experiment. Observe several pions ($3 \sim 4$) in a half sphere to determine the side of antiproton annihilation. Then take the energy spectrum of pion coming towards the opposite side of the $\bar{p}$ annihilation in coincidence. It should show a clear dip at the resonance energy in the pion yield.

In summary, we have studied the pion spectra after antiproton annihilation at rest in nuclei by considering the nuclear medium effects on the outgoing pions. The medium effects on the outgoing pions seem to account for the feature of the pion spectra, although more detailed cascade model type calculations are needed to establish the above conclusion. If we were to find out a multinucleon effect on the antiproton annihilation mechanism itself, we need to have more explicit data. In addition, we need to develop a cascade model code for antiproton annihilation in nuclei in order to find signs of any exotic component of antiproton annihilation in nuclei.

5) W. J. Willis, Phys. Rev. 116 (1959), 753.