

論文の内容の要旨

Measurement of the In-flight Antiproton Annihilation Cross Section on Carbon at 100 MeV/c

(100 MeV/cにおける反陽子・炭素
原子核消滅断面積の測定)

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Antiprotons(\bar{p}) and antineutrons(\bar{n}) are antiparticles of protons and neutrons. One of characteristics of antimatters is their annihilations with usual matters. When antiprotons or antineutrons strike target nuclei, they annihilate with surface nucleons. The cross section is called annihilation cross sections and used to construct optical potentials between them.

Recent studies revealed that \bar{n} -annihilation cross sections on some nuclei (C, Al, Cu and Pb) at momenta ~ 100 MeV/c show anomalous behaviors when compared to theoretical calculations of \bar{p} -annihilation cross sections [1]. Due to lack of the enhancement caused by Coulomb focusing effects, the \bar{p} -annihilation cross sections were expected to be consistently larger than the \bar{n} -annihilation cross sections for the same target and energy of the incident particle. However the \bar{n} cross sections measured by the OBELIX experiment [2] were larger than the expected values based on the generalized optical potential model as shown in Fig 1. In fact they behaved like \bar{p} -annihilation cross sections. It has been discussed whether the enhancement had some physics reason or was caused by other experimental issues, but so far the deviation is not understood.

Antineutrons were produced from antiprotons via a charge exchange reaction ($p + \bar{p} \rightarrow n + \bar{n}$). Its production rate was low (10^{-6}) and there were difficulties in identifying antineutrons. On the other hand, the theoretical calculations were constructed to reproduce the \bar{p} -nuclei interactions in the other momentum region and extrapolated to this region. Its validity has not studied well.

The \bar{p} -annihilation cross sections can be a good prove to study both \bar{n} data and theoretical calculations. However, comparisons of experimental \bar{p} - and \bar{n} -annihilation cross sections were performed for only p and Sn targets because these were the only data sets available. They found that \bar{p} -p cross sections were larger than \bar{n} -p cross sections, but \bar{p} -Sn cross section was smaller than a corresponding \bar{n} data. This means that if the inversion is real, it has a mass dependence.

There is a general lack of \bar{p} experimental data which can be compared with the existing \bar{n} data. Of particular importance is the measurement of four types of nuclei which should enable the direct comparison with the corresponding experimental data of antineutrons. In our study, we measured the \bar{p} -C annihilation cross section and compared to the corresponding \bar{n} data and theories at the Antiproton Decelerator of CERN, which provides pure antiproton pulsed beam of 100 MeV/c.

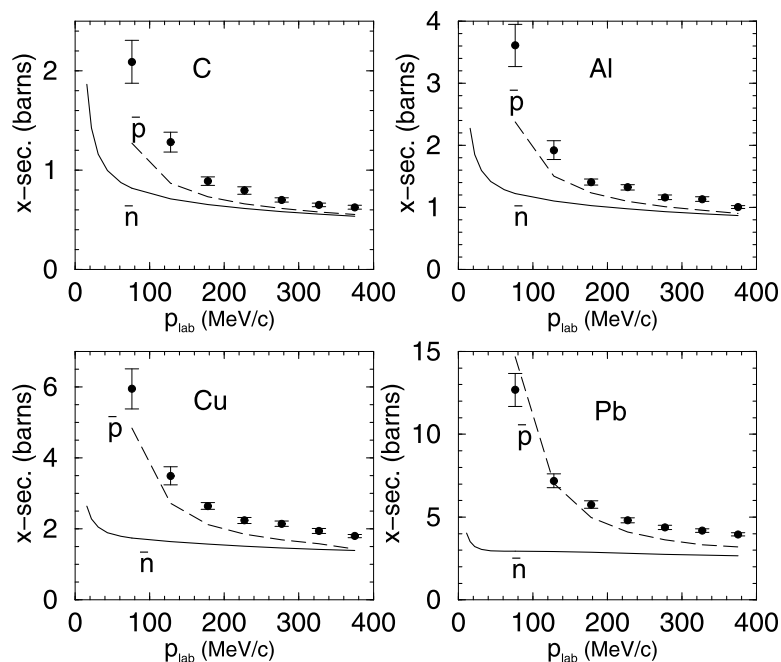


Figure 1: Annihilation cross sections of antineutrons on C, Al, Cu and Pb. They are shown with black circle points. Dashed lines are theoretical calculations of \bar{p} -nuclei annihilation cross sections, and solid lines show ones of antineutrons. This figure is taken from [1].

There are some technical difficulties in carrying out experiments with slow antiprotons. In order not to make antiprotons slow down and coming to rest in the foil, the thickness of the target had to be thin (less than $1\mu\text{m}$) and its precise thickness can not be understood easily. The probability of signal annihilations at the target foil is low ($\sim 10^{-5}$), and most of the antiprotons transversed and scattered at the foils. The antiprotons which hit the experimental apparatus made inevitable backgrounds.

We developed a new experimental setup which was specialized to cross section measurements, in which \bar{p} -annihilation cross section was calculated with respect to the elastic cross section. The incident antiproton of $p=100\text{ MeV}/c$ transversed the foil in a vacuum chamber. Some charged particles were emitted per one annihilation, and resulting charged particles were detected as signals of in-flight annihilations. In a different run, we set a circler ring downstream of the target foil. Some antiprotons scattered elastically and hit the ring. Those antiprotons also annihilated and emit some charged particles, which were detected as signals of annihilations on the ring. The \bar{p} -annihilation cross section can be derived by calculating the ratio of the numbers of counts with and without the ring, and elastic scattering cross section calculated by the Rutherford scattering formula. Most of the antiprotons passed through the foil, annihilated at the beam dump and made background events. They were separated by the time-of-flight method. We used carbon target to reduce backgrounds caused by antiproton scattered and hit the experimental apparatus.

We operated two kinds of detectors during the experiment. Nine planes consisting of scintillation bars were used to detect particles from the target position. Since signals with and without the ring were obtained in different runs, spectra needed to be normalized by beam intensities. A Cherenkov counter, which was set close to the beam dump, detected particles emerging from the annihilations there. Since almost all antiprotons annihilated there, the signals could be used to monitor relative intensities of the beams.

In order to determine the cross section with a precision of $\sim 10\%$, it was desired to monitor the relative intensities with a precision of a few percents. We developed a Cherenkov counter consisting lead fluoride crystals. The readout was carried out by using the avalanche photodiode to guarantee the linearity. We studied photo yields of some crystals and backgrounds of some photodiodes for this construction. The study is one of main topics in the thesis and described in detail. The detector was operated during the experiment stably, and monitored the intensities with a precision of $\sim 2\%$.

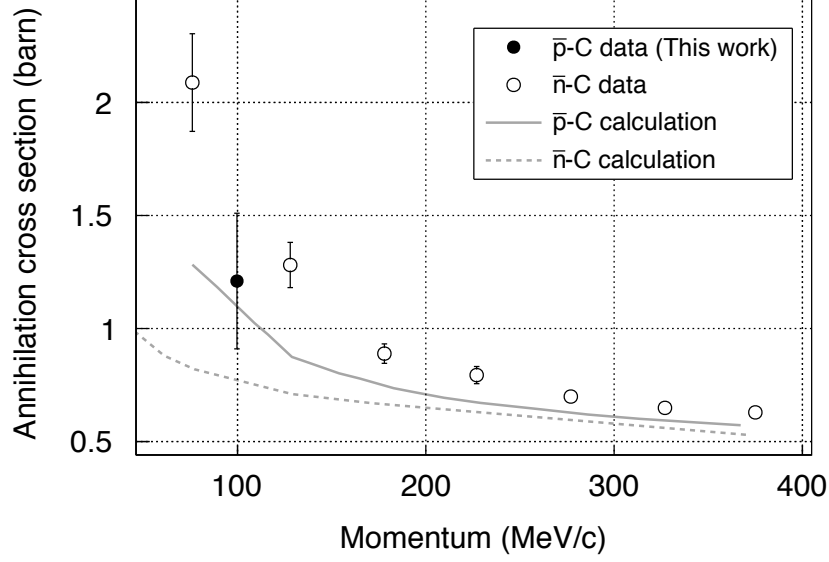


Figure 2: The \bar{p} -annihilation cross section on carbon at 100 MeV/c obtained in this measurement, and comparisons to corresponding \bar{n} -data and theories.

Analysis was carried out and the annihilation cross section on carbon at 100 MeV/c was derived to $\sigma_{\text{anni}} = 1.21 \pm 0.31$ (barn). The cross section was compared to the corresponding \bar{n} -annihilation cross section and theories. The comparisons are shown in Fig 3. The cross section was consistent to the theoretical prediction within 1σ , therefore the large enhancement seen in \bar{n} -annihilation cross sections was not observed in the case of antiprotons.

A mass dependence of the \bar{p} -annihilation cross sections at 100 MeV/c was studied using the past data of Ni, Sn and Pt, and it followed the theoretical calculation. However cross sections in the past experiments have large errors of 50%, and it is not possible to deepen the discussion with only the current data. It is desired to determine annihilation cross sections with various targets and with better precisions. It can be achieved by applying our experimental method to those measurements.

References

- [1] E. Friedman *et al.*, Nucl. Phys. A **925** 141 (2014)
- [2] M. Astrua *et al.*, Nucl. Phys. A **697** 209 (2002)