New Insight into Antiproton Production and Reabsorption Using Proton-Nucleus Collisions at the AGS

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Antiproton ($\bar{p}$) yields are presented for proton-nucleus collisions, with targets Be, Cu, and Au, at beam momenta of 12.3 and 17.5 GeV/c. In addition to target size and beam momentum, the number of projectile collisions $\nu$, as derived from the number of “grey” tracks (slow protons and deuterons), is used to disentangle the $\bar{p}$ reabsorption from the production. By quantifying the amount of reabsorption of the $\bar{p}$ within the nucleus as a function of $\nu$, the annihilation within the nucleus is estimated and compared to the free annihilation cross section. Preliminary results on antilambda ($\bar{\Lambda}$) production as a function of $\nu$ are also presented for comparison.

1. Introduction

Sub-threshold $\bar{p}$ production as well as an apparently reduced $p - \bar{p}$ annihilation cross section in the nucleus have been under debate since the discovery of the $\bar{p}$ and until recently [1–8]. The observation of enhanced antimatter production has been proposed as a signature of the Quark Gluon Plasma [9]. Due to the annihilation of antibaryons in baryon-rich nuclear matter, it has also been proposed to use $\bar{p}$ yields as a measure of the baryon density in heavy ion collisions [10]. These interesting prospects for using antibaryons to help determine the properties of the hot, dense phase in a heavy ion collision require a deeper understanding of both the production and reabsorption of the $\bar{p}$ within the nucleus. Proton-nucleus collisions provide a cleaner environment for testing $\bar{p}$ production and reabsorption within the nucleus than heavy ion collisions. In this paper, we present measurements of $\bar{p}$ production in $p + A$ collisions at the AGS that may help address the questions of production and reabsorption in the nucleus.

2. Data Reduction

The E910 apparatus has been described elsewhere [11]. The time-of-flight (TOF) wall, used to identify the $\bar{p}$, is located approximately 8 m from the target and covers approximately $5 \times 2$ m$^2$. Using the measured times of flight to identify particles, the $\bar{p}$ band is

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well separated from the pions and kaons up to 3.5 GeV/c. Momentum dependent cuts on the number of standard deviations of the measured TOF from the expected TOF of a proton are applied. To reduce background in the identified \( \bar{p} \) sample, we apply cuts on the particle’s ionization energy loss in the TPC and the measured photoelectrons in the Cerenkov detector. Quality cuts on the hits on the TOF include a cut on the difference in horizontal position between a projected track and the center of the hit TOF slat and a cut on the energy deposited on the TOF slat. Tracks are matched to the TOF wall with a 90±5% efficiency. We estimate and subtract a momentum-dependent background of approximately 5%. Feeddown from \( \bar{\Lambda} \) in our \( \bar{p} \) sample is estimated to be less than 5%. The data have been acceptance corrected within our \( y \) coverage, and corrected for the efficiencies of the cuts mentioned above. All results are shown within our \( y \) coverage, \( y = (1, 2) \) and \( p_T = (10, 800) \) MeV/c.

3. Measured Antiproton Yields

The \( \bar{p} \) yields are shown in Fig. 1. We observe a strong increase in \( p+Au \) \( \bar{p} \) yields from beam momentum 12.3 to 17.5 GeV/c as expected, since production of \( \bar{p} \) near threshold should depend sensitively on the available phase space. Although the likelihood of producing a \( \bar{p} \) may be greater in a larger nucleus [12], the likelihood of reabsorption is also greater in the presence of more baryons. These two countervailing effects can be studied by investigating the target dependence of \( \bar{p} \) yields. Results for Be, Cu, and Au at beam momentum 12.3 GeV/c are also shown in Fig. 1.

![Figure 1](image1.png)

**Figure 1.** Beam momentum and target dependence of rapidity densities (left) and transverse mass densities (right). The open squares are 17.5 GeV/c \( p+Au \) yields, solid squares are 12.3 GeV/c \( p+Au \), solid triangles are 12.3 GeV/c \( p+Cu \), and solid circles are 12.3 GeV/c \( p+Be \).

![Figure 2](image2.png)

**Figure 2.** Integrated rapidity density as a function of target A. The triangles are yields from 12.3 GeV/c beam momentum, and the open square is 17.5 GeV/c.

Figure 2 shows the integrated rapidity densities for all four data sets. The yields decrease from \( p+Be \) to \( p+Au \) collisions by 34 ± 22%.
4. Reabsorption of the Antiprotons

By characterizing collision “centrality,” E910 can provide new insight into $\bar{p}$ absorption. Events are characterized by the mean number of collisions $\nu$ that the projectile undergoes within the nucleus (as determined by the number of “grey” tracks $N_g$) \cite{11}. The $\nu$ dependence of the mean $\bar{p}$ multiplicity in 17.5 GeV/c $p+Au$ collisions is shown in Fig. 3. A preliminary measurement of the mean $\bar{\Lambda}$ multiplicity as a function of $\nu$ is also shown in Fig. 4. The mean multiplicity of both tends to decrease as $\nu$ increases. Although not convincingly significant, the increase from $N_g = 0$ to $N_g = 1$ in the mean $\bar{p}$ yield may be evident of a contribution to production beyond the first $p+N$ collision. The increase is more pronounced in the mean $\bar{\Lambda}$ yield versus $\nu$ and thus strengthens the evidence for production beyond a first collision model. With the following assumptions, we quantify the “effective” absorption cross section in the nucleus and show that it is greatly reduced relative to the free $p-\bar{p}$ annihilation cross section. The first assumption is that the $\bar{p}$ is predominantly produced in the first $p+N$ collision. Since the beam energy is near the production threshold, this is generally assumed to be true at AGS energies \cite{13}. If there are contributions to production beyond $\nu = 1$, as we have conjectured, they are not large enough to change our conclusion dramatically. The second assumption is that the $\bar{p}$ follows the path of the projectile through the nuclear matter. This is also a reasonable assumption because we observe strongly forward-peaked angular distributions for the $\bar{p}$. Then the survival probability of the $\bar{p}$ can be described by the following equation (although one should note that a formation time is not taken into account by this description),

$$
\sigma(pA \rightarrow \bar{p}X) = \sigma(pp \rightarrow \bar{p}X)e^{-\frac{\sigma_{abs}}{\sigma_{pN}}(\nu-1)}.
$$

(1)

Since the value $\nu$ plotted on the x-axis of Figs. 3 and 4 is simply an average value, $\bar{\nu}(N_g)$, and each value of $N_g$ actually has a distribution of $\nu$ values associated with it, $P_{N_g}(\nu)$, we fold the above exponential with $P_{N_g}(\nu)$. We determine $\sigma_{abs}$ by fitting with,

$$
\sigma(pA \rightarrow \bar{p}X) = \sigma(pp \rightarrow \bar{p}X)P_{N_g}(\nu)e^{-\frac{\sigma_{abs}}{\sigma_{pN}}(\nu-1)}.
$$

(2)

In one fit, the first data point is not included (because of the initial increase in yield from $N_g = 0$ to $N_g = 1$), and in the second fit, the $N_g = 0$ point is included. The parameter, $\sigma_{abs}/\sigma_{pN}$, resulting from the fit is 0.23 $\pm$ 0.09 when neglecting the first data point in the fit, and 0.13 $\pm$ 0.05 when including it. Taking the more conservative estimate of 0.23 and assuming $\sigma_{pN}$ to be 30 mb, one obtains an absorption cross section, $\sigma_{abs}$, of 6.9 $\pm$ 2.7 mb. At $p = 2.5$ GeV/c, the mean measured momentum of the $\bar{p}$ sample we detect, this is approximately 1/5 of the free annihilation cross section \cite{12}, $\sigma_{ann}$. The large discrepancy between $\sigma_{abs}$, as derived from our model, and $\sigma_{ann}$ suggests a modification of the $p-\bar{p}$ annihilation cross section within the nuclear medium. Figure 4 shows a very similar dependence of the mean $\bar{\Lambda}$ yield on $\nu$. Fitting with the same function that was used for the $\bar{p}$ yields, the extracted fit parameter is 0.22 $\pm$ 0.04. The effective absorption cross section is thus the same (within errors) for $\bar{\Lambda}$ as for $\bar{p}$. This suggests an intermediate state that emerges from the nuclear medium as a $\bar{p}$ or a $\bar{\Lambda}$. 
5. Conclusions

We have found that, at AGS energies, the $\bar{p}$ yields dramatically increase with beam momentum and moderately decrease with increasing target size. We have found evidence that even at these beam momenta, near the production threshold of the $\bar{p}$ and the $\bar{\Lambda}$, there is production beyond the first $p+N$ collision for the $\bar{\Lambda}$, and a similar behavior for the $\bar{p}$ is not excluded. Finally, the “effective” absorption cross section, calculated within the context of a simple model, is significantly reduced relative to the free $p-\bar{p}$ annihilation cross section. The similarity between the calculated absorption cross sections for $\bar{p}$ and $\bar{\Lambda}$ may indicate the presence of a single intermediate state which leads to both final states.

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