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HIGH ENERGY ANTIPROTON ANNIHILATION ON NUCLEI AND MULTIPLE SCATTERING MODELS

By M. Jeżabek and K. Zalewski

Institute of Nuclear Physics, Cracow*

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We point out that according to multiple scattering models an antiproton incident on a heavy nucleus is likely to annihilate, even at incident momenta of a few hundreds GeV/c, when the annihilation probability in $\bar{p}p$ collisions is very small. Experimentally, a comparison of the leading p and leading $\bar{p}$ spectra in pA and $\bar{p}$A collisions at the same energy gives a good chance of discovering this effect, if it exists. Quantitative predictions valid for a wide class of multiple scattering models are presented and discussed.

1. Introduction

There is a widespread belief that studying hadron-nucleus collisions one gains interesting information about the time evolution of hadronic states produced in hadron-nucleon collisions. However, with the available data at hand, one can hardly say that this is really the case [1]. The available data have been fitted starting from quite different models, as for instance the non-interacting fireball model [2, 3], the Capella–Krzywicki model [4], or the coherent tube model [5]. Since these models imply completely different pictures for the space-time evolution of the process, a more selective piece of information would be of great interest. In this paper we argue that annihilation cross-section on nuclei and/or a comparison of leading particle spectra in $\bar{p}$A and pA interactions provide information of this type.

We limit our discussion to leading particle cascade models, where a high energy hadron-nucleus collision is described as a sequence of incoherent collisions with quasi-free target nucleons. The probability distribution for the number of such collisions is obtained from simple probabilistic considerations (cf. e.g. [6]). In each collision with a nucleon the incident object is assumed to interact as the beam particle would, except that the collisions may decrease its energy. The motivation for this choice of a model is that it yields unambiguous predictions for annihilation, while e.g. the models from Refs [4] and [5] would require extensions, which the authors of these models might object to.

* Address: Instytut Fizyki Jądrowej, Kawiory 26a, 30-057 Kraków, Poland.

For the models considered here the cross-sections for some processes grow faster with the atomic number A that the total inelastic cross-section. Annihilation is an example [7], [8]. In what follows, we show that for heavy nuclei annihilation processes can dominate even at energies, where they are only a small fraction of the inelastic cross-section on hydrogen. Consequently, there should be much more fast protons in final states of pA collisions than fast antiprotons in final states of $\bar{p}$A collisions at the same energy. This effect is particularly strong, if the projectile loses energy when propagating across the nucleus. Thus, a simple experiment can either eliminate a wide class of multiple scattering models, or fix the parameters of some multiple scattering model, better than do the data on angular distributions, which have been used up to now.

We present our calculations of annihilation cross-sections in Section 2, discuss the spectra of fast baryons and antibaryons in Section 3, and close the paper with some concluding remarks in Section 4.

2. *Cross-sections for annihilation in multiple scattering models*

The cross-section $\sigma_{A,R}$ for a reaction R in a collision with nucleus A can be obtained (cf. e.g. Ref. [6], or the Appendix in Ref. [1]) by integrating

$$\sigma_{A,R}(\boldsymbol{b}) = 1-[1-\tilde{\sigma}_R(\boldsymbol{b})]^A, \tag{2.1}$$

where

$$\tilde{\sigma}_R(\boldsymbol{b}) = \int d^2s\sigma_{H,R}(\boldsymbol{s}-\boldsymbol{b}) \int dz\varrho_A(\boldsymbol{s}, z), \tag{2.2}$$

over the impact parameter ($\boldsymbol{b}$) plane. Here the z axis is parallel to the beam direction and ϱ_A denotes the normalized density of hadronic matter in the nucleus. We will use (cf. e.g. [6], [9])

$$\varrho_A(b, z) = \varrho_0\left[1+\exp\frac{\sqrt{b^2+z^2}-R}{c}\right]^{-1}, \tag{2.3}$$

where

$$\varrho_0 = \frac{3}{4\pi R^3}\left[1+0.518\left(\frac{4.394\pi c}{R}\right)^2\right]^{-1} \tag{2.4}$$

and

$$R = 1.07\, A^{1/3}\ \text{fm}; \qquad c = 0.545\ \text{fm}. \tag{2.5}$$

Relation (2.1) holds, if the cross-section $\sigma_{H,R}$ depends little on energy. For annihilation this is certainly not the case. The annihilation cross-section on protons has been measured at low energies only, but there are strong indications that at all energies it is equal to the well measured difference between the total $\bar{p}p$ and pp cross-sections [10]. A good fit to both the low energy annihilation data and the high energy cross-section differences is [10]

$$\sigma_{H,\text{annih}} = 61\ \text{mb}\ P_{\text{lab}}^{-0.61}, \tag{2.6}$$

where the laboratory momentum should be expressed in GeV/c. Since this cross-section decreases with increasing energy, models, where the cascading particle loses energy, predict more annihilation than formula (2.1) would.

In order to calculate the annihilation cross-section including energy losses, it is necessary to know how energy changes from one collision with a quasi-free nucleon to the next. Here there are many possibilities and consequently many models. In order to keep the discussion general, we consider two limiting cases. For most other multiple scattering models of the leading particle cascade type the predictions should fall between our limits.

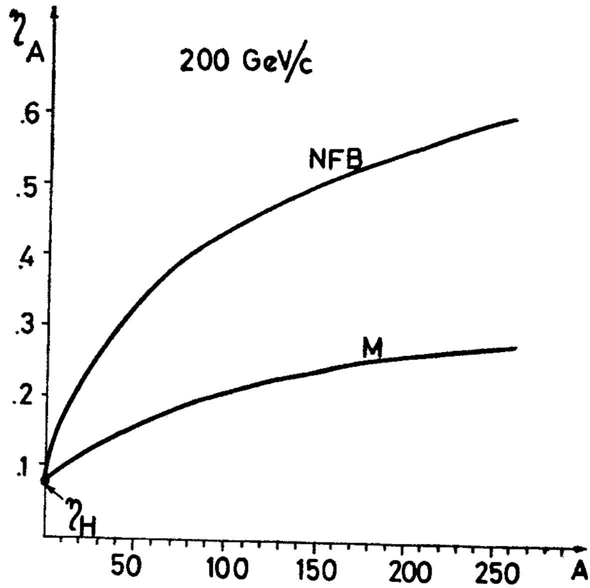

Fig. 1. M and NFB predictions for the A dependence of the ratio (2.7) at 200 GeV/c incident antiproton momentum

The smallest annihilation cross-section corresponds to a model, where the energy loss of the colliding particle is negligible. Further this version of the model is called the M (for minimal) scheme. As the opposite extreme, we have chosen the non-interacting fireball (NFB) model [2], [3]. In this model the energy difference between the incident leading particle and the outgoing one (which will be incident in the next collision, if any) is calculated as if the leading particle and the target nucleon were free particles colliding at the same energy. In the calculations we put for the outgoing particle a momentum spectrum, which in the centre of mass system of the hN collision is flat and extends from zero to the incident momentum value. In either model the normalization of the leading particle spectrum after each collision is reduced by a factor equal to the ratio of the non--annihilation inelastic cross-section to the total inelastic cross-section at the current energy.

The calculations for the M-scheme have been performed using standard formulae, and for the NFB scheme a Monte Carlo program has been written. Plots of the ratio

$$\eta_A = \frac{\sigma_{A,annih}}{\sigma_{A,inel}} \tag{2.7}$$

versus the atomic mass number A at incident momentum 200 GeV/c are shown for both schemes in Fig. 1. The ratio η_H, which is model independent, is also shown in the figure. It is seen, that the predicted annihilation cross-section rapidly becomes an important fraction of the inelastic cross-section according to either scheme. According to the NFB scheme it even becomes dominant for heavy nuclei. The predicted effects of multiple scattering (difference between η_H and η_A as calculated in the M-scheme) and of energy losses, if there is multiple scattering (difference between the values of η_A as calculated according to the two schemes) are so dramatic that even a very crude experiment can discredit some models. This is to be contrasted with the predictions for multiplicity distributions and inclusive angular distributions, where all decent models give very similar predictions.

From the experimental point of view, however, there is an important drawback: it is very difficult to distinguish an annihilation event from a non-annihilation event. Therefore, we have calculated also the spectra of leading antiprotons. With the low momentum region cut off, this is easily measurable and might provide a good practical method for studying annihilations in $\bar{p}$A scattering.

3. *Spectra of leading antiprotons*

The probabilistic schemes described in the preceding section lead to definite predictions for the spectra of leading particles. We call leading a nucleon (for pA collisions) or an antinucleon (for $\bar{p}$A collisions), if it does not come from pair production. The large increase of the annihilation cross-section in $\bar{p}$A scattering, as compared with $\bar{p}$p scattering, results in a decrease of the number of leading antinucleons. Denoting the average number of leading antibaryons by $\langle n_{\bar{B}} \rangle_A$, one has the simple relation

$$\langle n_{\bar{B}} \rangle_A = 1 - \eta_A. \tag{3.1}$$

In many experiments, however, only charged particles can be detected. Consequently, the spectra of leading antiprotons are easier to measure than the complete spectra of leading antibaryons. In order to subtract the difference, i.e. the spectrum of leading antineutrons, it is necessary to make some assumption about the probability of isospin flip processes.

In this paper we assume (cf. [8]) that the probability of isospin flip is in each collision with a quasifree nucleon equal to 0.25. This value and its energy independence are suggested by pp scattering data [11]. The results of Monte Carlo calculations for leading protons in pA collisions and for leading antiprotons in $\bar{p}$A collisions are shown in Fig. 2. For leading protons the two schemes give very similar predictions, but for leading antiprotons both the effect of multiple scattering responsible for the difference with respect to protons, and the effect of energy losses present in the NFB scheme, but absent in the M-scheme, are clearly visible.

In Fig. 3 the ratio of the difference $\langle n_p \rangle_A - \langle n_{\bar{p}} \rangle_A$ to $\langle n_p \rangle_A$ is plotted. The predictions for this ratio seem particularly reliable, because some of the systematic errors introduced

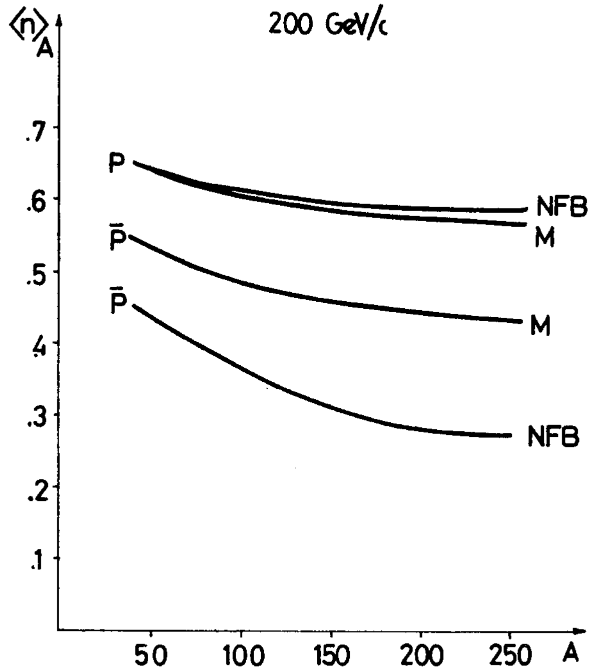

Fig. 2. M and NFB predictions for the A dependence of the average number of leading protons and leading antiprotons for incident hadron (p or $\bar{p}$) momentum 200 GeV/c

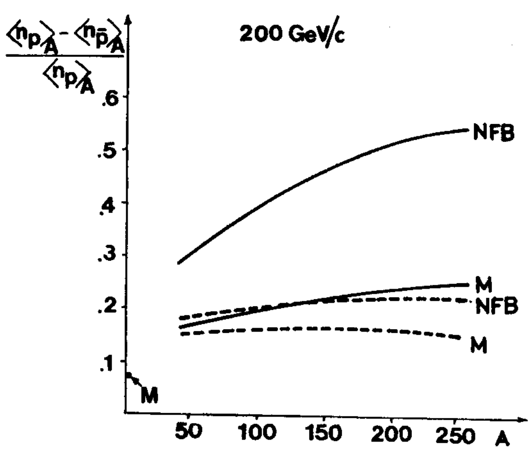

Fig. 3. M and NFB predictions for the ratio $(\langle n_p \rangle_A - \langle n_{\bar{p}} \rangle_A)/\langle n_p \rangle_A$ at 200 GeV/c incident momentum. The lines ——— are obtained without and the lines ---- with the cut off $p_{\text{leading}} \geqslant 20$ GeV/c

by the simplifications in the models are likely to cancel. Besides the results for the complete sample, which could have been obtained from the results shown in Fig. 2, the results for leading particles with momenta above 20 GeV/c are also plotted. As seen from the figure, even after this cut off, the predictions according to the two schemes are easily distinguishable.

4. Conclusions

Our conclusions can be summarized as follows:

— Multiple scattering models of the leading particle cascade type predict a dramatic increase of the annihilation cross-sections in $\bar{p}$A scattering. This results from two factors: multiple collisions provide more opportunities for annihilation and energy degradation in the subsequent collisions makes annihilation in a single collision more probable.

— A measurement of the annihilation cross-section in $\bar{p}$A scattering would shed much light on the space-time evolution of scattering processes on nuclei. It might for instance exclude the leading particle cascade mechanism, or give information about energy losses in individual collisions.

— A comparatively simple experiment would consist in a comparison of the fast proton spectra in pA collisions with fast antiproton spectra in $\bar{p}$A collisions at the same energy. Our calculations show that also this measurement can give the necessary informations about the evolution of the intranuclear process.

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