Mechanisms for the suppression of annihilationless breakup of nuclei by low-energy antiprotons

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The mechanism for the suppression (due to the narrowness of the cone in $\bar{p}N$ scattering) of the cross section for annihilationless breakup of nuclei by antiprotons is rapidly replaced by a different mechanism (which is linked with the large $\bar{p}N$ annihilation cross section) on going from a deuteron to heavier nuclei. Both mechanisms are equally important in the $\bar{p}\,^4$He interaction studied experimentally by Batusov *et al.* (Brief Communications JINR No. 12-85, Dubna, 1985, p. 6) and Balestra *et al.* [Phys. Lett. **194B**, 343 (1987)].

The first experimental data on the cross section σ_b of annihilationless breakup of an ^{4}He nucleus by 48.7- and 179.6- MeV anitprotons were obtained by Batusov *et al.*[1] and Balestra *et al.*[2] They found that the cross section σ_b is suppressed significantly (an order of magnitude) in comparison with a similar cross section for protons of the same energies and the cross section of elastic $\bar{p}\,^4$He scattering.

Batusov *et al.*[1] and Balestra *et al.*[2] gave two different qualitative explanations of this phenomen.

1) According to Ref. 1, the cross section σ_b is suppressed because of the extremely narrow cone of the $\bar{p}N$ scattering. At $T_{\bar{p}} = 50$ MeV the parameter of the slope B is $B = 35.6\ (\text{GeV}/c)^{-2} = 1.4\ \text{fm}^2$, i.e., it is of the nuclear order of magnitude, whereas pN scattering is nearly isotropic at this energy. The antiproton, in contrast with the proton, therefore scatters principally in the forward direction and the momentum transfer turns out to be too small for an effective breakup of the nucleus.

2) According to Ref. 2, the cross section σ_b is suppressed because of the large cross section of the $\bar{p}N$ annihilation, $\sigma_a^{\bar{p}N}$, which amounts to 70% of the total cross section $\sigma_{\text{tot}}^{\bar{p}N}$ at 50 MeV. The antiproton therefore has a chance to break up the nucleus and thus to survive only if it interacts with a narrow circle of nucleons at the de-excited periphery of the nucleus.

The first mechanism for the suppression of σ_b is said to be valid for light nuclei and the second mechanism is valid for the intermediate and heavy nuclei. In this letter we report the results of a quantitative analysis of the contribution of these two mechanisms to the suppression of the cross section σ_b for various nuclei and identify the nuclei that cause the first mechanism to give way to the second.

We use the Glauber[3]-Sitenko[4] method to calculate the cross sections. The validity of this method for the description of $\bar{p}A$ interaction up to very high antiproton energies, $T_{\bar{p}} \sim 50$ MeV, was demonstrated by Dal'karov *et al.*[5] The Glauber-Sitenko method was previously used effectively for $\bar{p}d$ scattering at low and intermediate energies.[6]

Glauber[3] and Glauber and Matthiae[7] calculated the cross section σ_b as a sum of the cross sections of the inelastic processes, including the excitation and breakup of nuclei but not the production of new particles. We do not use here the standard expressions[3,7] for the cross section σ_b (called the inelastic scattering cross section in Refs. 3 and 7), for the elastic cross section σ_{el}, and for the total cross section σ_{tot}. The cross section of the reaction $\sigma_r = \sigma_{tot} - \sigma_{el}$ differs from the cross section σ_b in that it includes all inelastic channels (in this case even the annihilation). The $\bar{p}N$ amplitude was parametrized as

$$f(q) = \frac{k\sigma_{tot}^{\bar{p}N}(i+\epsilon)}{4\pi}\exp\left(-\frac{1}{2}Bq^2\right). \quad (1)$$

The deuteron cross sections were expressed in terms of the charge form factor of the deuteron in the parametrization given by Eq. (7), which was taken from a review,[8] and the cross sections for other nuclei were expressed in terms of the nuclear density in the Gaussian form (with $R = 1.37$ fm for ^{4}He). In the second case, the elastic amplitude was corrected for the nuclear recoil.

Figure 1 is a plot of the cross sections of $\bar{p}$ ^{4}He interaction versus the slope parameter B. The calculation was carried out for typical parameter values $\sigma_{tot}^{\bar{p}N} = 200$

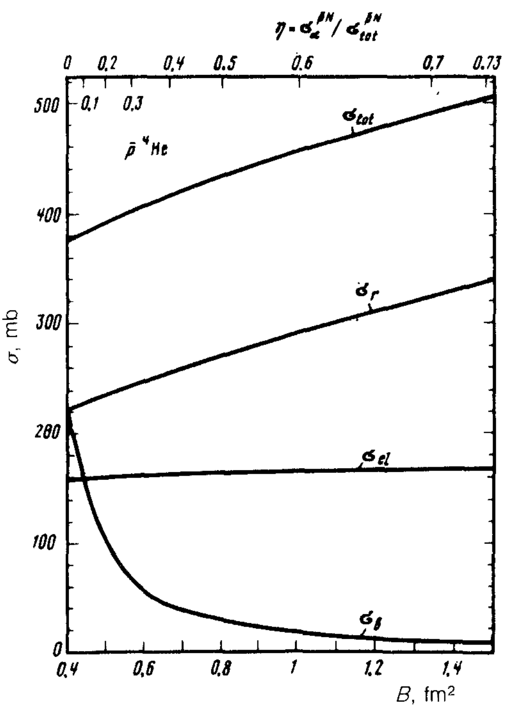

FIG. 1. Cross section of $\bar{p}$ ^{4}He interaction as functions of the slope parameter of the $\bar{p}N$ amplitude with simultaneous variation of the relative value η of the cross section for $\bar{p}N$ annihilation according to Eq. (2) (upper scale).

mb and $\epsilon = 0$. The upper scale is the ratio η of the annihilation $\bar{p}N$ cross section to the total cross section.

$$\eta = \frac{\sigma_a^{\bar{p}N}}{\sigma_{tot}^{\bar{p}N}} = \frac{\sigma_{tot}^{\bar{p}N} - \sigma_{el}^{\bar{p}N}}{\sigma_{tot}^{\bar{p}N}} = 1 - \frac{\sigma_{tot}^{\bar{p}N}(1+\epsilon^2)}{16\pi B} . \quad (2)$$

We see that the cross section σ_b of the annihilationless breakup, in contrast with σ_{tot}, σ_{el}, and σ_r, depends very strongly on B. For $B \approx 0.4$ fm^2 the annihilation does not come into play ($\eta = 0$), so that $\sigma_b = \sigma_r$. With an increase in B to the observable value $B = 1.4$ fm^2, the cross section σ_b decreases by more than an order of magnitude. As the value of B increases, however, the relative value of the annihilation cross section also increases in accordance with Eq. (2), reaching a value $\eta = 0.7$ when $B = 1.4$ fm^2. Illustrating a sharp suppression of σ_b at large values of B and η, Fig. 1 therefore does not yet allow us to choose between the two physical pictures of this suppression which are discussed above.

Figure 2 shows the ratio $\gamma = \sigma_b^{\bar{p}A}/\sigma_{el}^{\bar{p}A}$ versus the relative value of the annihilation cross secion η. Curves 1 were obtained for a fixed value of B, $B = 1.4$ fm^2, and when

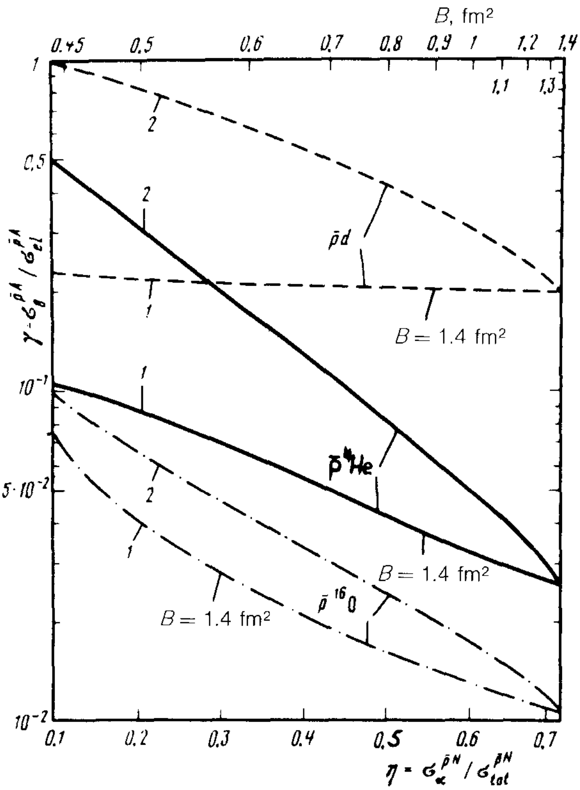

FIG. 2. The ratio $\gamma = \sigma_b^{\bar{p}A}/\sigma_{el}^{\bar{p}A}$ for various nuclei versus the relative value η of the cross section for $\bar{p}N$ annihilation. Dashed curves — For d (multiplied by 0.7); solid curves — for ^{4}He (multiplied by 0.49); dot-dashed curves — for ^{16}O (multiplied by 0.105). Curves 1 correspond to a fixed value $B = 1.4$ fm^2; curves 2 correspond to a variation in the values of B in accordance with Eq. (2) for $\epsilon = 0$ (upper scale).

the value of η was changed, relation (2) was satisfied by changing the value of ϵ. Curves 2 were obtained for a relation between η and B given by Eq. (2) with $\epsilon = 0$. The corresponding values of B appear on the upper scale.

We see that for a deuteron (dashed curves) the ratio γ with $B = \text{const}$ (curve 1) is nearly independent of η. As a result of simultaneous variation of B and η, the ratio γ (curve 2) decreases rapidly with increasing B. This means that the cross section σ_b for the deuteron is suppressed not because of the large value of the annihiliation cross section $\sigma_a^{\bar{p}N}$ but because of the large value of the slope parameter B.

In the case of an ^{4}He nucleus (solid curves) the ratio γ decreases fivefold as η increases from 0.1 to 0.7 while the value of B remains constant (curve 1). When the B dependence comes into play, the ratio γ decreases by a factor of 20 (curve 2). In the case of an ^{4}He nucleus both suppression mechanisms therefore contribute about equally.

Finally, in the case of an ^{16}O nucleus the application or removal of the B dependence affects only slightly the behavior of the relative value of the cross section σ_b as a function of η (dot-dashed curves 1 and 2 are approximately the same). The suppression of the cross section σ_b for the ^{16}O nucleus is therefore determined by the large value of the $\bar{p}N$ annihilation cross section.

Table I gives the calculated values of the $\bar{p}$ ^{4}He and $\bar{p}d$ cross sections (in mb) relative to the available experimental data. The parameters of the $\bar{p}N$ amplitudes are the same as those used in the calculations of Ref. 5. The calculated cross sections σ_b and σ_r are in good agreement with the experimental values of Ref. 1 and 2 (except for σ_r at $T_{\bar{p}} = 50$ MeV) and with the calculated values of Ref. 2 at $T_{\bar{p}} = 180$ MeV. The value of σ_b for ^{4}He is smaller than that for d and smaller than the calculated values[2] of σ_b for ^{12}C and heavier nuclei.

Figure 3 shows the predicted differential cross sections of annihilationless breakup of an ^{4}He nucleus by 50- and 180-MeV antiprotons.

Our analysis shows that the first of the aforementioned mechanisms for the sup-

TABLE I.

Nucleus	Energy $T_{\bar{p}}$, MeV	$\sigma_{tot}^{theor.}$	$\sigma_{el}^{theor.}$	$\sigma_r^{theor.}$	σ_r^{exp}	$\sigma_b^{theor.}$	σ_b^{exp}
^{4}He	50	511	176	335	293.7 ± 9.1 Ref. 9	9.8	8.9 ± 19.1 Ref. 1
	180	377	132	245	239.2 ± 5.0 Ref. 2	15.7	15.5 ± 2.9 Ref. 2
d	50	358	90	269	–	26.5	–
	180	259	63	196	–	32.5	–

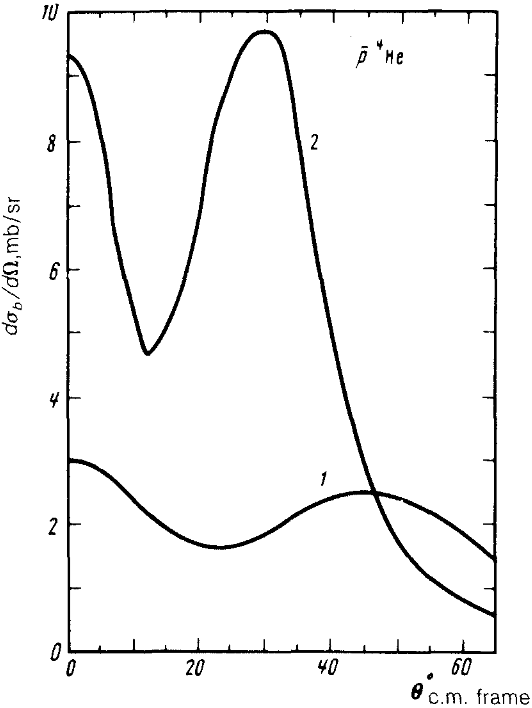

FIG. 3. Differential cross sections in the c.m. frame without annihilation breakup of an ^{4}He nucleus by 50-MeV antiprotons (curve 1) and 180-MeV antiprotons (curve 2).

pression of σ_b holds for a deuteron and the second mechanism holds for intermediate and heavy nuclei. As A is increased, the first mechanism begins to be replaced by the second very early: as early as with ^{4}He nucleus, where both mechanisms participate in the suppression of σ_b approximately equally.

The theory can be compared with experiment in more detail by measuring the cross sections σ_b of the annihilationless breakup of various nuclei by antiprotons and also the differential cross sections $d\sigma_b/d\Omega$.

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