Below-threshold and near-threshold production of antiprotons in collisions with nuclei

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Measurements of the inclusive cross section $E(d^3\sigma/d^3p)$ for the production of antiprotons in proton-nucleus collisions are reported. The results show that most of the antiprotons are produced in direct reactions at a kinetic energy >4.5 GeV of the accelerated protons. Estimates of the numbers of two- and three-nucleon clusters in Be, Al, and Cu nuclei are reported.

Information on the internal structure of a nucleus at a small relative distance between nucleons can be obtained by studying the production of particles (preferably heavy) near the kinematic threshold for their production at the free nucleon. This problem has been solved in extremely few studies. Dorfan *et al.*[1] have measured the $\bar{p}/$

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TABLE I. The invariant cross sections $E(d^3\sigma/d^3p)$ [nbn·(GeV)$^{-2}$·s^3·(sr)$^{-1}$]

T_{kin}, GeV	Be	Al	Cu	T_{kin}, GeV	Be	Al	Cu
9.2	19320	47000	66960	5.5	559	1230	1965
8.7	14590	35750	50375	5.3	385	844	1330
8.2	11510	27880	40395	5.1	219	547	898
7.7	8053	19640	28750	4.9	148	292	502
7.2	4845	11700	17190	4.7	77.5	177	263
6.8	3250	8219	11480	4.5	34.2	98.5	182
6.4	2093	4919	7359	4.37	23.8	62.0	93.0
6.1	1366	3294	4623	4.1	6.0	15.1	27.4
5.9	1037	2221	3432	3.9	2.3	6.1	10.0
5.7	787	1795	2895	3.7	0.40	0.97	2.3

π^- yield ratio in collisions with copper nuclei at impinging-proton energies from 3 to 6.1 GeV. Abrosimov *et al.*[2] have studied the production of K^+ mesons at several nuclei at energies well below the threshold.

We have measured the inclusive cross sections $E(d^3\sigma/d^3p)$ for $\bar{p}$ production with a momentum of 1.76 GeV/c at an emission angle of 188 mrad in collisions with Be, Al, and Cu nuclei at 20 values of the kinetic energy of the impinging protons, ranging from 9.2 to 3.7 GeV. These experiments were carried out at the synchrophasotron of the Institute of Theoretical and Experimental Physics. The internal targets were Be, Al, and Cu foils. The $\bar{p}$ particles were detected through measurements of their velocity with a differential Čerenkov counter and on the basis of their time of flight. The π mesons were suppressed by a gas-filled threshold counter.[3] The experiment consisted of two independent parts. In the first part, the $\bar{p}/\pi^-$ yield ratio was determined for all values of the energy. In the second part, the cross sections $E(d^3\sigma/d^3p)$ for the production of π^- mesons in collisions with these nuclei were measured.[4] The experimental results are shown in Table I. The values of the errors are 15% for the energy interval 9.2–4.37 GeV, 19% for 4.1 and 3.9 GeV, and 37% for 3.7 GeV. The figures for the errors do not include the overall uncertainty in the normalization of the data, which is estimated to be 20%.

The near-threshold production of particles in collisions with nuclei can occur both in direct reactions and in two-step processes involving a meson in an intermediate state. Below-threshold production in direct reactions occurs either as a result of the motion of nucleons in the nucleus or in processes involving multiquark configurations. At an energy of 3.9 GeV, for example, under these experimental conditions, $\bar{p}$ production would require a nucleon with an intranuclear momentum of 0.5 GeV/c or a configuration with a mass on the order of 2.5 nucleon masses. The two-step production of $\bar{p}$ particles under the same conditions might occur as a result of ordinary Fermi motion, but the contribution of the two-step mechanism would be small at initial energies $T_{\rm kin} > 4.6$ GeV, as can be seen from the experimental data. Specifically, at energies well above the threshold the antiprotons are produced for the most part in direct reactions involving nucleons of the nucleus. While the contribution of two-step processes begins to dominate as the initial energy is lowered, the A dependence of the cross sections for $\bar{p}$ production should be intensified[5] [the value of α in the parametrization $E(d^3\sigma/d^3p) \sim A^\alpha$ would increase]. However, the ratios of the $\bar{p}$ production cross sections for the Cu and Al nuclei, on the one hand, to the cross section at the Be nucleus, on the other, do not vary over the initial-energy range $T_{\rm kin} \geqslant 4.6$ GeV, within the experimental errors, and we have $\alpha = 0.64 \pm 0.04$ for 4.6 GeV$\leqslant T_{\rm kin} \leqslant 9.2$ GeV. Approximately the same values of α were found under similar kinematic conditions in Ref. 6 at $T_{\rm kin} = 12.9$ GeV and in Ref. 7 at $T_{\rm kin} = 70$ GeV. This invariant A dependence is a strong argument in favor of the production of antiprotons primarily in direct reactions in this energy range. At $T_{\rm kin} < 4.6$ GeV we observe a growth of α; we have not identified the reasons for the change in α. It should be kept in mind that the absorption in the nuclei of the antiprotons which are produced is slight[8]; at any rate, it would not alter the $T_{\rm kin}$ dependence of the $\bar{p}$ production cross section in two-step processes. For direct processes the A dependence might be weakened slightly at energies below the threshold.

In view of the discussion above, we will describe the energy behavior of the cross section under the assumption that the production of antiprotons in this energy range occurs in a single event in which a proton interacts with a nucleon in the nucleus or with a multiquark configuration (a cluster) in the reaction $p + (nN) \to \bar{p} + p + p + (nN)$, where $n = 1,2,3$. The cluster (nN) does not disintegrate. The cross section for the process is written as the sum of the cross sections for the production at the nucleon and at the configurations:

$$E\frac{d^3\sigma}{d^3p} = \sum_{n=1}^{3} \beta_n |T_n|^2 \int f_n(p_F) \frac{R_n(T_{\rm kin}, p_F)}{J_n(T_{\rm kin}, p_F)} d^3p_F \ , \qquad (1)$$

where β_n is the probability for finding a cluster with n nucleons in the nucleus ($\beta_1 = 1$), J_n is a flux factor, R_n is the three-particle phase space, and $|T_n|$ is the modulus of the corresponding reaction matrix element. We are assuming $|T_n| = \text{const}$, since the contribution of each of the terms in the sum is predominant in a rather narrow energy interval. Here p_F is the Fermi momentum, and $f_n(p_F)$ is the distribution function of the corresponding "particles" in the nucleus. In these calculations we assumed that the nucleons in the nucleus form a degenerate Fermi gas. The momentum distributions of the nucleon clusters were calculated under the assumption that the nucleons in the nucleus can coalesce at short distances and that the momentum of the configuration that forms is equal to the geometric sum of the momenta of the constituent nucleons. From expressions (1) we found the four values p_F and $\beta_n |T_n|^2$ which describe the experimental data best for each nucleus. The relationship between the amplitudes T_2 and T_3, on the one hand, and T_1, on the other, was found in the colored-tube model in Ref. 9: $|T_n|^2 \simeq n^{2/3}|T_1|^2$. The relative probabilities (β_n) for observing multiquark configurations are shown along with the corresponding values of the Fermi momentum for the Be, Al, and Cu nuclei at the left in Table II. The values of the Fermi momentum given in this table for the Al and Cu nuclei are 20–30 MeV/c

TABLE II.

A	Be	Al	Cu	Be	Al	Cu
p_F MeV/c	225 + 10%	190 + 11%	210 + 11%	0	0	0
β_2	0.025 + 15%	0.026 + 15%	0.027 + 15%	0.038 + 21%	0.036 + 20%	0.040 + 20%
β_3	0.0010 + 50%	0.0019 + 35%	0.0024 + 35%	0.0024 + 50%	0.0031 + 50%	0.0039 + 50%
χ^2/n	1	1	1.1	2.7	1.95	2.0

smaller than the customary values, possibly because of a slight absorption of the antiprotons which are produced at energies near the threshold in the central part of the nucleus. Shown at the right in Table II are values of the probabilities β_n for the case in which p_F is small, so that β_n is an upper estimate.

A description on the basis of the cluster model indicates that the relative 6-quark admixture in the nuclei remains constant from Be to Cu. The admixture of 9-quark configurations more probably increases with increasing A. The estimate of the number of multiquark clusters found in this study is substantially lower than the estimates which follow from analysis of other processes.[10]

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