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Neutron-to-proton ratio in intermediate-energy nuclear reactions

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The ratio of inclusive spectra of neutrons and protons in antiproton-, pion-, and proton-nucleus interactions at intermediate energies has been considered in the framework of the intranuclear cascade (INC) model. The ratio predicted by the standard INC model is consistent with the experimental data for pion- and proton-induced reactions, but contradicts the ratio obtained in antiproton-nucleus annihilation measurements. It has been shown that for pion-nucleus interactions the n/p ratio is much affected by isotopic effects in pion absorption and mainly depends on pion charge. Nevertheless, due to the presence of positive, negative, and neutral pions in antiproton-nucleon annihilation the calculated n/p ratio becomes close to the N/Z ratio of the target nucleus. The coalescence of nucleons, preequilibrium emission of particles, interaction of annihilation pions with the nuclear Coulomb field, neutron halo effects, and many body annihilation have been considered as possible candidates which would affect the n/p ratio in antiproton-nucleus annihilation. A simple quark counting estimation for the n/p ratio in many body annihilation has been made.

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I. INTRODUCTION

A specific feature of intermediate-energy nuclear reactions is the production of one or several pions by a projectile and their subsequent interaction with nuclear matter. Some characteristics of these reactions are still poorly understood. This is particularly true for the ratio of the neutron yield to the proton yield (n/p ratio). As few as two measurements of the n/p ratio had been done in the range of primary energies in question. These are the experiment [1] with 1.3 GeV pions and 6.6 GeV protons and the experiment [2] with 1 GeV protons. The n/p ratio was measured recently [3] for the annihilation of stopped antiprotons in nuclei. These data will be analyzed in the framework of the intranuclear cascade (INC) model [4] in the present paper so as to reveal the sensitivity of n/p ratio to the specific nature of projectile and some peculiarities of its interaction with a nucleus.

II. COMPARISON BETWEEN THE DATA ON n/p RATIO IN πA, pA, AND $\bar{p}A$ REACTIONS AND THE STANDARD INC MODEL

There is a great deal of data on the inclusive spectra of neutrons and protons emitted in intermediate-energy nuclear reactions. As an example, the data [3] for annihilation of stopped antiprotons in the U nucleus are shown in Fig. 1. The standard INC model [5] describes the inclusive spectra rather well (see Fig. 1).

The ratio of neutron inclusive spectrum to proton one is a more delicate characteristic of nuclear reaction than an inclusive spectrum in itself. The data on the n/p ratio for πA, pA, and $\bar{p}A$ reactions are shown in Fig. 2. Intuition suggests that the ratio between knocked-out neutrons and protons tends to the ratio of their numbers N/Z in the target nucleus. The calculated results are close to this intuitive estimation (see Fig. 2). The data on n/p ratio for πA and pA reactions are also close to the N/Z value (at least, for light C and medium weight Cu nuclei, and for not so high energy of nucleons $E_N \leq 100$ MeV). But in the case of $\bar{p}A$ annihilation, the experimental values of the n/p ratio are considerably greater than the N/Z value and twice as large as that for πA and pA reactions.

The most prominent feature of the experimental data [3] is a great value of the n/p ratio for carbon. Indeed, one can obtain this experimental value if the proton spectrum calculated by the INC model shifted left by 50 MeV (see Fig. 19 of [3]), while it is hard to expect the same difference between average removal energies for neutrons and protons in the case of light nucleus with $N = Z$ since neutron and proton states are not so different (even taking into account the Coulomb barrier of 3 MeV) and one needs also to average the removal energies over these states.

Let us consider the main distinctions between $\bar{p}A$ annihilation and πA and pA interactions. In the case of πA and pA reactions, the n/p ratio was measured at the large angle $\theta_N = 120°$ in the nucleon energy range $100 \leq E_N \leq 200$ MeV. (It should be noted that the n/p ratio is practically independent of angle in the region $\theta_N \geq 60°$.) The nucleon spectrum at large angles is formed mainly by the products of the multiple rescattering of cascade nucleons and two-nucleon absorption of cascade pions $\pi + NN \to NN$ inside the nucleus. (The role of the latter subprocess increases in importance with the nucleon energy E_N.)

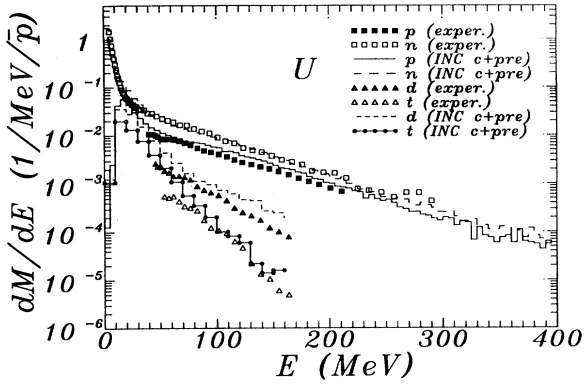

FIG. 1. Inclusive energy spectra of protons, neutrons, deuterons, and tritons produced in antiproton annihilation at rest in uranium. Squares and triangles: experiment [3]. Histograms: results of the intranuclear cascade model with coalescence and preequlibrium emission of complex particles.

As the cross sections of elementary πN and NN collisions are isospin dependent, the n/p ratio will hold its dependence on the third projection of isospin of primary particle (i.e., on the charge of projectile). The calculations performed in the framework of the INC model [4] show that the n/p ratio depends rather strongly on the projectile charge both in πA interaction (see Fig. 3) and pA interaction (see Fig. 4). The effects of the final state interaction weaken this dependence in the range of lower energies E_N (see Figs. 3 and 4). To eliminate the dependence on the charge of the projectile, the neutron and proton yields which were measured [1] separately on beams of π^+ and π^- mesons for the given target were averaged: $n/p = [Y(\pi^- A \to n + X) + Y(\pi^+ A \to n + X)]/[Y(\pi^- A \to p + X) + Y(\pi^+ A \to p + X)]$. The same averaging was carried out also in our calculations, with the result that the n/p ratio became close to the N/Z value (see Fig. 3).

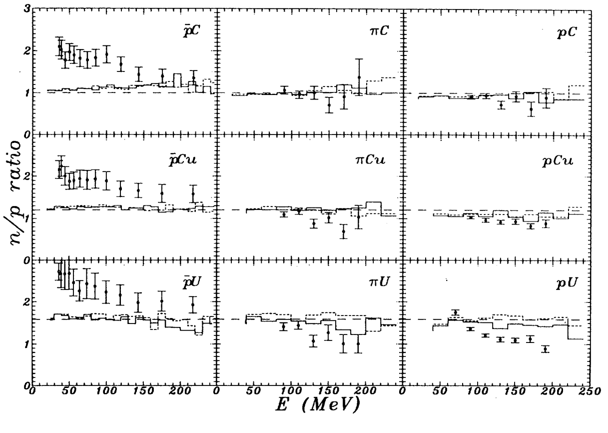

FIG. 2. Ratio of inclusive energy spectra of neutrons and protons. Points denote the results of experiments on interactions of stopped antiprotons [3], 1.3 GeV pions (averaged on pion charge), and 6.6 protons [1] with carbon, copper, and uranium. In πA and pA interactions neutron and proton yields were measured at 120°. Solid histograms: standard intranuclear cascade model results. Dashed histograms: INC model calculation with inclusion of isospin effects in pion absorption. Dashed horizontal lines: N/Z values of target nuclei.

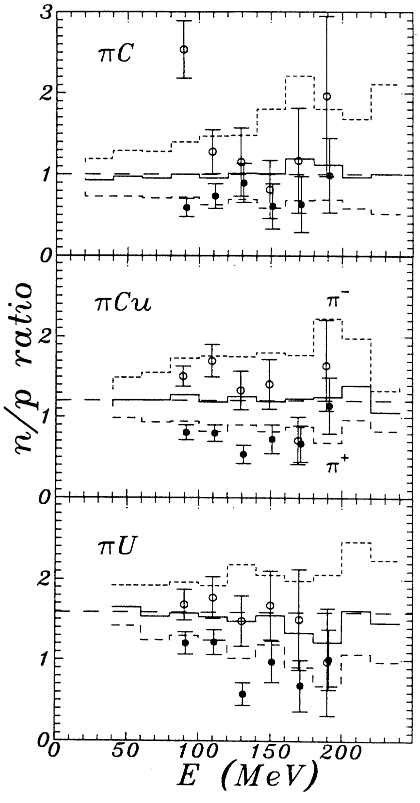

FIG. 3. Ratio of yields of neutrons and protons emitted at 120° in $\pi^+ A$ (full circles and dashed histograms) and $\pi^- A$ interactions (open circles and dotted histograms) at pion energy 1.3 GeV. The circles denote experiment [1]. The histograms correspond to the INC model results with account of isospin effects in pion absorption. The solid histograms show the calculation results averaged on pion charge. N/Z values for carbon, copper, and uranium are presented by dashed horizontal lines.

A stopped antiproton is absorbed at the nuclear periphery with a very low nuclear matter density [4,5]. The main mechanism of absorption is the annihilation of antiprotons with a quasifree nucleon $\bar{p}N \to n\pi$; then a part of annihilation pions interacts with a nucleus. The averaged multiplicity of pions produced in $\bar{p}N$ annihilation is $\bar{n}_\pi \approx 5$, and their averaged energy is $\bar{E}_\pi \approx$ 210 MeV. As an equal number of pions with opposite charges $n_{\pi^+} = n_{\pi^-}$ are produced in $\bar{p}p$ annihilation ($n_{\pi^-} - n_{\pi^+} = 1$ for $\bar{p}n$ annihilation), the averaging over the charge of pions which interact with a nucleus is inherent in the $\bar{p}A$ reaction. This situation is similar as in the experiment [1], but the averaged energy of secondary pions in the πA reaction was much higher than in the case

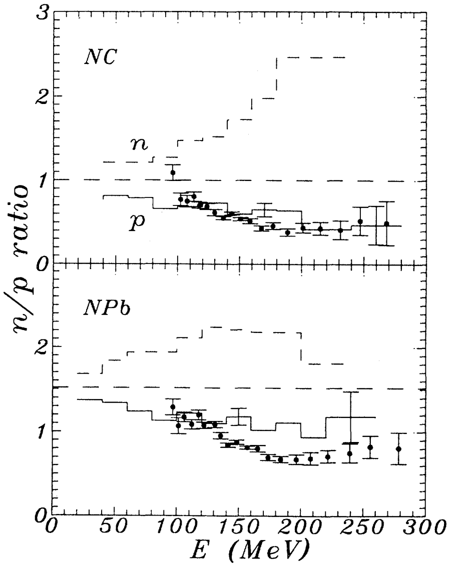

FIG. 4. Ratio of yields of neutrons and protons emitted at 120° in pA (circles and solid histograms) and nA interactions (dashed histograms) at nucleon energy 1 GeV. The circles denote experiment [2]. The histograms correspond to the INC model results with account of isospin effects in pion absorption. N/Z values for carbon, copper, and uranium are presented by dashed horizontal lines.

of $\bar{p}A$ annihilation. Therefore it is reasonable to consider the n/p ratio in πA and pA interactions at lower primary energy than in the experiment [1].

The data [2] on the n/p ratio for interaction of 1 GeV protons with nuclei, which were measured at the same angle $\theta_N = 120°$ as in paper [1], are shown in Fig. 4. The results of calculations by the standard INC model are in agreement with this data (see Fig. 4). Unfortunately, there are no data on the n/p ratio for a πA interaction at the primary energies $E_0 \approx 100$–200 MeV which are close to the averaged energy of annihilation pions. Therefore, only the calculated results for the πA reaction at $E_0 = 140$ MeV are presented in Fig. 5. Here the dependence of the n/p ratio on the pion charge is much more pronounced than at high primary energies. But the n/p ratio becomes close to the N/Z value after averaging over pion charge even in this energy region.

So, the standard INC model [4,5] describes satisfactorily the data [1,2] on the n/p ratio for pA and πA reactions. The value of the n/p ratio in these reactions is close to the N/Z value for light target nuclei and somewhat lower than the N/Z value for heavy nuclei. This is a result of averaging over the projectile charge in the case of the πA interaction. As such averaging takes place also in $\bar{p}A$ annihilation, the INC model predicts for this case the value of the n/p ratio which is close to the N/Z value. However, the experimental value [3] of the n/p ratio in $\bar{p}A$ annihilation is nearly twice as large as both the calculated value and the experimental value [1,2] in πA and pA interactions. Probably, this distinction is caused by a manifestation of specific effects in $\bar{p}A$ annihilation which were not taken into account in the standard INC model [4,5]. Let us consider some of these effects.

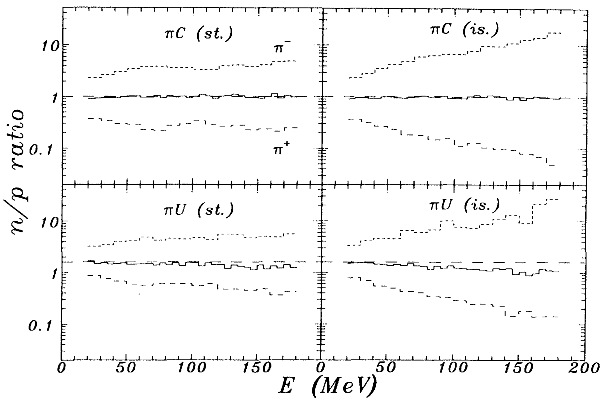

FIG. 5. Ratio of inclusive spectra of neutrons and protons emitted in $\pi^+ A$ (dashed histograms) and $\pi^- A$ interactions (dotted histograms) at pion energy 140 MeV. The solid histograms present the result of averaging on pion charge. The left and right parts correspond to the standard INC model and the model with account of isospin effects in pion absorption, respectively. N/Z values for carbon and uranium are presented by dashed horizontal lines.

III. INFLUENCE OF VARIOUS EFFECTS ON n/p RATIO IN $\bar{p}A$ ANNIHILATION

The nucleon inclusive spectrum considered in the present paper is formed by products of the deep-inelastic interaction. For this interaction, the condition $\Delta A \gg 1$ takes place and the quantum and nuclear structure effects become not so important due to a series of sequentional rescatterings of secondary nucleons inside the nucleus [4]. The models based on the kinetic approach (the exciton model, intranuclear cascade model, BUU equation model, and so on) describe this part of the nucleon spectrum very well both for nucleon-nucleus deep-inelastic interaction and for nuclear absorption of pions on a pair of nucleons. All these models use the Fermi-gas description of a nucleus and neglect the nuclear structure effects. Nevertheless, they describe very nicely the neutron and proton spectra in πA and pA reactions, and it is an evidence that these effects are not so important in the deep-inelastic interaction. Evidently, it is true also for $\bar{p}A$ annihilation.

A. Isospin effects in two-nucleon absorption of pions

As was mentioned above, $\bar{p}A$ annihilation may be reduced to the interaction of several pions, which have the averaged energy nearby the (3,3) resonance, with the nucleus. The standard INC model [4,5] takes into account exactly the isospin dependence of the cross sections for all channels of elementary πN interactions except for the channel of two-nucleon absorption of a pion.

The elementary reactions of two-nucleon absorption of pions in the nucleus are as follows:

$$\begin{gathered}\pi^+ + np \to pp(I=0,1),\quad \pi^- + np \to nn(I=0,1),\\ \pi^+ + nn \to np(I=1),\quad \pi^- + pp \to np(I=1)\ ,\\ \pi^0 + np \to np\ (I=0,1),\\ \pi^0 + pp \to pp\ (I=1),\\ \pi^0 + nn \to nn\ (I=1).\end{gathered}$$

(Here I is the isospin of the NN pair.) The state with isospin $I = 0$ plays the main role in absorption of a pion by an np pair, and a contribution from the state with $I = 1$ may be neglected. Then, as a result of the isospin symmetry, the relations between the cross sections of these reactions are as follows:

$$\begin{aligned}&\sigma(\pi^+ + np \to pp) = \sigma(\pi^- + np \to nn),\\ &\sigma(\pi^- + pp \to np) = \sigma(\pi^+ + nn \to np),\\ &\sigma(\pi^0 + pp \to pp) = \sigma(\pi^0 + nn \to nn),\\ &\sigma(\pi^0 + np \to np) = \tfrac{1}{2}\sigma(\pi^+ + np \to pp).\end{aligned}$$

The ratio of probabilities of absorption of a pion by np and pp pairs $R = W_{np}/W_{pp}$ is measured in πA experiments (see review [6]). To extract from this quantity the ratio of the cross sections of absorption from the states with isospin $I = 0$ and $I = 1$,

$$R_0 = \sigma(\pi^+ + np \to pp)/\sigma(\pi^- + pp \to np),$$

the combinatorial factor is separated out. This factor is equal to the ratio of the number NZ of np pairs to the number $Z(Z-1)/2$ of pp pairs in the nucleus. Then a simple relation takes place:

$$R = \frac{2N}{Z-1} R_0.$$

Firm data on the isospin ratio R_0 which are not practically influenced by the effects of the final state interaction were obtained in experiments [6] with the lightest nucleus ^{3}He. These data evidence that the energy dependence of the isospin ratio R_0 is nearly the same as for the cross section of the $\pi d \to NN$ reaction (see Fig. 6). This is an indication of the dominant role of $N\Delta$ intermediate state in the πNN interaction. As a result, the isospin ratio has the maximum value $R_0 \simeq 20$ similar to the energy of the (3,3) resonance.

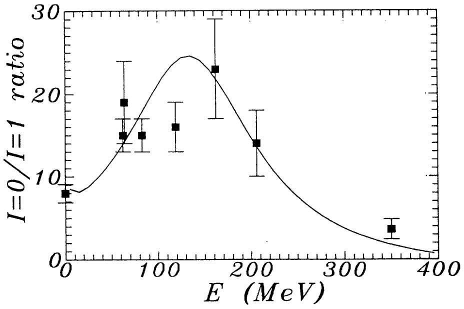

FIG. 6. Approximation of energy dependent isospin ratio R_o as a function of pion energy. The points were taken from review [6].

The standard INC model [4] uses the combinatorial value $R_0 = 1$. It means that the probability of absorption of the pion by a given NN pair is proportional to the number of pairs of a given type in the nucleus. This value is strongly different from the experimental one (see Fig. 6). To study the influence of the isospin effects on the n/p ratio, the energy dependent isospin ratio R_0 which is depicted by the curve in Fig. 6 was introduced to the INC model. The isospin effects in the πA interaction are most pronounced at primary energy $E_0 = 140$ MeV where the n/p ratio reaches the values ~ 10 in the $\pi^- A$ reaction and ~ 0.1 in the $\pi^+ A$ reaction (see Fig. 5). To study the isospin effects, it would be desirable to measure the n/p ratio at this energy E_0. But these effects are compensated for by an averaging over pion charge even at the energy $E_0 = 140$ MeV, and the n/p ratio tends to the N/Z value for light and medium weight nuclei (see Fig. 5). The n/p ratio becomes slightly lower than the N/Z value for heavy nuclei due to the isospin effects, and the experimental data for πA and pA reactions are more reproducible by the calculations (see Fig. 2). As to $\bar{p}A$ annihilation, the isospin effects in the two-nucleon absorption of pions cannot explain the anomalously large value of the n/p ratio in this case.

B. Effects of coalescence and preequilibrium emission of complex particles

As a result of the interaction of several annihilation pions with a nucleus, a branchy intranuclear cascade is developed which involves a lot of nucleons. A part of them may associate into complex particles if the difference between their momenta $\vec{p}_i$ and the cluster momentum $\vec{p}_{\rm cl} = \sum_{i=1}^{n} \vec{p}_i/A_{\rm cl}$ is small: $\mid \vec{p}_i - \vec{p}_{\rm cl} \mid \leq p_0$, where p_0 is the empirical coalescence parameter [7]. The relation between the emitted neutrons and protons may be changed as a result of a coalescence of cascade nucleons. Indeed, the n/p ratio increases if a neutron associates with a proton into a deuteron because the proton number is much less than the neutron one (see Fig. 1). Besides, the n/p ratio may be changed due to emission of complex particles during the establishment of the equilibrium in the residual nucleus produced upon completion of the intranuclear cascade (the exciton coalescence in the residual nucleus) [7].

The modified INC model [7] was used here to estimate the effects of coalescence and preequilibrium emission of complex particles. This model describes rather well the inclusive spectra of deuterons and tritons measured in the same experiment [3]. As it is seen from Fig. 7, these effects have no important bearing on the n/p ratio. It is caused by a low probability of emission of complex particles in $\bar{p}A$ annihilation (the multiplicity of deuterons comprise about 15% , and tritons about 4% in respect to the proton multiplicity; see Fig. 1).

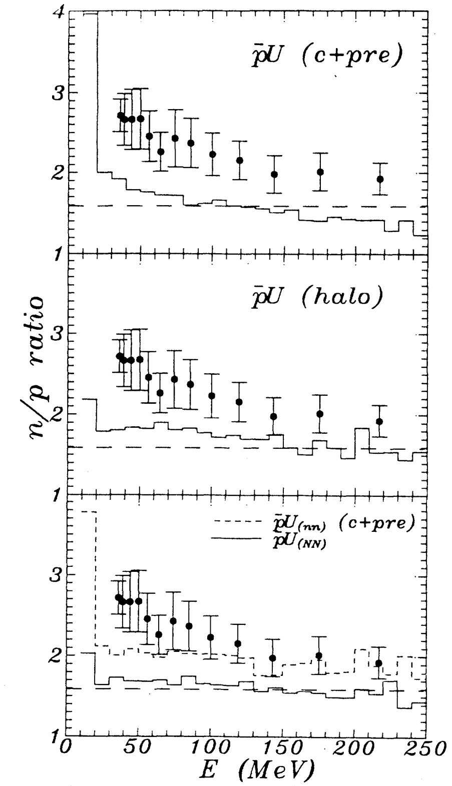

FIG. 7. Ratio of inclusive spectra of neutrons and protons produced in antiproton annihilation on uranium. The points are experiment [3]. Upper figure: the INC calculation with coalescence and preequilibrium emission of complex particles. Middle figure: the INC calculation with neutron halo effects. Lower figure: the INC calculation with 100% probability for $B = 1$ annihilation (solid histogram). The dotted histogram presents an extreme assumption that the antiprotons are absorbed by nn pairs.

C. Coulomb effects in the interaction of annihilation pions with a nucleus

As it was shown in experiment [8], the cross section of absorption of low energy ($E_0 \leq 50$ MeV) π^- mesons by heavy nuclei is much larger than for π^+ mesons due to the Coulomb effects. Obviously, similar effects may manifest themselves also in $\bar{p}A$ annihilation. Coulomb interaction tends to decrease the part of π^+ mesons and to increase the part of π^- mesons absorbed by the nucleus. In its turn, this leads to an increase in the n/p ratio.

But these Coulomb effects are weak for light nuclei [8], whereas the anomalously large value of the n/p ratio takes place in $\bar{p}C$ annihilation (see Fig. 2). Moreover, Coulomb effects are also weak in antiproton annihilation in heavy nuclei due to a small part of low-energy pions in the very wide annihilation spectrum which extends up to $E_\pi \sim 1$ GeV. The data on the averaged multiplicity of π^+, π^-, and π^0 mesons emitted in $\bar{p}A$ annihilation also support the conclusion about the small role of Coulomb effects because the INC model describes the data without considering these effects. If somebody would try to explain the anomalously large value of the n/p ratio by a preferential absorption of π^- mesons by a nucleus, the relation between π^+ and π^- mesons will be changed so drastically that it will contradict the experiment (see Table I).

D. Effects of neutron halo

A stopped antiproton is absorbed at a large distance from the nuclear center where the nuclear density is anomalously low. If a neutron halo exists in the nucleus, the neutron $\rho_n(r)$ and proton $\rho_p(r)$ densities are different, so that there is rarefied neutron matter at the nuclear periphery. As a result, an antiproton will annihilate with an intranuclear neutron more often than with proton and it may affect the value of the n/p ratio.

The basic quantity of our model [5] which determines the initial conditions for the intranuclear cascade is the probability of absorption from the $\bar{p}$ atom state with principal quantum number n and orbital number l:

$$W_{\text{abs}} \sim \text{Im}V(r) \mid \Psi_{nl}(r) \mid^2 r^2 . \tag{1}$$

Here Ψ_{nl} is the $\bar{p}$ wave function, and $V(r)$ is the optical $\bar{p}A$ potential:

$$V(r) = \frac{2\pi}{\mu}[a_{\bar{p}p}\rho_p(r) + a_{\bar{p}n}\rho_n(r)] , \tag{2}$$

where μ is the $\bar{p}$ reduced mass, $a_{\bar{p}N}$ is the $\bar{p}N$ scattering length. Then the ratio of probabilities of annihilation with neutron and proton is proportional to the ratio of

TABLE I. Averaged pion multiplicities and relationship between π^+ and π^- mesons emitted in $\bar{p}A$ annihilation.

	$\bar{n}_{\pi^0}$		$\bar{n}_{\pi^+}$		$\bar{n}_{\pi^-}$		$\bar{n}_{\pi^+}/\bar{n}_{\pi^-}$		$\bar{n}_{\pi^-}$-$\bar{n}_{\pi^+}$	
	INC	Exper.	INC	Exper.	INC	Exper.	INC	Exper.	INC	Exper.
$\bar{p}C$	1.46	1.81 ± 0.30 [9] 1.73 ± 0.14 [10] 1.14 ± 0.40 [11]	1.04	1.22 ± 0.01 [9] 1.25 ± 0.07 [10] 1.35 ± 0.12 [11]	1.47	1.57 ± 0.02 [9] 1.59 ± 0.09 [10] 1.50 ± 0.10 [11]	0.71	0.77 ± 0.01 [12]	0.43	0.36 ± 0.02 [12]
$\bar{p}$Cu	1.42		0.96	0.95 ± 0.02 [9]	1.40	1.49 ± 0.03 [9]	0.69	0.73 ± 0.02 [12]	0.44	0.40 ± 0.04 [12]
$\bar{p}$U	1.37	1.36 ± 0.12 [10]	0.86	0.99 ± 0.06 [10]	1.40	1.48 ± 0.09 [10]	0.62	0.60 ± 0.04 [12]	0.53	0.49 ± 0.09 [12]

neutron and proton densities:

$$\frac{W_n(r)}{W_p(r)} = \frac{\mathrm{Im}a_{\bar{p}n}}{\mathrm{Im}a_{\bar{p}p}} \frac{\rho_n(r)}{\rho_p(r)} .$$

The calculations [13] of $\bar{p}$ atoms based on the Hartree-Fock nuclear densities $\rho_n(r)$ and $\rho_p(r)$ showed that the probability of $\bar{p}$ absorption on neutron $W_n(r)$ expands to the very large distance $r \sim 15$ fm where $W_n \gg W_p$ (see Fig. 8) as a result of existence of a neutron halo.

The standard model [4,5] supposes that the neutron and proton densities have the same radial dependence $\rho_N(r)$, i.e., the combinatorial estimation $W_n/W_p = N/Z$ is used. To study the neutron halo effects in the n/p ratio, the radius dependent ratio $W_n(r)/W_p(r)$ which is depicted by the curves in Fig. 8 was introduced into the model [5] instead of this estimation. As it is seen from Fig. 7, the neutron halo effects increase the n/p ratio, but it is not enough to describe the experimental data [3].

To reproduce the large experimental n/p ratio [3], it was supposed in paper [14] that there is a rather thick ($\sim$ 3 fm) neutron skin in the nucleus whose density is close to the central one $\rho(0)$. On the one hand, it contradicts the experimental data [15] which show that the neutron and proton radii are very close each other. On the other hand, it does not give any description of the experimental data [13] on the yield ratio of $(N-1,Z)$ and $(N,Z-1)$ nuclides in $\bar{p}A$ annihilation. These data are in a good agreement with our calculations which take into account the neutron halo effects (see Table II).

E. Effects of two-nucleon absorption of antiprotons

The main mechanism of $\bar{p}$ absorption by a nucleus is the annihilation of an antiproton with a single nucleon $\bar{p}+N \to iM$ where $M \equiv$ meson, and $2 \le i \le 8$ (so-called $B=0$ annihilation). Also two-nucleon $\bar{p}$ absorption by the nucleus $\bar{p}+NN \to N+iM$ (so-called $B=1$ annihilation) is possible along with a single-nucleon one. A number of models predict the total rate of two-nucleon absorption $\sim 1-25\,\%$ (see references cited in [16]). To estimate the effects of $B=1$ annihilation, let us use the extension of INC model to this case which was formulated in paper [16].

TABLE II. Yield of $(N-1,Z)$ and $(N,Z-1)$ nuclides in annihilation of stopped antiprotons in ^{232}Th nucleus.

	Yield per $10^3\bar{p}$		
	Experiment [13]	Calculation without halo	Calculation with halo
^{231}Th($\bar{p}$ n)	100 ± 27	25.6	120
^{231}Ac($\bar{p}$ p)	12.9 ± 1.6	12.6	15.4
$\frac{N(\bar{p}n)}{N(\bar{p}p)}$	7.8 ± 2.2	2.03	7.79

1. *Isospin effects in $B=1$ annihilation*

At first, let us suppose that the neutron and proton densities have the same radial dependence $\rho_N(r)$, and use the combinatorial estimation for the probability of antiproton to annihilate with the nucleon pair of a given charge: $W_{pp} \sim Z(Z-1)/2$, $W_{np} \sim NZ$, $W_{nn} \sim N(N-1)/2$. Let us assume also that the nucleon pair which absorbs the antiproton inside the nucleus exists in $I=0$ and $I=1$ isospin states with equal probability. The statistical model with Lorentz invariant phase volume and SU(3) symmetry [16] is applied to describe the meson production in $\bar{p}NN$ annihilation. In this model the averaged multiplicities of protons $\bar{n}_p$ and neutrons $\bar{n}_n$ are different in $\bar{p}$ annihilation with distinct NN pairs: $\bar{n}_p = 0.55$, $\bar{n}_n = 0.45$ in $\bar{p}pp$ annihilation, and $\bar{n}_p = 0.45$, $\bar{n}_n = 0.55$ in $\bar{p}pn$ annihilation and $\bar{n}_p = 0.33$, $\bar{n}_n = 0.67$ in $\bar{p}nn$ annihilation.

So, the n/p ratio in $B=1$ annihilation must be larger

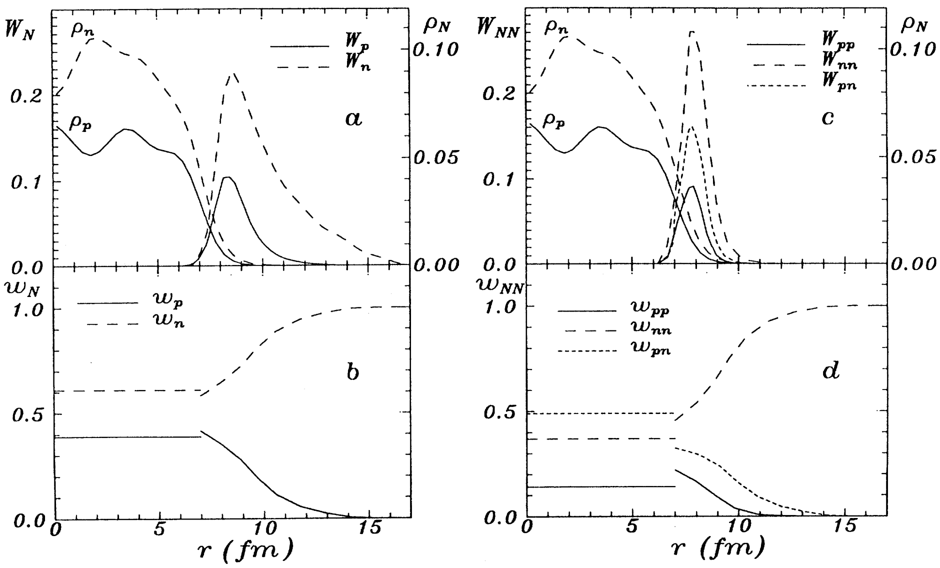

FIG. 8. (a) The single-nucleon absorption probability $W_N(r)$ and nucleon densities $\rho_N(r)$, fm^{-3} [13] for Th. (b) The relative probability of $\bar{p}$ absorption on neutron or proton $w_N \equiv W_N/(W_p+W_n)$ as a function of nuclear radius. The straight lines present the combinatorial estimation. (c) The two-nucleon absorption probability $W_{NN}(r)$. (d) The relative probability of $\bar{p}$ absorption by different NN pairs $w_{NN} \equiv W_{NN}/(W_{pp}+W_{nn}+W_{pn})$ as a function of nuclear radius. The combinatorial estimation is shown by straight lines.

than in $B = 0$ annihilation. This conclusion holds for the high-energy part of nucleon spectrum because it is formed by the nucleons from $\bar{p}NN$ annihilation that will not undergo rescattering inside the nucleus (see Fig. 9). Those parts of the nucleon spectrum where the effect of the final state interaction is dominant were measured in experiment [3]. Here the value of the n/p ratio is close to the N/Z value even in a limiting case of 100% probability for $B = 1$ annihilation (see Figs. 7 and 9). Below 100 MeV, however, the n/p ratio for uranium is quite larger than the N/Z ratio in all cases.

2. Neutron halo effects in B = 1 annihilation

As it was noted above, the neutron $\rho_n(r)$ and proton $\rho_p(r)$ densities are different, and the combinatorial estimation for the probability of $\bar{p}$ annihilation with the nucleon pair of a given charge cannot be used if a neutron halo exists in a nucleus. A more correct estimation for this case was done in paper [16]. To this end, the term which is responsible for $B = 1$ absorption was introduced to the optical potential (2):

$$V(r) = \frac{2\pi}{\mu}[a_{\bar{p}p}\rho_p(r) + a_{\bar{p}n}\rho_n(r)] + B_0[\rho_p^2(r) + \rho_n^2(r) + 2\rho_p(r)\rho_n(r)] \ . \qquad (3)$$

Here B_0 is the two-nucleon parameter. Then one can get from expressions (1) and (3) that the total absorption probability has the form:

$$W_{\rm abs}(r) = W_p(r) + W_n(r) + W_{pp}(r) + W_{nn}(r) + W_{np}(r) \ , \qquad (4)$$

where the densities W_{NN} of $\bar{p}$ absorption on the NN pair are expressed via the densities W_N of $\bar{p}$ absorption on a single nucleon: $W_{pp}(r) \sim \rho_p(r)W_p(r)$, $W_{nn}(r) \sim \rho_n(r)W_n(r)$, $W_{np}(r) \sim \rho_n(r)W_p(r)$.

As it is seen from Fig. 8, where the results of calculations [16] with Hartree-Fock nuclear densities [13] are shown, the relative probability of $\bar{p}$ absorption on different NN pairs is strongly dependent on radius and deviates considerably from the combinatorial estimation. $B = 1$ annihilation is suppressed at the far nuclear periphery due to the quadratic dependence of the two-nucleon term of optical $\bar{p}A$-potential (3) on the nucleon density $\rho_N(r)$. As a result, the distribution $W_{NN}(r)$ is much more narrow than $W_N(r)$. The calculations on the base of the modified model [16] with the probabilities $W_{NN}(r)$ depicted by the curves in Fig. 8 showed that the neutron halo practically has no affect on n/p ratio in $B = 1$ annihilation.

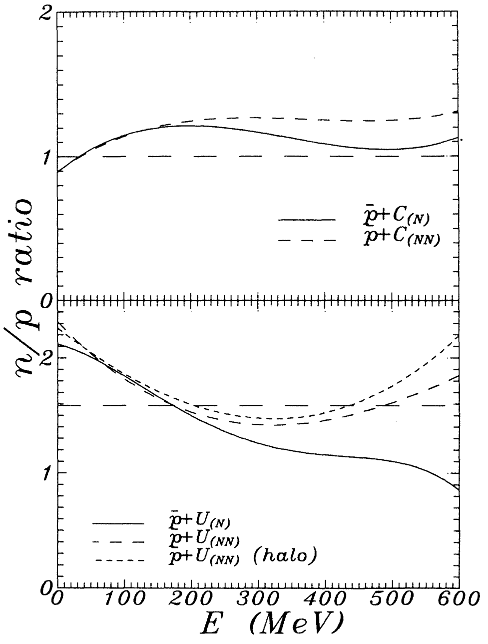

FIG. 9. Ratio of inclusive spectra of neutrons and protons. The solid line denotes the calculation with $B = 0$ annihilation process. The dashed line is obtained with $B = 1$ annihilation only. The dotted line for uranium presents the calculation results with $B = 1$ annihilation and halo effect. The N/Z values for carbon and uranium are presented by dashed horizontal lines.

So, the model [16] of two-nucleon absorption of an antiproton by the nucleus cannot reproduce the large experimental value [3] of the n/p ratio. The only extreme assumption that the antiprotons are absorbed by nn pairs gives a possibility to describe satisfactorily the data on the n/p ratio (see Fig. 7).

F. Effects of multinucleon absorption of antiprotons

Nuclear clusters consisting of three or four nucleons may also absorb an antiproton ($B = 2$ and $B = 3$ annihilation). A number of models [17–19] predict the total rate of multinucleon absorption $\sim 1-10\,\%$. Let us generalize the simplest model of constituent quarks [20] on the case of multinucleon absorption and estimate the value of the n/p ratio on this bases.

The n/p ratio would be expressible as a ratio of the number of ways $C^1_{n_u}C^2_{n_d}$ to build a neutron (udd) to the number of ways $C^2_{n_u}C^1_{n_d}$ to build a proton (uud) from the total number n_u of u quarks and n_d of d quarks in the final state of multinucleon annihilation:

TABLE III. n/p ratio in multinucleon antiproton annihilation.

Type	Mesons	Clusters						
		NN		NNN		$NNNN$		
		nn	pn	nnn	pnn	$nnnn$	$pnnn$	$ppnn$
R	3	3	1	2.5	1.333	2.333	1.5	1
$C_{\bar{u}u}$	4	1.5	0.667	1.667	1	1.75	1.2	0.833
$C_{\bar{d}d}$	4	4	1.5	3	1.667	2.667	1.75	1.2
$C_{\bar{u}u\bar{d}d}$	5	2	1	2	1.25	2	1.4	1
Average		2.6	1	2.3	1.3	2.2	1.5	1
SU(3) model		2	1.2					

$$R_q(n_u, n_d) = \frac{C^1_{n_u} C^2_{n_d}}{C^2_{n_u} C^1_{n_d}} , \tag{5}$$

where

$$C^k_l = \begin{cases} l!/k!(l-k)! & \text{for } k \le l, \\ 0 & \text{otherwise,} \end{cases} \tag{6}$$

and k and l are any integers. This relation is akin to estimation of n/p ratio used in the paper [21] for multiquark clusters in nuclei. In this case the simplest process of quark rearrangement (R) with production of three mesons and a corresponding number of baryons may be accompanied by the process with creation of $\bar{u}u$ pair ($C_{\bar{u}u}$) or $\bar{d}d$ pair ($C_{\bar{d}d}$) which leads to production of baryons and four mesons, or with creation of both these pairs ($C_{\bar{u}u\bar{d}d}$) which leads to production of baryons and five mesons. As the channels with large multiplicity (three or more) dominate in the annihilation, the contribution of processes with annihilation of $\bar{u}u$ or $\bar{d}d$ pairs (i.e., with a decrease of number of antiquarks which are incorporated into mesons) may be neglected.

Such combinatorial estimation for some nuclear clusters absorbing the antiproton, is presented in Table III. The value of the n/p ratio for other combinations of charges of nucleons associated into a cluster can be obtained by a relation $R_q(i,j) = R_q(j,i)^{-1}$ where i and j are any integers. As it is seen from Table III, the n/p ratio is large for the absorption of antiproton by the neutron-rich cluster. The n/p ratio reaches the largest value in the $C_{\bar{d}d}$ process of $\bar{p}nn$ annihilation with the creation of a $\bar{d}d$ pair. As the contributions of processes of different types are unknown, it is a possible way to average the n/p ratio over the types in assumption of equiprobable contributions. It should be noted that the result of such averaging in $B = 1$ annihilation is close to the predictions of the SU(3) statistical model. The value of the n/p ratio averaged over different processes in annihilation of an antiproton on a multinucleon cluster decreases with a rise in its neutron number.

To apply this estimation to $\bar{p}A$ annihilation, first the averaging over various types of nuclear clusters must be performed. As a result, the n/p ratio becomes close to the N/Z value. Second, the final state interaction must be taken into account, and this leads to the same result. So, it is possible to obtain the n/p ratio which exceeds considerably the N/Z value if a predominant absorption of antiprotons by a neutron-rich nuclear cluster is assumed. In this case the attraction is toward the nn pair because the n/p ratio has the maximum at $\bar{p}nn$ annihilation (see Table III), and the theory [17,18] predicts that $B = 1$ annihilation dominates in multinucleon $\bar{p}$ absorption.

IV. CONCLUSIONS

The n/p ratio in NA and πA reactions averaged over projectile charge is close to the N/Z value both in the experiment [1,2] and standard INC model [4]. The same averaging over the charge of pions which interact with the nucleus takes place also in $\bar{p}A$ annihilation, and the n/p ratio calculated in the framework of the INC model is close to the N/Z value in this case. But the experimental [3] value of the n/p ratio in $\bar{p}A$ annihilation is twice as large as that for NA and πA experiments [1,2], and INC calculation. None of the effects which are peculiar to the absorption of a stopped antiproton by a nucleus (the isospin effects in two-nucleon absorption of pions, the effects of coalescence and preequilibrium emission of complex particles, Coulomb effects in the interaction of annihilation pions with the nucleus, the effects of neutron halo) can explain an anomalously large value of the n/p ratio in the experiment [3], especially for $E_N \le 100$ MeV. It should be possible to describe the experimental data [3] on the assumption that a stopped antiproton is absorbed by a neutron-rich nuclear cluster (mainly, by an nn pair). However this assumption seems to be questionable because the main mechanism of $\bar{p}A$ absorption is the single-nucleon one. In addition, for the present there is an evidence for enrichment of the nuclear periphery by dineutrons only for nuclides with a very large neutron excess lying nearby the proton drip line [22]. If such a kind of clusterization exists in stable nuclides at large distances from the nuclear center where absorption of stopped antiprotons takes place, the n/p ratio must decrease for high-energy antiprotons which penetrate inside the nucleus. Therefore a measurement of the dependence of the n/p ratio on the primary energy is of undoubted interest, as is a search for another explanation for distinction of the n/p ratio between $\bar{p}A$ annihilation, and πA and pA interactions.

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