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E4-86-487

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INTERACTIONS OF ANTIPROTONS WITH NEUTRONS AND NUCLEI AT LEAR ENERGIES

Submitted to "Ядерная физика"

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1986

1. Introduction

Glauber model is one of those few theoretical schemes which are now successfully applied for description of interactions between slow antiprotons ($p_L \geq 300$ MeV/c) and nuclei [1-5]. A possibility of Glauber's model being applied to antiproton-nuclear scattering at intermediate energies is analysed in detail in Ref.[1-2]. We shall only stress that conditions for application of the eiconal approximation are quite good even at comparatively low energies owing to a very distinct diffraction structure of the elementary $\bar{N}N$ amplitude. (For example, the slope parameter in the differential cross section of elastic $\bar{p}p$- scattering is $b \sim 32\ (\mathrm{GeV/c})^{-2}$ even at $T \sim 40$ MeV [6], while in pp-scattering $b \sim 6\ (\mathrm{GeV/c})^{-2}$ at $T \sim 1$ GeV). Therefore the main requirement for application of Glauber's model $p_L r >> 1$ in the case of $\bar{p}A$-scattering implies that $p_L\, r \sim 3$-4 : already at these energies the Glauber model describes the experimental data quite well. One should also bear in mind that the model cannot be applied to description of a large angle scattering. Besides, the elementary amplitude f must not vary with the energy too rapidly, i.e. it is important that the following inequality was valid: $df/dE \cdot 1/f \cdot \Delta E << 1$, where $\Delta E \sim k_F^2/2m$, k_F is a characteristic Fermi momentum.

A common difficulty of all $\bar{p}A$- scattering models is a poor experimental knowledge of the main parameters of the $\bar{N}N$-interaction amplitude. Beside the fact that there is no phase analysis of $\bar{N}N$-scattering, and the spin and isospin structures of the $\bar{N}N$-amplitude are insufficiently studied, there are practically no accurate experimental low-energy data on the value of such fundamental characteristic of the elementary act as the total cross section for interactions of antiprotons with neutrons $\sigma^{tot}_{\bar{p}n}$. The available data on direct measurements of $\bar{n}p$-scattering either have 50% statistical errors[7] or are of preliminary character[8]. In principle, the value of $\sigma^{tot}_{\bar{p}n}$ can be determined with the help of potential models of $\bar{N}N$ - interactions via fitting the parameters of the $\bar{N}N$-potentail by differential cross sections for elastic $\bar{p}p$-scattering and charge exchange $\bar{p}p \to \bar{n}n$.

However, these results strongly depend on the type of the $\bar{N}N$-potential employed. Extraction of information on $\sigma^{tot}_{\bar{p}n}$ from the data on antiproton scattering on deuterium is much more model-independent[9-12]. Still, in this case there exist some problems related to final state interactions (e.g. see Ref.[1,2]). Neglecting of these corrections leads to a wrong conclusion that cross sections for annihilation of free neutrons and neutrons bound in the nucleus are the same[9]. This error is reflected even in the compilation[13] where $\sigma^{ann}_{\bar{p}n}$ is taken from the data[9] on antiproton-neutron annihilation in the deuterium with no corrections.

This paper analyses the problem of determination of cross sections $\sigma^{tot}_{\bar{p}n}$ from the data on antiproton-deuterium interactions at p_L = = 200 - 800 MeV/c . It has appeared that the available data on the value of $\sigma^{tot}_{\bar{p}d}$ [9-12] lead to completely different values of $\sigma^{tot}_{\bar{p}n}$. Recently, however, cross sections for interactions of antiproton with different nuclei have been measured at LEAR (CERN)[5,14,15]. This additional experimental information allows selecting the most preferable version of the energy dependence of $\sigma^{tot}_{\bar{p}n}$. Calculation of cross sections for inelastic $\bar{p}A$- scattering shows that the best agreement with the experimental data is achieved for $\sigma^{tot}_{\bar{p}n}$ obtained from measurements of $\sigma^{tot}_{\bar{p}d}$ by Hamilton's group[11]. In the interval $200 \leq p_L \leq 800$ MeV/c $\sigma^{tot}_{\bar{p}n}$ is well approximated by the following simple expression:

$$\sigma^{tot}_{\bar{p}n}\ (\mathrm{mb}) = 65.52 + 38.09\ /\ p_L\ (\mathrm{GeV/c}) \ .$$

The material is presented in the following way. In Section 2 [...]metrisation of the elementary amplitude of the $\bar{N}N$-interaction is [dis]cussed. In Section 3 the procedure of extraction of $\bar{p}n$ cross [sect]ions from $\bar{p}d$-scattering data is analysed. In Section 4 the results [of ca]lculations of $\bar{p}A$-scattering cross sections are given. Discussion [of t]he results and the main conclusions are in Section 5.

[2]. Parametrisation of the elementary amplitude of the $\bar{N}N$ interaction

[W]e parametrised the amplitude of $\bar{N}N$-scattering in the following

$$f_j(\vec{q}) = \frac{ik}{4\pi}\,\sigma_j^{tot}\,(1 - i\rho_j)\exp(-\tfrac{1}{2} b_j q^2), \qquad (1)$$

$$j = p, n$$

here $\vec{q} = \vec{k}' - \vec{k}$; $\vec{k}$ is momentum in the c.m.s., σ_j^{tot} is the total cross section for $\bar{p}p$- or $\bar{p}n$-scattering, b_j is the slope parameter, $\rho_j = \mathrm{Re}\, f_j(0) / \mathrm{Im}\, f_j(0)$. The spin dependence of the $\bar{N}N$-interaction is not taken into account in (1); there are experimental indications that spin effects in $\bar{p}$ scattering are small/6,16/. An expression like (1) is quite often used for analysis of data on $\bar{p}p$- and $\bar{p}A$-scattering, but one should keep in mind that it is not valid for description of large-angle scattering.

The total cross section $\sigma_{\bar{p}p}^{tot}$ was determined from the results of the recent LEAR experiment, which showed that the simple dependence

$$\sigma_{\bar{p}p}^{tot}(\mathrm{mb}) = 65.78 + 53.759/p_L\ (\mathrm{GeV/c}) \qquad (2)$$

works well in the interval p_L = 388 - 599 MeV/c /17/. Unfortunately, the discrepancy in available data on $\sigma_{\bar{p}p}^{tot}$ is quite large (e.g. see Ref./13/). The use of approximation (2) at $p_L > 600$ MeV/c leads to values of $\sigma_{\bar{p}p}^{tot}$ which are 10-20 mb higher than the results in the compilation /13/.

To determine the energy dependence of the ratio ρ_j , we approximated the experimental data/18,19,6/ by a polynomial:

$$\rho_p = 1.3347 - 10.342 \cdot p_L + 22.277 \cdot p_L^2 - 13.634 \cdot p_L^3 \cdot \qquad (3)$$

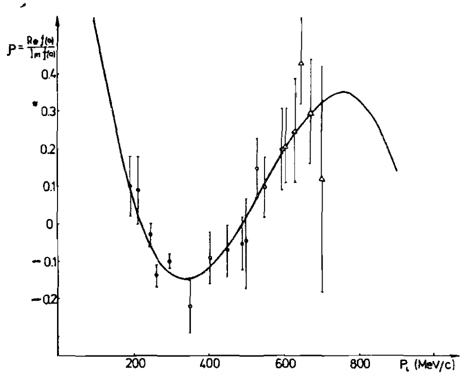


Fig. 1 . Energy dependence of the value ρ_p = Re f(0)/Im f(0) . The solid line is the result of fitting by formula (3). Experimental data are taken from/6,18,19/.

Here p_L is in GeV/c . A degree of description of the data by parametrisation (3) can be estimated from Fig. 1 . It is seen that (3) works well in the interval p_L = 200 - 750 MeV/c . However, its threshold behaviour is incorrect. For example, it follows from (3) that $\rho_p(0) = 1.33$, while from analysis of $\bar{p}$-atomic data/20/ it follows that $\rho_p(0) = -1.42$. But this defect of parametrisation (3) is of no effect in calculations of $\bar{p}A$ cross sections in the range of relatively high energies.

Further it was assumed that $\rho_p = \rho_n$. Since ρ_p and ρ_n are small in the energy region under consideration, this assumption does not practically affect the final results (see discussion in sect. 4.3).

The energy dependence of the slope parameter b_p was determined by fitting the data from Ref./6,18,21,22/ using the following formula:

$$b_p = 0.25 \cdot (R_o + A/k)^2 , \qquad (4)$$

where R_o = 1.3395 Fm, A = 0.691 , k (GeV/c) is the antiproton momentum in the c.m.s. . Parametrisation (4) describes the experimental data in the region p_L = 0.2 - 2 GeV/c quite well (see Fig. 2).

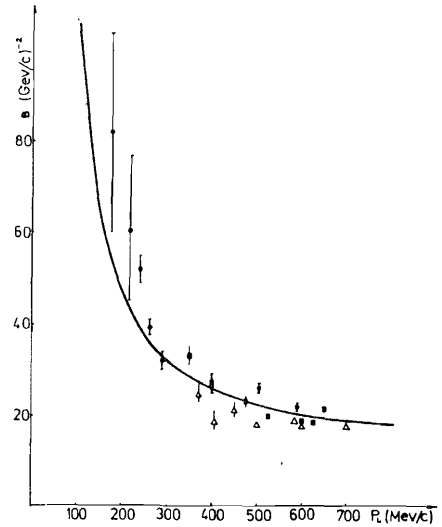


Fig. 2 . Energy dependence of the slope parameter b_p of the differential cross section for elastic $\bar{p}p$ scattering. The solid line is the result of fitting by formula (4) . Experimental data are taken from Ref./6,18,21/ .

For determination of the slope parameter in $\bar{p}n$ scattering it was assumed that $b_n/b_p = R$, where R is defined by the ratio

$$R = \sigma_{\bar{p}n}^{tot} / \sigma_{\bar{p}p}^{tot} . \qquad (5)$$

This relation is characteristic of a purely diffractive scattering.

3. Determination of $\bar{p}n$ cross sections from the data on $\bar{p}d$ scattering

The total cross section for the $\bar{p}n$ interaction can be determined from the data on $\bar{p}d$ scattering by means of a standard Glauber technique (see e.g. Ref./1,23,24/). It is shown in Ref./1/ that the total cross section for the $\bar{p}n$ scattering $\sigma^{tot}_{\bar{p}n}$ is related to $\sigma^{tot}_{\bar{p}d}$ in the following way:

$$\sigma^{tot}_{\bar{p}d} = \sigma^{tot}_{\bar{p}p} + \sigma^{tot}_{\bar{p}n} - \frac{\sigma^{tot}_{\bar{p}p}\sigma^{tot}_{\bar{p}n}}{8\pi}(1-\rho^2)\sum_{j=1}^{2}\frac{C_j}{\gamma_j + \frac{1}{2}b_p(1+R)} \quad (6)$$

Coefficients C_j and γ_j are defined by parametrisation of the deuteron formfactor in the form

$$F_d(q) = \sum_{j=1}^{2} C_j \exp(-\gamma_j q^2) . \quad (7)$$

For Hamada-Jonhston NN-potential $C_1 = 0.4$, $C_2 = 0.6$, $\gamma_1 = 4.6\ \mathrm{Fm}^2$, $\gamma_2 = 0.88\ \mathrm{Fm}^2$.

Relation (6) can be written in the form of a cubic equation with respect to R from (5) and solved by assigning values to $\sigma^{tot}_{\bar{p}d}$, $\sigma^{tot}_{\bar{p}p}$, ρ, b_p as well as to deuteron parameters C_j and γ_j.

The energy dependence of the total cross section $\sigma^{tot}_{\bar{p}d}$ is well expressed by a simple formula:

$$\sigma^{tot}_{\bar{p}d} = A_d + B_d/p_L . \quad (8)$$

However, there is great difference between coefficients A_d and B_d, obtained in different experiments (see Table 1). Therefore we defined A_d and B_d from the data by fitting the $\sigma^{tot}_{\bar{p}d}$ taken from the compilation /13/, where the results of three experiments are given for the range $p_L \leq 900$ MeV/c /9,10,25/.

Table 1. Parametrisation coefficients of $\sigma^{tot}_{\bar{p}d} = A_d + B_d/p_L$.

Refs.	A_d (mb)	B_d(mb·GeV/c)	p_L range(GeV/c
1. Hamilton et al./11/	132	71	0.355- 1.066
2. Kalogeropoulos et al./9/	30	126	0.27 - 0.465
3. Carroll et al./12/	129	78	0.36 - 1.05
4. Present paper (fitting by the data of compilation/13/)	108.59	94.6	0.27 - 0.813

It is shown in Fig.3 (upper part) how our approximation of $\sigma^{tot}_{\bar{p}d}$ describes the data /9,10/ (dashed line). The solid line shows the experimental data from Ref./11/, the dash-and-dot line is for Ref./12/. The total cross sections $\sigma^{tot}_{\bar{p}d}$ from Refs./9,10/ are seen to differ from the data of Ref./11/, especially in the region $p_L < 400$ MeV/c. The difference may seem of small importance, but it leads to differences in $\sigma^{tot}_{\bar{p}n}$ which strongly affect calculations of cross sections for the antiproton-nuclear scattering.

The lower part of Fig.3 shows the value of the ratio R from (5). One obtains the value when solving (6) with $\sigma^{tot}_{\bar{p}d}$ based on data from /11/ (solid line), Ref./9,10/ (dashed line) or Ref./12/ (dash-and-dot line). It is well seen that the largest difference between these dependences is in the low energy region $p_L < 400$ MeV/c, where R from /9,10/ is noticeably larger than one, and it follows from /11,12/ that $R < 1$ in the whole energy region under consideration.

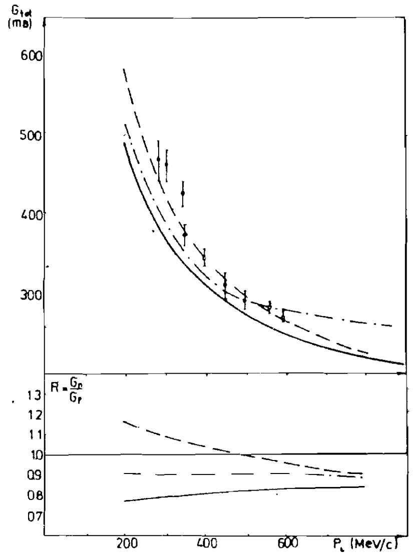


Fig. 3 (above). Energy dependence of the total cross section for $\bar{p}d$ scattering. The solid line shows results of the experiment /11/, the dash-and-dot line is for results of /12/. The dashed line is approximation of the data /9,10/ by formula (8). Experimental points are taken from /9,10/.

(below). Energy dependence of the ratio $R = \sigma^{tot}_{\bar{p}n}/\sigma^{tot}_{\bar{p}p}$. The solid line is the result of calculations by (6) with $\sigma^{tot}_{\bar{p}d}$ from data of /11/, the dashed line is for calculations with $\sigma^{tot}_{\bar{p}d}$ from /9,10/ and from Ref. /12/ (dash-and-dot line.

4. Calculation of cross sections for scattering of antiprotons on nuclei

Calculation of cross sections for the antiproton-nuclear scattering was performed in order to find which of the dependences for $\sigma^{tot}_{\bar{p}n}$

discussed in Sect. 3 is better in describing the experimental data.

The amplitude of the antiproton-nuclear interaction in the Glauber approach has the form /23/:

$$F_{fi}(\vec{q}) = \frac{i p_L}{2\pi} \int e^{i\vec{q}\vec{b}} \Psi_f^* \{\vec{r}_j\} \Gamma(\vec{b}, \vec{s}_1, \ldots, \vec{s}_A) \cdot$$

$$\cdot \Psi_i \{\vec{r}_j\} \cdot \prod_{j=1}^{A} d^3 r_j \, d^2 b \, \delta\left(\frac{1}{A}\sum_{k=1}^{A} \vec{r}_k\right), \tag{9}$$

where p_L is the antiproton momentum in the lab frame, Ψ_f and Ψ_i are the wave functions of a nucleus in the final and initial states, and $\Gamma(\vec{b}, \vec{s}_1, \ldots, \vec{s}_A)$ is the nuclear profile function which is expressed via nucleon profile functions $\Gamma_j(\vec{b}-\vec{s}_j)$ in the following way:

$$\Gamma(\vec{b}, \vec{s}_1, \ldots, \vec{s}_A) = 1 - \prod_{j=1}^{A} \left[1 - \Gamma_j(\vec{b}-\vec{s}_j)\right], \tag{10}$$

here $\vec{b}$ is the impact parameter, $\vec{s}_j$ are projections of the radius-vector $\vec{r}_j$ on the plane, perpendicular to $\vec{p}_L$. The function Γ_j is a Fourier transform of the amplitude $f_j(q)$ from (1).

4.1 Calculation of cross sections for $\bar{p}\,^4He$ scattering

For wave functions of ^4He ground state the approximation of independent particles is used:

$$|\Psi(\vec{r}_1, \ldots, \vec{r}_4)|^2 = \prod_{j=1}^{4} \rho_j(r_j), \tag{11}$$

where one-particle densities $\rho_j(r_j)$ were determined in the oscillator basis:

$$\rho(r_j) = (\sqrt{\pi}\, a)^{-3} \exp(-r_j^2/a^2). \tag{12}$$

The value of the parameter a^2 was determined from the data of /26/ by the ^4He charge radius $R_{ch} = 1.672$ Fm. The corresponding value of a^2 for this R_{ch} is $a^2 = 1.916$ Fm^2.

From (9)-(12) we obtain the following form for the amplitude of the elastic $\bar{p}\,^4He$ scattering:

$$F_{ii}(\vec{q}) = 2 i K_{ACM}\, e^{\frac{q^2 a^2}{16}} \left(\sum_{j=p,n} D_j(q^2) + C_{pn}(q^2)\right), \tag{13}$$

where k_{ACM} is the antiproton momentum in the nuclear c.m.s., and the terms $D_p(q^2)$ and $D_n(q^2)$ describe single and double scattering on protons and neutrons of ^4He:

$$D_j(q^2) = \sum_{m=1}^{2} C_2^m \varepsilon_j^m (-1)^{m+1} \frac{\gamma_j^2}{m} \exp\left(-\frac{q^2\gamma_j^2}{m}\right), \tag{14}$$

the term $C_{pn}(q^2)$ corresponds to a consequent rescattering on protons and neutrons:

$$C_{pn}(q^2) = \sum_{m=1}^{2}\sum_{k=1}^{2} C_2^m C_2^k \varepsilon_p^m \varepsilon_n^k (-1)^{m+k+1} \cdot \tag{15}$$

$$\cdot \gamma_{pn}^2(m,k) \cdot \exp(-\gamma_{pn}^2(m,k)\cdot q^2).$$

Here

$$\varepsilon_j = \sigma_{\bar{p}j}^{tot} / 8\pi\gamma_j^2, \quad j = p, n; \tag{16}$$

$$\gamma_j^2 = \frac{a^2}{4} + \frac{b_j}{2}, \quad j = p, n \tag{17}$$

$$\gamma_{pn}^2(m,k) = \gamma_p^2 \gamma_n^2 / (m\gamma_n^2 + k\gamma_p^2).$$

4.2 Cross sections for scattering of antiprotons on nuclei with $A \geq 12$

To describe the nuclear structure of nuclei with $A \geq 12$ a single-particle density of the form

$$\rho(r) = \rho_0 \left(1 + \exp\left(\frac{r-d}{t}\right)\right)^{-1} \tag{18}$$

was used. The parameters d and t were taken from the eA-scattering data[27] with account of the difference between the charge density and the nuclear density (see the discussion in Sect. 4.3) .

Using expression (9), we transform the amplitude of the elastic scattering of the antinucleon on the nucleus to get the following:

$$\mathcal{F}_{ii}(q) = i\kappa\, e^{\frac{q^2 R_{ch}^2}{6A}} \int_0^{b_{max}} J_0(qb)\,\Gamma_a(b)\, b\, db, \tag{19}$$

where $b_{max} = 4\cdot k^2$, and

$$\Gamma_a(b) = 1 - (1 - \varphi_0^p(b))^Z (1 - \varphi_0^n(b))^N. \tag{20}$$

Here $\varphi_0^j(b)$, $j = p,n$ are profile functions

$$\varphi_0^j(b) = \frac{\sigma_{\bar{p}j}^{tot}(1 - i\rho)}{4\pi b_j}\,\varphi^j(b), \quad j = p, n, \tag{21}$$

where

$$\varphi^j(b) = 2\pi\, e^{-b^2/2b_j} \int_0^{s_{max}} T(s)\cdot$$

$$\cdot \exp(-s^2/2b_j)\cdot I_0(b\cdot s/b_j)\, s\, ds. \tag{22}$$

Here $I_0(b\cdot s/b_j)$ is the modified Bessel function, $T(s)$ is the so-called thickness function

$$T(s) = \int_{-\infty}^{\infty} \rho(z, s)\, dz; \tag{23}$$

where $z^2 = r^2 - s^2$, and $\rho(z,s)$ is the nuclear density from (18) .

The optical approximation [23] is good for calculation of cross sections for interactions between antiprotons and heavy nuclei. In this approximation the profile function $\Gamma_a(b)$ is defined by averaged parameters of $\bar{p}p$ and $\bar{p}n$-amplitudes:

$$\Gamma_a(b) = 1 - \exp(-A\cdot \tilde{\varphi}_0(b)), \tag{24}$$

where $\tilde{\varphi}_0(b)$ is given by (21) with the following parameters:

$$\tilde{\sigma}^{tot} = 0.5\cdot(\sigma_{\bar{p}p}^{tot} + \sigma_{\bar{p}n}^{tot}); \quad \tilde{b} = 0.5\cdot(b_p + b_n). \tag{25}$$

Note that the use of $\Gamma_a(b)$ in the form (20) or (24)-(25) in calculation of cross sections for the inelastic scattering of antiprotons on nuclei with $A \geq 12$ makes little difference.

Presently the most complete experimental data are available for reaction cross sections σ_R , defined as

$$\sigma_R = \sigma_{tot} - \sigma_{el}.$$

Therefore we mainly analysed this feature of the $\bar{p}A$ scattering. Another reason for consideration of just σ_R is that it is determined through σ_{tot} and σ_{el} which depend, mainly, on the scattering amplitude at small angles. So, the Glauber approach is more reliable for calculations of these cross sections.

4.3 Influence of various model parameters on values of $\bar{p}A$ cross sections

In our scheme the amplitude of the elementary $\bar{N}N$ interaction is given by four experimental parameters: $\sigma_{\bar{p}p}^{tot}$, b_p , ρ_p and $\sigma_{\bar{p}d}^{tot}$. Besides, two assumptions are made: $\rho_p = \rho_n$ and $b_n/b_p = R$. Therefore we first checked to what extent these assumptions influence calculations of $\bar{p}A$ scattering cross sections. It appeared that a 20% change in the relation $b_n/b_p = R$ only causes a 2-3% change in the value of $\sigma_R(^4He)$. The amplitude of $\bar{N}N$ scattering being considered purely imaginary ($\rho_p = \rho_n = 0$) leads to practically negligible variation of σ_R . At last, if the value of b_p is simply changed by 20% , this leads to a 5% change in $\sigma_R(^4He)$. Undoubtedly, such variations of $\bar{N}N$ interaction parameters must affect the differential cross sections for $\bar{p}A$ scattering much stronger (see [4]) , total cross sections for $\bar{p}A$ scattering are mainly defined by the total cross sections $\sigma_{\bar{p}p}^{tot}$ and $\sigma_{\bar{p}n}^{tot}$ as well as by nuclear density parameters.

For description of $\bar{p}A$ scattering one must in expressions (18)-(23) give the nuclear matter distribution. For this purpose one should determine relation between parameters of the charge distribution, measured in eA scattering, and parameters of nuclear density (18) .

It is known [28] that the root-mean-square radius of the point-like nucleon density $\langle r_m^2 \rangle$ is related to parameters of the Fermi density (18) with a good accuracy in the following way:

$$\langle r_m^2 \rangle = \frac{3}{5} d_m^2 + \frac{7}{5} \pi^2 t_m^2 \tag{26}$$

where d_m and t_m are the half-density radius and diffuseness of nuclear matter distribution. A similar relation for the charge distribution like (18) is :

$$\langle r_{ch}^2 \rangle = \frac{3}{5} d_p^2 + \frac{7}{5} t_p^2 + \langle r_p^2 \rangle , \tag{27}$$

where $\langle r_p^2 \rangle$, $\langle r_{ch}^2 \rangle$ are r.m.s. radii of charge distribution for the proton and for the nucleus.

The values of d_p and t_p differ in general from d_m and t_m . We assumed that $d_m = d_p$. Then the diffuseness parameter t_m can be determined from (26)-(27) :

$$t_m^2 = \frac{5}{7\pi^2} \left(\langle r_{ch}^2 \rangle - \langle r_p^2 \rangle - \frac{3}{5} d_p^2 \right). \tag{28}$$

In Fig.4 one can see how this renormalisation of the diffuseness parameter changes the results of calculation of σ_R for interactions of antiprotons with ^{20}Ne and ^{27}Al nuclei. A strong dependence of σ_R on t_m is seen. In principle, the antiproton-nuclear scattering must indeed be most sensitive to the size of the nuclear diffuse edge, since this is the region the majority of $\bar{p}$A-annihilation events occur [30]. Table 2 lists t_m and d_m values used.

Table 2. Parameters of the Fermi density (23).
Data on $\langle r_{ch} \rangle$, d_p and t_p were taken from [27].

A	$\langle r_{ch} \rangle$ (Fm)	d_p(Fm)	t_p(Fm)	t_m(Fm)
^{64}Cu	3.88	4.2	0.569	0.527
^{40}Ca	3.43	3.51	0.563	0.52
^{27}Al	3.05	2.84	0.569	0.526
^{20}Ne	2.969	2.805	0.571	0.5

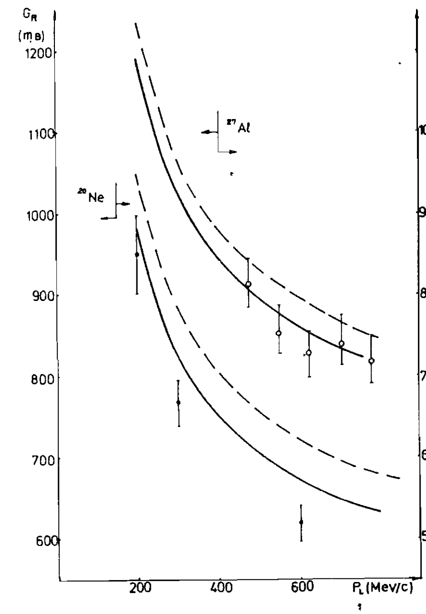
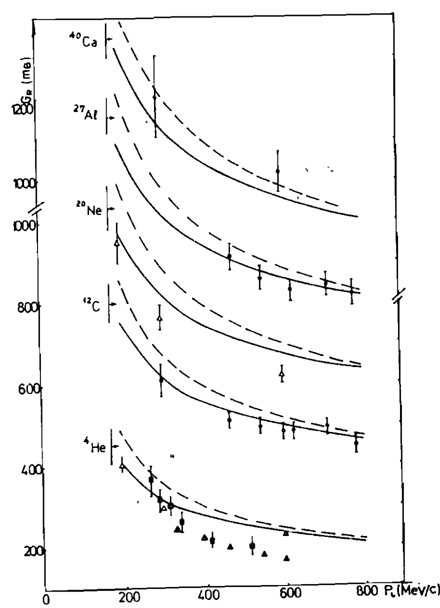


Fig. 4 . Influence of renormalisation of the diffuseness parameter t on the cross section σ_R for inelastic reactions. The solid lines show the results of calculation of σ_R with t determined from (28) , the dashed line is the same with t from eA-scattering data (see Table 2) . Experimental data are taken from [5,29] .

Fig.5 . Dependence of the cross section $\sigma_R = \sigma_{tot} - \sigma_{el}$ on the antiproton momentum p_L for different nuclei. The solid lines are the results of calculations with the data of Hamilton et al.[11], the dashed lines are the same with the data from [9,10]. Experimental points: △ -from [5,14], ● - from [29], ○ - from [31], where the data of Garretta et al. [15] are analysed. The data on σ_R for $\bar{p}$d scattering [9,10] are shown by black squares and triangles ▲ , ■ .



5. Discussion of results and conclusions

Now let us consider influence of various neutron cross sections $\sigma^{tot}_{\bar{p}n}$ on σ_R. Fig.5 shows results of calculation of σ_R for two extreme cases: $\sigma^{tot}_{\bar{p}n} < \sigma^{tot}_{\bar{p}p}$ (i.e. the ratio R from (5) is less than one) - solid lines, $\sigma^{tot}_{\bar{p}p} > \sigma^{tot}_{\bar{p}n}$ ($R > 1$) at low energies - dashed lines. In the former case $\sigma^{tot}_{\bar{p}d}$ was taken from [11], while the latter from a fit of the results by data from [9,10].

It is well seen that the description of $\bar{p}A$ cross sections is much better for $R < 1$. This is most evident for low energies and light nuclei.

Thus, comparison with the experimental data on antiproton-nuclear scattering is in favour of the solution with $R < 1$, i.e. the total cross section for the scattering on protons must be larger than the cross section for the antiproton-neutron scattering. A similar dependence is also observed at energies over 1 GeV (e.g. see [32]). Taking into account the isospin structure of the $\bar{N}N$ amplitude, one may obtain the following relation:

$$R = \frac{\sigma^{tot}_{\bar{p}n}}{\sigma^{tot}_{\bar{p}p}} = \frac{2\sigma(I=1)}{\sigma(I=0)+\sigma(I=1)} < 1. \qquad (29)$$

It means that the amplitude of the $\bar{N}N$ scattering in the state with isospin I=0 is larger than in the state with I=1. This conclusion agrees with calculations of potential models of the $\bar{N}N$ interaction[33-35]. Despite completely different forms for $\bar{N}N$ potentials, all theoretical models predict domination of the isosinglet state in the $\bar{N}N$ amplitude.

The energy dependence of the total cross section $\sigma^{tot}_{\bar{p}n}$ can be successfully approximated by the following simple expression :

$$\sigma^{tot}_{\bar{p}n}\,(\mathrm{mb}) = 65.52 + 38.09/p_L\ (\mathrm{GeV/c})\ . \qquad (30)$$

This value was determined from (6) with the data on $\sigma^{tot}_{\bar{p}d}$ from[11] and on $\sigma^{tot}_{\bar{p}p}$ from[6]. So the validity region for approximation (30) should not be too large ($p_L \leq 600$–800 MeV/c). It is however interesting that the value of the energy-independent term in (30) turned out to be the same as in parametrisation of $\sigma^{tot}_{\bar{p}p}$ (see (2)).

Energy dependence of $\sigma^{tot}_{\bar{p}n}$ having been determined (30) , one can calculate the total cross section for the elastic $\bar{p}n$ scattering:

$$\sigma^{el}_{\bar{p}n} = (\sigma^{tot}_{\bar{p}n})^2(\rho^2+1)/16\pi b_n \qquad (31)$$

and the cross section for $\bar{p}n$ annihilation:

$$\sigma^{ann}_{\bar{p}n} = \sigma^{tot}_{\bar{p}n} - \sigma^{el}_{\bar{p}n}. \qquad (32)$$

It has appeared that these quantities can be satisfactorily described by approximate formulae:

$$\sigma^{el}_{\bar{p}n}\,(\mathrm{mb}) = 29.3 + 13.04/p_L\ (\mathrm{GeV/c}), \qquad (33)$$

$$\sigma^{ann}_{\bar{p}n}\,(\mathrm{mb}) = 36.22 + 25.05/p_L\ (\mathrm{GeV/c}). \qquad (34)$$

Noteworthy is that the value of $\sigma^{el}_{\bar{p}n}$ calculated by formula (31) must be, generally speaking, somewhat underestimated, since the elementary amplitude $F_{ii}(q)$ was expressed via (1), which is valid only for scattering at small angles. Consequently, the value of the annihilation cross section $\sigma^{ann}_{\bar{p}n}$ obtained from (32) will be a little overestimated.

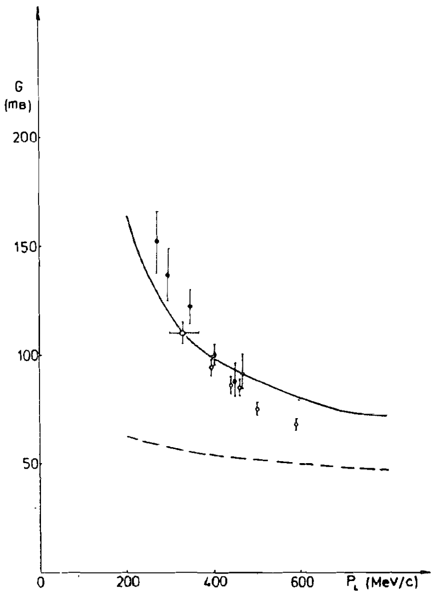


Fig. 6 . Cross sections of annihilation on free and bound neutrons (solid and dashed lines, respectively).

The solid line in Fig.6 shows the energy dependence of $\sigma^{ann}_{\bar{p}n}$ calculated by (31)-(32). Experimental points correspond to measurements of $\sigma^{ann}_{\bar{p}n}$ with a deuterium target. It is important that $\sigma^{ann}_{\bar{p}n}$ data from these experiments cannot be identified with cross sections for annihilation on the free neutron. This problem arose long ago as a result of experiments [10] where the cross section for annihilation on the proton in deuterium $\tilde{\sigma}^{ann}_{\bar{p}}$ was found almost to coincide with the cross section of annihilation on the free proton $\sigma^{ann}_{\bar{p}}$, i.e.

$$\tilde{\sigma}^{ann}_{\bar{p}} \approx \sigma^{ann}_{\bar{p}} .$$

This unexpected result gave rise to a wrong conclusion that a similar relation is valid for annihilation on the neutron:

$$\tilde{\sigma}^{ann}_{n} \approx \sigma^{ann}_{n}$$ [9,10].

Besides, applicability of Glauber's model for $\bar{p}d$ scattering was doubted [9,36], because the Glauber corrections were to lead to a noticeable difference between $\tilde{\sigma}^{ann}_{p}$ and σ^{ann}_{p}. An accurate consideration [1] showed, however, that beside shadow corrections δ_n and δ_p the corrections for rescattering of annihilation π-mesons should be taken into account:

$$\tilde{\sigma}^{ann}_{n} = \sigma^{ann}_{n} - \delta_n + C_1 , \qquad (35)$$
$$\tilde{\sigma}^{ann}_{p} = \sigma^{ann}_{p} - \delta_p + C_2 ,$$

where C_1 and C_2 are corrections for rescattering effects. It was proved in [37] that

$$C_1 + C_2 = 0 . \qquad (36)$$

Thus, if $\tilde{\sigma}^{ann}_{p} \approx \sigma^{ann}_{p}$, then $\delta_p = C_2$. Taking account of (36), we find that renormalisation of the cross section for annihilation on the coupled neutron $\tilde{\sigma}^{ann}_{n}$ is the largest

$$\tilde{\sigma}^{ann}_{n} = \sigma^{ann}_{n} - \delta_n - \delta_p . \qquad (37)$$

The dashed line in Fig.6 show the result of calculation of $\tilde{\sigma}^{ann}_{n}$ under an assumption of the maximal renormalisation (37). The values of $\tilde{\sigma}^{ann}_{n}$ and σ^{ann}_{n} are seen to differ from 100 to 20 mb. Hence, one must take account of this difference.

We think, however, that the results of measurement of cross sections for $\bar{p}d$ scattering in bubble chambers [9,10] are somewhat overestimated. Evidence of this is, firstly, that they lead to $R > 1$ for R from (5) at low energies, while this is in contradiction with both theoretical predictions [33-35] and the experimental data at higher energies [32]. Secondly, the cross section σ_R for reactions on deuterium obtained in [9,10] is almost the same as σ_R for the $\bar{p}^4He$ scattering (see Fig.5). It is difficult to imagine the reason why $\sigma_R(\bar{p}d)$ differs so little from $\sigma_R(\bar{p}^4He)$. Therefore it is quite possible that σ^{ann} on the free and bound protons differ slightly from each other. Then renormalisation of the annihilation cross section on the neutron will be less than the maximum one (37). Consequently, one can expect that the solid and dashed lines in Fig.6 determine only the upper and lower limits for σ^{ann}_{n}, and more accurate determination of σ^{ann}_{n} requires fresh reliable information on antiproton annihilation in deuterium.

The main conclusions of the paper are as follows. Reaction cross section σ_R for interactions of antiprotons with nuclei have been analysed within Glauber's model for various $\sigma^{tot}_{\bar{p}n}$ assumed.

Values of $\sigma^{tot}_{\bar{p}n}$ were determined from the data on $\bar{p}d$ scattering. It turned out that the value of σ_R has a quite a strong dependence on the diffuseness parameter of nuclear distribution. The nuclear data are shown to have the best description with $\sigma^{tot}_{\bar{p}n} < \sigma^{tot}_{\bar{p}p}$. The energy dependence of $\sigma^{tot}_{\bar{p}n}$ is well described by relation (30). The elastic and annihilation cross sections for antiproton-neutron interactions have been calculated. It is shown that cross sections for annihilation on free and bound neutrons can strongly differ from each other. To clear the problem up, more experiments on annihilation in deuterium at LEAR energies are desirable.

The authors are greatly thankful to B.O.Kerbikov, Yu.A.Simonov, A.Rotondi, F.Nichitiu, V.V.Burov, B.Z.Kopeliovich, G.Piragino, S.A.Bunyatov and I.V.Falomkin for their interest to the work and valuable discussions.

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Received by Publishing Department
on July 16, 1986.

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Взаимодействие антипротонов с нейтронами и ядрами при энергиях LEAR

Выполнен анализ экспериментальных данных по полным сечениям рассеяния антипротонов на дейтерии в интервале p_L = 200-800 МэВ/с с целью определения величины полного сечения взаимодействия антипротонов с нейтроном $\sigma^{tot}_{\bar{p}n}$. Полученные разные наборы для $\sigma^{tot}_{\bar{p}n}$ использовались в качестве исходных для вычисления сечений антипротон-ядерного взаимодействия. Оказалось, что данные по $\bar{p}A$-рассеянию описываются лучше всего, если $\sigma^{tot}_{\bar{p}n}$ (мб) = 65,52 + 38,09/p_L (ГэВ/с). Рассмотрен вопрос об определении сечения аннигиляции антипротонов на нейтронах.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1986

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Interactions of Antiprotons with Neutrons and Nuclei at LEAR Energies

Experimental data on total cross sections for antiproton scattering on deuterium in the interval p_L = 200 - 800 MeV/c has been analysed in order to determine the value of the total cross section for the antiproton-neutron interaction $\sigma^{tot}_{\bar{p}n}$. Different sets obtained for $\sigma^{tot}_{\bar{p}n}$ were used as $\bar{p}n$ input data for calculations of cross sections for antiproton-nuclear interactions. It turned out that $\bar{p}A$-scattering data are best described if $\sigma^{tot}_{\bar{p}n}$ (mb) = 65.52 + 38.09/p_L (GeV/c). Determination of the cross section for antiproton annihilation on neutrons is discussed.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna 1986