CERN-EP/87-43
24 February 1987

$\bar{p}$ -⁴He BREAK-UP CROSS SECTION AT 180 MeV

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ABSTRACT

We have measured (15.5 ± 3.1) mb for the $\bar{p}$ -⁴He break-up cross section at 179.6 MeV. This low value is in agreement with the prediction of a Glauber model and is due to the large probability for the antiproton to annihilate into the nuclei, which makes only a surface layer of the nuclear volume effective for the break-up process.

(Submitted to Physics Letters)

1. Measurement of the break-up cross section

In previous papers we reported the reaction cross section of the $\bar{p}$ - ^4He interaction at 19.6, 48.7 and 179.6 MeV [1,2] and the charged prong multiplicity distribution at the same energies [1,2] and at rest [3]. In this paper we report the first measurement of the $\bar{p}$ - ^4He break-up cross section at 179.6 MeV .

This measurement has been performed at the LEAR facility of CERN with an 1 atm. self-shunted streamer chamber in a magnetic field [4].

The non elastic $\bar{p}$ - ^4He interaction at low energy includes the annihilation process and the following inelastic reactions:

The reactions (1) contribute only to the events with one charged prong, the reaction (2) to the two charged prong events and the reactions (3) to the three charged prong events only. The events with a higher multiplicity are due only to annihilation. However, at 19.6 MeV the reactions (1-3) are forbidden and also the events with multiplicity between 1 and 3

are due only to annihilation, because the threshold for inelastic processes in the laboratory is about 25 MeV .

We can write the reaction cross section σ_R for non elastic events as:

$$\sigma_R = \sigma_{ANN} + \sigma_{BU} + \sigma_{CEX} \quad (4)$$

where ANN means annihilation, the scattering cross section (with a $\bar{p}$ in the final state) as:

$$\sigma_{SC} = \sigma_{BU} + \sigma_{EL} \quad (5)$$

where EL means elastic, and the total cross section as:

$$\sigma_T = \sigma_R + \sigma_{EL} = \sigma_{SC} + \sigma_{ANN} + \sigma_{CEX} \quad (6)$$

Since the percentages of events with one, two and three charged prongs are the same, within the experimental errors, below and above 20 MeV, in ref.[2] we concluded that the inelastic processes are less than about 3% and annihilation is by far the dominant mechanism in the $\bar{p}$ - ^4He interaction, a result in agreement with the measurements on the $\bar{p}$ - ^{12}C interaction [5]. A subsequent simplified analysis of the data led to the following estimation of the inelastic cross section at 48.7 and 179.6 MeV: (8.9 ± 19.1) mb and (13.6 ± 12.3) mb respectively [6].

In this paper we give the values of the cross section σ_{BU} of the reactions (2) and (3) at 179.6 MeV (600 MeV/c) obtained directly by measuring a sample of $\bar{p}$ - ^4He events, following the criteria described in ref.[7]. We have selected the two-prong and the three-prong events with a $\bar{p}$ in the final state recognized by the ionization-momentum relation and/or with good kinematical

fit to the reactions (2) and (3). As a test of the filter procedure, we have analyzed a sample of events at 19.6 MeV and we have not found any inelastic events, as expected.

We have found that the events belonging to the reaction (2) are $(30.8 \pm 9.0)\%$ of all non elastic two-prong events and that the events belonging to the reaction (3) are $(15.1 \pm 3.4)\%$ of all non elastic three-prong events.

Our cross section measurements are affected by a systematic error (mainly due to the transparency of the gas target and to the dose measurement) that in our previous works [1,2] was estimated to be less than 2.5%. In addition, the break-up cross section is affected by a further systematic error due to the undetected inelastic $\bar{p}$ emitted into a small forward cone within the acceptance of our beam scintillation counter behind the streamer chamber (0.25% of the whole solid angle)[4]. The maximum undetected scattering angle varies from about 3° up to about 13° , depending on the vertex position along the beam trajectory. The inefficiency can be revealed by analyzing the vertex distribution of the events along the beam path, which is expected to be uniform in the case of no lack of events. Since, within the limits of the statistics considered, we have not observed any loss of break-up events due to our final detector, to evaluate quantitatively this effect we have calculated the angular distribution predicted for break-up events by the Glauber model discussed in the next section. We have used some of the approximated formulae reported in ref.[8] obtaining at small angles, as expected, a flat distribution depressed in the forward direction. Using this distribution, we have evaluated the loss of events with a Monte Carlo method, obtaining a break-up cross

section defect less than 1.5 mb.

In the present analysis we have utilized a statistics two times higher than that of ref.[1] obtaining for the two-prong, three-prong and total reaction cross sections the values (13.5 ± 2.2) mb, (75.2 ± 2.6) mb and (239.2 ± 5.0) mb, respectively. Hence, the two-prong, three-prong and total break-up cross sections are (4.2 ± 1.7) mb, (11.3 ± 2.6) mb and (15.5 ± 3.1) mb, respectively (see Tab.I). The quoted errors are only statistical; in addition, on the basis of the above discussion, systematic errors of 3% and 12.2% must be assigned to the total reaction and break-up cross sections, respectively.

It is important to note that the $\bar{p}$ - ^4He break-up channel appears to be depressed if compared with the same reactions induced at low energy by other hadrons such as nucleons [9] and pions [10,11]. For instance, the value of 15 mb is much smaller than the value of (107.7 ± 4.4) mb found for the p - ^4He break-up at 53 MeV [9] and the branching ratio $\sigma_{\text{BU}} / \sigma_{\text{R}} \simeq 6\%$ is much smaller than that for the π - ^4He interaction, which is 70-80% even in the region of the Δ -resonance excitation [11].

2. Glauber theory analysis and discussion

Here we study the physical reasons of the above mentioned break-up suppression. The Glauber theory [8], which is in practice the eikonal approximation to the first order in the Watson multiple scattering expansion [12], is the most direct and simple way to perform this analysis. The reasons for the applicability of this method in low energy $\bar{p}$ -nucleus scattering are explained in some detail in refs.[3,13]; we recall only that, because of the large annihilation probability, the elementary

$\bar{p}$ -nucleon amplitude assumes a typical diffractive structure, so that the eikonal approximation is valid even at low momenta ($\lesssim 300$ MeV/c).

Under the assumption of the completeness of the nuclear wave functions we can write the break-up cross section, in the Glauber approximation, as follows [8,14]:

$$\sigma_{BU} = \left[\int \psi^*({r}_1) \Gamma^*(b, \{s_1\}) \Gamma(b, \{s_1\}) \psi({r}_1) d^2b \prod_i d^3r_i \right] - \sigma_{EL} \quad (7)$$

where ψ is the nuclear ground state wave function, b is the impact parameter, $\{r_i\}$ are the coordinates of the nucleons, $\{s_i\}$ their transverse components and $\Gamma(b, \{s_i\})$ is the nuclear profile function, which can be expressed in a standard form [8] in terms of the $\bar{p}$ -nucleon scattering amplitude:

$$f_j(q) = \frac{k}{4\pi} \sigma_j (1 + \rho_j) \exp\left(-\frac{1}{2} \beta_j^2 q^2\right) \quad (8).$$

Here σ_j is the total cross section of the $\bar{p}$ -p and $\bar{p}$ -n interaction ($j=n, p$, i.e. neutron or proton), β_j^2 the slope parameter, $\rho_j = \text{Re } f_j(0)/\text{Im } f_j(0)$, k the projectile wave number and q the transferred momentum.

As in ref.[8], we calculate eq.(7) assuming $\psi(\{r_i\})$ as a product wave function and using one particle densities deduced from the harmonic oscillator basis for the light nuclei ($A \leq 16$) and Wood-Saxon densities for the heavier ones. For numerical details on these calculations see refs.[8,14,15].

The calculations require the determination of the six parameters σ_n , ρ_n^2 , β_n^2 , σ_p , ρ_p , β_p^2 in eq.(8). The existing data

on the proton parameters, deduced from $\bar{p}$ -p scattering experiments, are summarized by the empirical formulae of refs.[16,17], which at 600 MeV/c give $\sigma_p = 150$ mb, $\beta_p^2 = 21$ (GeV/c) $^{-2}$ and $\rho_p = -0.2$. We note that the values of σ_p are 5-10 % higher than those recently measured at LEAR [18]. In the following we neglect this small discrepancy and refer to the detailed discussion of ref.[3].

For the neutron parameters, we use the results of recent analyses of total $\bar{p}$ -nucleus cross sections [3,17,19]. All these analyses give consistent values of σ_n and predict a ratio $R = \sigma_n / \sigma_p < 1$ for $0.2 < p < 0.6$ GeV/c, in agreement with the results given recently in refs.[18] and [20]. Here we use the results of ref.[3], which predict $R = 0.9$ at $p = 0.6$ GeV/c, that is $\sigma_n = 135$ mb. For the other parameters, it results that ρ_n and ρ_p affect negligibly the total cross section, so that usually one puts $\rho_n = \rho_p$, and that a change of 10% in the slope parameters leads to a 2% change in σ_R and σ_{EL} [14,17]. Hence, usually one puts [3,13,19,21] $\beta_n^2 = \beta_p^2$ or $R = \sigma_n / \sigma_p = \beta_n^2 / \beta_p^2$. We have found that, σ_n being fixed, the calculation of σ_{BU} by eq.(7) is insensitive to the values of ρ_n and ρ_p , whereas it is determined mainly by the values of the slope parameters. Indeed, a 10% change in β_n^2 leads to a 15% change in σ_{BU} . For this reason, we have fixed $\sigma_n = 135$ mb, $\rho_n = \rho_p = 0.2$ and have calculated σ_{BU} according to the two generally accepted values for β_n^2 .

The results, reported in Tab.I, show that the model is in fair agreement with our data. In Tab.II we report also the calculated values of the reaction and break-up cross sections for other nuclei for which experimental data on the reaction cross

section exist.

To understand more clearly the possible reasons of the low value of the break-up cross section observed experimentally, let us consider a $\bar{p}$ scattering on a nucleus with sharp surface, i.e. with a square well density of radius R_N . In the optical limit for the Glauber approximation, where $A \gg 1$ and $\beta^2 \ll R_N^2$ and $\rho = 0$, one has:

$$\sigma_{BU} = \int d^2b (\exp[-\sigma_a T(b)] - \exp[-\sigma_t T(b)]) \quad (9)$$

where σ_a and σ_t are the averaged $\bar{p}$ -p and $\bar{p}$ -n annihilation and total cross sections, respectively, and $T(b)$ is the nuclear thickness function [8]. In the case of sharp nuclear surface, from this equation we obtain:

$$\sigma_{BU} = \frac{\pi}{4} (\lambda_a^2 - \lambda_t^2) (1 + O(\frac{\lambda_t}{R_N})) \quad (10)$$

where $\lambda = (n \sigma)^{-1}$ with $n = 0.17 \text{ f}^{-3}$ is the mean free length corresponding to annihilation or total $\bar{p}$ -nucleon scattering. Since at 600 MeV/c $\sigma_a = 90 \text{ mb}$ and $\sigma_t = 150 \text{ mb}$ [22], from eq(10) we obtain $\sigma_{BU} \simeq 2 \text{ mb}$, a value even smaller than those reported in Tabs. I and II. This shows that, due to the large annihilation probability, the break-up cross section is a small quantity determined mainly by the $\bar{p}$ interaction on the surface layer of the nucleus.

To test this surface dependence, we have calculated σ_R, σ_{EL} and σ_{BU} for ^{40}Ca , varying the nuclear radius and the diffuseness parameter in such a way to keep the r.m.s radius fixed at 3.43 fm. We have found that a 10% change in the diffuseness determines a 1% change in σ_R and σ_{EL} and a 10%

change in σ_{BU} . This calculation suggests also the degree of sensitivity for future measurements of σ_{BU} on medium-heavy nuclei [24].

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TABLE CAPTIONS

TABLE I

Experimental and calculated total cross sections for $\bar{p}$ - ${}^4\text{He}$ interaction at 180 Mev. The errors reported for the measured quantities are only statistical; a further systematic error less than 3% and 12.2% must be assigned to the reaction and break-up cross section, respectively.

The input parameters for the Glauber model are: $\sigma_p = 150$ mb, $\sigma_n = 135$ mb, $\beta_p^2 = 21$ (GeV/c) $^{-2}$, $\rho_p = \rho_n = 0.2$ (see text). The calculations are performed for two different values of β_n^2 , corresponding to the conditions $\sigma_n / \sigma_p = \beta_n^2 / \beta_p^2$ (case a) and $\beta_n^2 = \beta_p^2$ (case b). In the table, β_n^2 is in (GeV/c) $^{-2}$ and the cross sections are in mb. The nuclear radius for ${}^4\text{He}$ has been fixed at $R_N = 1.37$ fm.

TABLE II

Theoretical reaction and break-up cross sections (this work) and experimental reaction cross sections (mb) on various nuclei at 600 MeV/c. (C from refs.[5,23], Ne from ref.[19], Al and Cu from ref.[23] and Ca from ref.[5]). The theoretical cross sections are calculated with the Glauber model discussed in the text. The parameters for the $\bar{p}$ -nucleon scattering amplitudes are those of case b) of Tab.I. The radii R_N and the diffusenesses a (expressed in fm) refer to the point-nucleon densities and are taken from ref.[17].

T A B L E I

case	β_n	σ_{thR}	σ_{thBU}	σ_{thEL}	α_{expR}	σ_{expBU}
a	18.9	233.2	16.2	131.0	239.2 $\pm$ 5.0	15.5 $\pm$ 3.1
b	21.0	236.7	14.7	130.8		

T A B L E II

nucleus	R N	a	exp σ R	th σ R	th σ BU
¹² C	1.62	-	492 $\pm$ 20	476.4	34.7
²⁰ Ne	2.74	.500	619 $\pm$ 21	674.2	52.4
²⁷ Al	2.84	.526	737 $\pm$ 30	766.8	55.8
⁴⁰ Ca	3.51	.520	990 $\pm$ 50	963.0	62.7
Cu	4.20	.527	1213 $\pm$ 40	1235.3	71.8