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Antiproton-deuteron scattering at 600 MeV/c

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Abstract. Using Glauber's multiple-scattering theory, the elementary $\bar{p}$-neutron scattering amplitude has been obtained from an analysis of $\bar{p}$-deuteron elastic-scattering data at 600 MeV/c. The plane-wave expansion in the double-scattering amplitudes is treated more accurately than in earlier work. It is found that this leads to significantly better agreement with the data at high momentum transfer.

PACS. 25.43.+t Antiproton-induced reactions – 13.75.Cs Nucleon-nucleon interactions (including antinucleons, deuterons, etc.)

1 Introduction

To date, information about the elementary $\bar{p}n$ amplitude has been obtained from analyses of $\bar{p}d$ [1–4] and $\bar{p}$-nucleus [5–7] scattering data using Glauber's approximation to multiple-scattering theory [8,9] and the knowledge of the elementary $\bar{p}p$ scattering amplitude obtained from analyses of data at low and medium energies [10–12].

According to Glauber's approximation, valid for high incident energy and small scattering angles, the hadron-nucleus scattering amplitude is described in terms of the elementary hadron-nucleon scattering amplitudes and the bound-state nuclear wave functions. Thus, for $\bar{p}d$ scattering, the elementary $\bar{p}p$ and $\bar{p}n$ scattering amplitudes and the internal deuteron wave function are required. Since both the deuteron wave function and the elementary $\bar{p}p$ scattering amplitude are well known, information on the $\bar{p}n$ scattering amplitude can be extracted from analysis of elastic $\bar{p}d$ scattering data.

In the present paper, the plane-wave expansion in the double-scattering amplitudes is treated more accurately than in ref. [4]. The plane wave is taken to be

$$e^{i\vec{q}'\cdot\vec{r}} = 4\pi \sum_{\ell=0}^{\infty} \sum_{m_\ell=-\ell}^{+\ell} i^\ell j_\ell(q'r) Y^*_{\ell m_\ell}(\alpha,0) Y_{\ell m_\ell}(\theta,\varphi) , \quad (1)$$

where α is the polar angular coordinate of the vector $\vec{q}'$. In ref. [4], the approximation $\alpha = 0$ is made.

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The theoretical formulation is presented in sect. 2 and the results for $\bar{p}d$ elastic scattering at 179.3 MeV are given in sect. 3. Section 4 discusses these results and states the conclusions.

2 Theoretical formulation

Using Glauber's model, the amplitude for $\bar{p}d$ elastic scattering is given by

$$F_{M_f M_i}(\vec{q}) = \int \psi^\dagger_{M_f}(\vec{r}) F(\vec{q},\vec{r}) \psi_{M_i}(\vec{r}) \mathrm{d}^3 r , \quad (2)$$

where

$$F(\vec{q},\vec{r}) = f_{\bar{p}n}(\vec{q}) e^{i\frac{1}{2}\vec{q}\cdot\vec{r}} + f_{\bar{p}p}(\vec{q}) e^{-i\frac{1}{2}\vec{q}\cdot\vec{r}} + iT(\vec{q},\vec{r}) \quad (3)$$

and $\psi_M(\vec{r})$ is the usual deuteron wave function of spin projection M.

The amplitudes $f_{\bar{p}n}(\vec{q}), f_{\bar{p}p}(\vec{q})$ are the elementary scattering amplitudes of the neutron and the proton in the deuteron with the incident antiproton and $T(\vec{q},\vec{r})$ is given by

$$T(\vec{q},\vec{r}) = \frac{1}{2\pi k}\int \mathrm{d}^2 q' f_{\bar{p}n}\left(\frac{1}{2}\vec{q}+\vec{q}'\right) f_{\bar{p}p}\left(\frac{1}{2}\vec{q}-\vec{q}'\right) e^{i\vec{q}'\cdot\vec{r}} = \int \mathrm{d}^2 q' T(\vec{q},\vec{q}') e^{i\vec{q}'\cdot\vec{r}} . \quad (4)$$

Table 1. Parameters for $\bar{N}N$ scattering amplitudes at 600 MeV/c.

	$\bar{p}p$			$\bar{p}n$			$\chi^2/_{\rm d.f.}$
	$\sigma_{\bar{p}p}$ (mb)	$\rho_{\bar{p}p}$	$\beta^2_{\bar{p}p}$ (fm)^2	$\sigma_{\bar{p}n}$ (mb)	$\rho_{\bar{p}n}$	$\beta^2_{\bar{p}n}$ (fm)^2	
Theory [4]							
Nijmegen	154.8	−0.198	1.044	126.0	−0.144	0.809	
Dover-Richard	161.6	−0.107	0.984	152.8	−0.086	0.919	
Paris	153.2	−0.072	0.912	140.1	−0.057	0.806	
Analysis							
Present work	150.2	0.203	0.805	134.4 ±2.0	0.106 ±0.02	0.842 ±0.02	2.05
Bruckner *et al.* [10]	140.0 ±2.6	0.203 ±0.12	0.888 ±0.04				
Bendiscioli *et al.* [7]				135.2 ±2.0	0.035 ±0.02	0.849 ±0.02	1.53
Mahalanabis [4]	145.0	0.203	0.888	132.3 ±1.5	0.206 ±0.02	0.941 ±0.01	2.10

Inserting eqs. (1) and (3) and the deuteron wave function into (2) we find

$$F_{M_fM_i}(\vec{q}) = (f_{\bar{p}n}(\vec{q}) + f_{\bar{p}p}(\vec{q}))\cdot S^{(1)}_{M_fM_i}\left(\frac{1}{2}q\right) + i\int \mathrm{d}^2q' T(\vec{q},\vec{q}\,')\cdot S^{(2)}_{M_fM_i}(\vec{q}\,') \ , \qquad (5)$$

where

$$S^{(1)}_{00}\left(\frac{1}{2}q\right) = S_0\left(\frac{1}{2}q\right) + \sqrt{2}S_2\left(\frac{1}{2}q\right) \ , \qquad (6)$$

$$S^{(1)}_{11}\left(\frac{1}{2}q\right) = S^{(1)}_{-1-1}\left(\frac{1}{2}q\right) = S_0\left(\frac{1}{2}q\right) - \frac{1}{\sqrt{2}}S_2\left(\frac{1}{2}q\right), \qquad (7)$$

$$S^{(1)}_{-11}\left(\frac{1}{2}q\right) = S^{(1)}_{1-1}\left(\frac{1}{2}q\right) = 0 \ , \qquad (8)$$

and

$$S^{(2)}_{00}(\vec{q}\,') = S_0(q') + \frac{1}{\sqrt{2}}(3\cos^2\alpha - 1)S_2(q') \ , \qquad (9)$$

$$S^{(2)}_{11}(\vec{q}\,') = S^{(2)}_{-1-1}(\vec{q}\,') = S_0(q') - \frac{1}{\sqrt{8}}(3\cos^2\alpha - 1)S_2(q') \ , \qquad (10)$$

$$S^{(2)}_{-11}(\vec{q}\,') = S^{(2)}_{1-1}(\vec{q}\,') = \frac{3}{\sqrt{8}}(\sin^2\alpha)S_2(q') \ , \qquad (11)$$

where $S_0(q)$ and $S_2(q)$ are the usual spherical and quadrupole form factors of the deuteron [4]. Equations (7), (8), (10) and (11) follow from parity conservation and time reversal invariance.

The scattering amplitudes $f_{\bar{p}n}$ and $f_{\bar{p}p}$ are parametrized in the usual Gaussian form [7]

$$f_j(q) = \frac{ik\sigma_j}{4\pi}(1 - i\rho_j)e^{-\frac{1}{2}\beta_j^2\vec{q}^{\,2}} = f_j(0)e^{-\frac{1}{2}\beta_j^2\vec{q}^{\,2}} \ , \qquad (12)$$

where j stands for $\bar{p}n$ or $\bar{p}p$, σ_j is the total $\bar{p}N$ cross-section, β_j^2 is the slope parameter, ρ_j is the ratio of the real to imaginary forward-scattering amplitude, $\mathrm{Re}f_j(0)/\mathrm{Im}f_j(0)$ and k is the laboratory incident momentum.

Finally, the differential cross-section for $\bar{p}d$ elastic scattering is given by

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t} = \frac{\pi}{3}\Sigma_{M_fM_i} \mid F_{M_fM_i}(\vec{q}) \mid^2 \ . \qquad (13)$$

3 Results

The parameters of the $\bar{p}p$ scattering amplitude are derived from $\bar{p}p$ scattering experiments. The results obtained for momenta between 0.3 and 1.5 GeV/c are given by the following empirical formulae taken from refs. [7,13]:

$$\sigma_{\bar{p}p} = 61.2 + 53.4/k \ \ (\mathrm{mb}) \ , \qquad (14)$$

$$\beta^2_{\bar{p}p} = 65.6 - 129.4k + 109.0k^2 - 30.19k^3 \ \ (\mathrm{GeV}/c)^{-2}, \qquad (15)$$

$$\rho_{\bar{p}p} = 1.33 - 10.34k + 22.28k^2 - 13.63k^3 \ , \qquad (16)$$

where k is the incident momentum in GeV/c. The parameters derived from these formulae for $k = 600$ MeV/c, discussed here, are given in table 1.

In the present analysis we consider the data of Bruge *et al.* [14] on $\bar{p}d$ scattering at 179.3 MeV which consists of an elastic angular distribution with good angular resolution and extends up to $-t = 0.32$ (GeV/c)^2. The data of Bizzari *et al.* [1] are not included in the analysis since these data are highly contaminated with nonelastic processes. In order to determine the $\bar{p}n$ scattering amplitude, numerical fitting to the experimental data was performed using an iterative least-square programme and minimizing χ^2 with respect to the three parameters $\sigma_{\bar{p}n}, \beta^2_{\bar{p}n}$ and $\rho_{\bar{p}n}$. In these calculations, deuteron form factors corresponding to the Paris wave function [15] were used.

The parameters obtained for the $\bar{p}n$ scattering amplitude at 600 MeV/c are shown in table 1, together with the

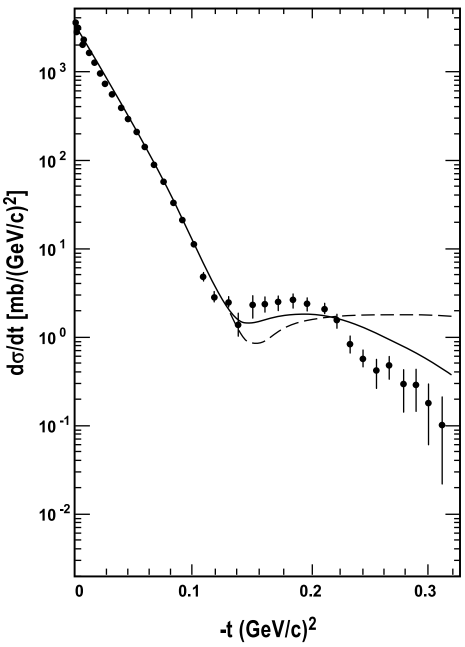

Fig. 1. Differential cross-sections for $\bar{p}d$ elastic scattering at 179.3 MeV. The solid curve is the prediction of eq. (19) and the dashed curve is the result of ref. [4], corresponding to $\alpha = 0$. The data are those of ref. [14].

values obtained from analyses of $\bar{p}$-nucleus data and the predictions of $\bar{N}N$ potential models. The corresponding parameters for the $\bar{p}p$ scattering amplitude are also given.

The results for the $\bar{p}n$ scattering amplitude agree closely with those of Bendiscioli *et al.* [7] also using the Paris deuteron wave function. However, the value obtained for the parameter $\rho_{\bar{p}n}$ differs significantly from the predictions of $\bar{p}N$ potential models [7], which indicate negative values for both $\bar{p}p$ and $\bar{p}n$ scattering amplitudes and also the value obtained from analysis of $\bar{p}$-nucleus data [7]. On the other hand, the value of $\rho_{\bar{p}n}$ is closer to the corresponding value of $\rho_{\bar{p}p}$ determined from the LEAR data [14].

Figure 1 shows the calculated differential cross-sections for $\bar{p}d$ elastic scattering at 179.3 MeV compared with the data of Bruge *et al.* [14]. The solid curve is the present result taking into account the angle α. The dash curve is the corresponding result of ref. [4], neglecting the angular dependence (α). It is seen that the approximation $\alpha = 0$ breaks down for larger values of $-t$.

4 Conclusion

The $\bar{p}d$ high-energy elastic-scattering amplitude has been derived using an internal wave function with a D-state component for the deuteron within the framework of Glauber's approximation to multiple-scattering theory.

Employing the Paris internal deuteron wave function and parameters for the $\bar{p}p$ scattering amplitude obtained from $\bar{p}p$ scattering experiments, the least-square fit to the experimental differential cross-section for $\bar{p}d$ elastic scattering at 179.3 MeV, varying the parameters of the elementary $\bar{p}n$ scattering amplitude, reproduces fairly well the data. The inclusion of a finite angle (α) in the plane-wave expansion of the double-scattering amplitudes improves the agreement with experiment for larger values of $-t$. The parameters for the elementary $\bar{p}n$ scattering amplitude at 179.3 MeV obtained agree closely with those of Bendiscioli. The parameter $\rho_{\bar{p}n}$ differs significantly from the predictions of potential models and also the value obtained from analysis of $\bar{p}$-nucleus data but is close to the value of $\rho_{\bar{p}p}$ determined from the LEAR data.

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