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Abstract. The status of our present knowledge on the antinucleon-nucleon interaction at low and medium energies is discussed. Special emphasis is put on aspects related to its spin dependence which are relevant for experiments planned by the PAX collaboration. Predictions for the spin-dependent $\bar{p}p$ cross sections σ_1 and σ_2 are presented, utilizing $\bar{N}N$ potential models developed by the Jülich group, and compared to results based on the amplitudes of the Nijmegen partial-wave analysis.

1. Introduction

While the interest in antinucleon physics waned somewhat after 1996 when the Low Energy Anti-Proton Ring (LEAR) at CERN was shut down, this trend has clearly reversed over the last couple of years. Hereby measurements of the antiproton-proton ($\bar{p}p$) invariant mass in the decays of J/ψ, B mesons, etc., definitely played an important role where in some of those studies a near-threshold enhancement in the mass spectrum was found [1, 2, 3]. In case of the radiative decay of J/ψ this enhancement turned out to be so spectacular that it even nourished speculations that one might have found evidence for the existence of $\bar{p}p$ bound states [1, 4]. The most important factor is certainly the proposed Facility for Antiproton and Ion Research (FAIR) in Darmstadt whose construction is finally on its way. Among the various experiments planned at this site is the PANDA Project [5] which aims to study the interactions between antiprotons and fixed target protons and nuclei in the momentum range of 1.5-15 GeV/c using the high energy storage ring HESR.

Another project suggested for the FAIR facility comes from the PAX collaboration. This collaboration was formed [6] with the aim to measure the proton transversity in the interaction of polarized antiprotons with protons. In order to produce an intense beam of polarized antiprotons, the collaboration intends to use antiproton elastic scattering off a polarized hydrogen target (^{1}H) in a storage ring [7]. The basic idea is connected to the result of the FILTEX experiment [8], where a sizeable effect of polarization buildup was achieved in a storage ring by scattering of unpolarized protons off a polarized hydrogen atoms at low beam energies of 23 MeV. Recent theoretical analyses [9, 10, 11, 12] have shown that the polarization buildup observed in Ref. [8] can be understood quantitatively. According to those authors it is solely due to the spin dependence of the hadronic (proton-proton) interaction which leads to the so-called spin-filtering mechanism, i.e. to a different rate of removal of beam protons from the ring for different polarization states of the target proton.
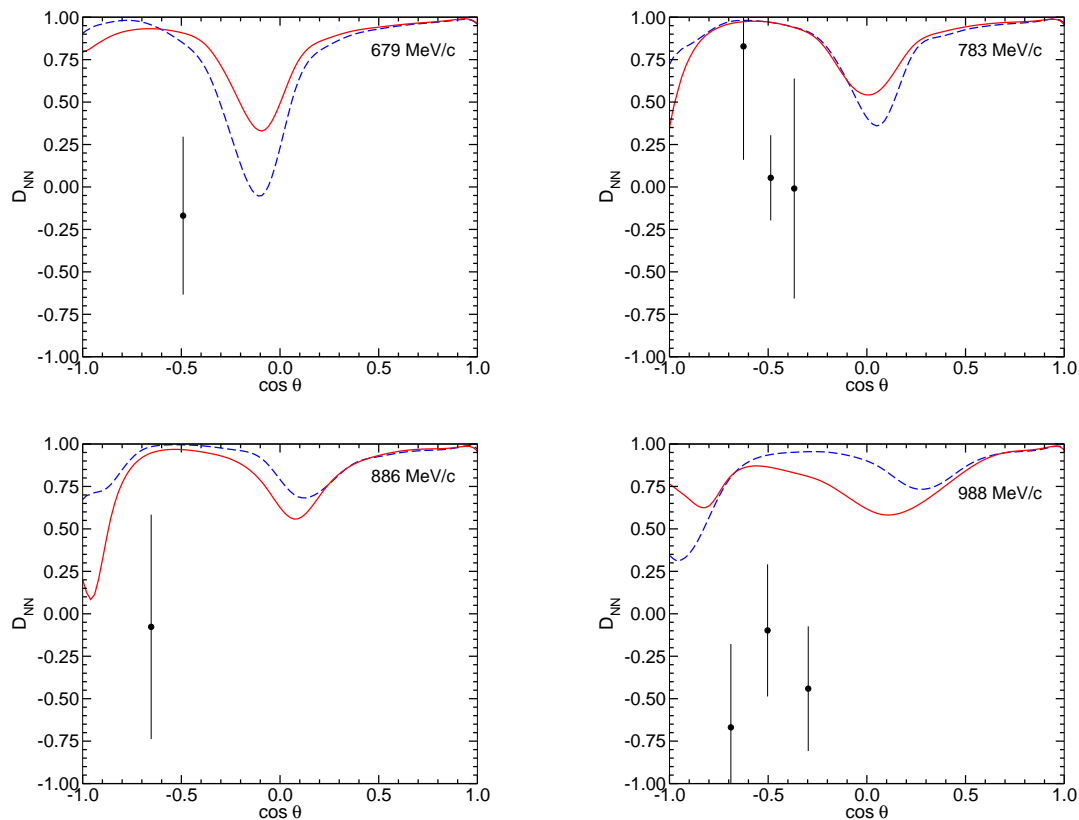
Figure 1. Depolarization parameter D_{NN} for $\bar{p}p \to \bar{p}p$ at selected beam momenta p_{lab}. The data are taken from Ref. [17]. Results for model D (solid line) and model A (dashed line) are shown.

In contrast to the NN case, the spin dependence of the $\bar{N}N$ interaction is poorly known. Therefore, it is an open question whether any sizeable polarization buildup can also be achieved in case of an antiproton beam based on the spin-filtering mechanism. Indeed, recently several theoretical studies were performed with the aim to estimate the expected polarization effects for antiprotons, employing different $\bar{p}p$ interactions [13, 14, 15, 16]. In this contribution I provide an overview and a comparison of the results of those investigations. Furthermore, I take the opportunity to briefly recall the status of our knowledge of the spin dependence of the $\bar{N}N$. Thereby I focus on the only double-polarization observables measured so far, namely the depolarization parameter D_{NN} and the spin parameter K_{NN} [17, 18, 19, 20]

Besides of using polarized protons as target one could also use light nuclei as possible source for the antiproton polarization buildup. A corresponding investigation for antiproton scattering on deuterons was presented in Ref. [14, 21], cf. also a related contribution to these proceedings [22].

2. The Jülich $\bar{N}N$ models

Since most of the results reported below are for $\bar{N}N$ interactions developed by the Jülich group let me briefly summarize the salient features of those potential models. In fact, the Jülich group has developed several $N\bar{N}$ models over the years [23, 24, 25, 26, 27]. In the following I am going to present results for the models A(BOX), introduced in Ref. [24], and D, described in Ref. [27]. Starting point for both models is the full Bonn NN potential [28]; it includes not only traditional one-boson-exchange diagrams but also explicit 2π- and $\pi\rho$-exchange processes as well as virtual Δ-excitations. The G-parity transform of this meson-exchange NN model provides
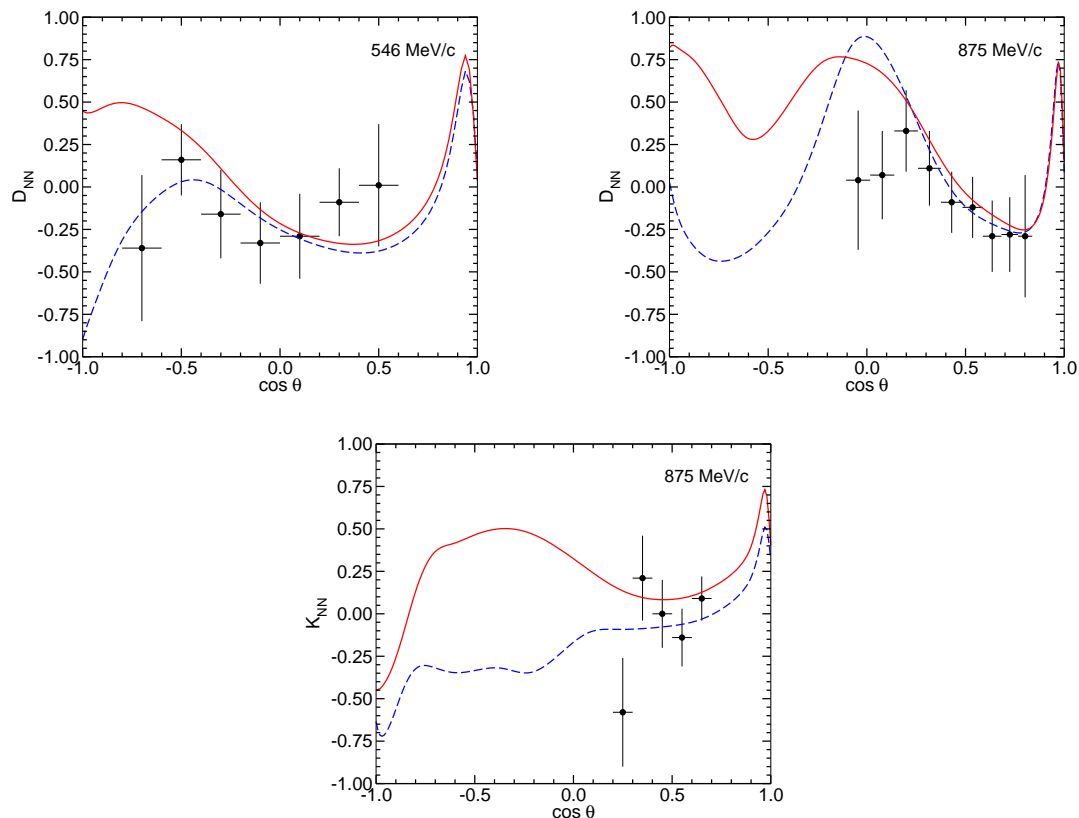
Figure 2. Double-polarization observables D_{NN} and K_{NN} for $\bar{p}p \rightarrow \bar{n}n$ at selected beam momenta p_{lab}. The data are taken from Refs. [18, 19, 20]. Results for model D (solid line) and model A (dashed line) are shown.

the elastic part of the considered $N\bar{N}$ interaction models. In case of model A(BOX) [24] (in the following referred to as model A) a phenomenological spin-, isospin- and energy-independent complex potential of Gaussian form is added to account for the $N\bar{N}$ annihilation. It contains only three free parameters (the strengths of the real and imaginary parts of the annihilation potential and its range), fixed in a fit to the available total and integrated $\bar{N}N$ cross sections. In case of model D [27], the most complete $N\bar{N}$ model of the Jülich group, the $N\bar{N}$ annihilation into 2-meson decay channels is described microscopically, including all possible combinations of π, ρ, ω, a_0, f_0, a_1, f_1, a_2, f_2, K, K^+ – see Ref. [27] for details – and only the decay into multi-meson channels is simulated by a phenomenological optical potential.

3. Results

Results for the total and integrated elastic ($\bar{p}p$) and charge-exchange ($\bar{p}p \rightarrow \bar{n}n$) cross sections and also for angular dependent observables for both models can be found in Refs. [24, 27]. As one can see there, with model A as well as with D a very good overall reproduction of the low- and intermediate energy $\bar{N}N$ data is achieved. Moreover, exclusive data on several $p\bar{p}$ 2-meson and even 3-meson decay channels are described with fair quality [25, 27, 29]. Recently it has been shown that the $\bar{N}N$ models of the Jülich group can also explain successfully the near-threshold enhancement seen in the $\bar{p}p$ mass spectrum of the reactions $J/\psi \rightarrow \gamma\bar{p}p$ [30], $J/\psi \rightarrow \omega\bar{p}p$ [31] and $B^+ \rightarrow K^+\bar{p}p$ [32] and in the $e^+e^- \rightarrow \bar{p}p$ cross section [33].

In Ref. [14] we presented a comparison of the Jülich $\bar{N}N$ interaction with existing data for the $\bar{n}p$ channel [34, 35], which is a purely isospin $I = 1$ system. It showed that the Jülich models are in nice agreement with the experimental information on the $\bar{n}p$ interaction too, despite the

fact that those data on total and annihilation cross sections have not been included in the fitting procedure.

Table 1. Partial cross sections predicted by the Jülich $\bar{N}N$ models A and D [24, 27] in comparison to results from the Nijmegen $\bar{N}N$ partial wave analysis [37].

		$\bar{p}p \to \bar{p}p$				$\bar{p}p \to \bar{n}n$			
	p_{lab} (MeV/c)	200	400	600	800	200	400	600	800
$^1S_0$	A	15.0	7.7	4.4	2.7	0.8	0.1		
	D	12.9	7.8	4.9	3.3	0.4			
	Nijmegen	14.6	6.8	3.7	1.9	0.5			
$^3S_1$	A	72.8	30.4	14.5	7.9	0.6	0.2	0.1	
	D	68.2	22.8	9.8	6.3	4.9	1.4	0.4	0.1
	Nijmegen	71.1	29.6	14.4	7.9	2.0	0.5	0.3	0.3
$^3P_0$	A	3.3	3.1	2.5	1.9	2.9	1.1	0.4	0.1
	D	2.0	2.3	2.4	2.3	2.5	0.6	0.1	
	Nijmegen	4.7	4.6	3.4	2.6	2.1	1.4	0.7	0.3
$^1P_1$	A	2.3	5.2	5.5	4.9	1.1	0.4	0.2	0.1
	D	4.1	7.5	7.2	6.0	0.7	0.8	0.5	0.3
	Nijmegen	1.7	2.6	2.5	2.4	1.3	0.4		
$^3P_1$	A	3.8	9.5	8.1	6.2	5.6	2.7	0.5	0.1
	D	4.6	10.4	8.3	5.8	4.9	2.4	0.7	0.2
	Nijmegen	1.8	7.6	7.6	6.2	6.7	6.2	2.8	1.4
$^3P_2$	A	4.9	14.8	13.4	10.1	0.6	0.7	0.2	0.1
	D	4.9	14.7	14.3	11.5	0.6	0.6	0.2	0.1
	Nijmegen	6.3	16.1	15.5	12.9	0.8	1.2	0.5	0.3

As already mentioned in the Introduction, the spin dependence of the $\bar{N}N$ interaction is not well known. There is a fair amount of data on analyzing powers, for $\bar{p}p$ elastic as well as for $\bar{p}p \to \bar{n}n$ charge-exchange scattering, cf. Ref. [36] for a recent review. The predictions of the Jülich models A and D are in reasonable agreement with the experimental polarizations up to beam momenta of $p_{lab} \approx 550$ MeV/c as can be seen in Ref. [27]. In fact, model A gives a somewhat better account of the data and reproduces the measured $\bar{p}p$ polarizations even quantitatively up to $p_{lab} \approx 800$ MeV/c ($T_{lab} \approx 300$ MeV).

As far as other spin-dependent observables are concerned, specifically with regard to double-polarization observables, there is only scant information on the depolarization D_{NN} [17, 18, 19] and also on the spin parameter K_{NN} [20]. Moreover, those data are of rather limited accuracy so that they do not really provide serious constraints on the $\bar{N}N$ interaction. In order to illustrate the present status I show here those data together with predictions of the Jülich models. They can be found in Fig. 1 (for $\bar{p}p \to \bar{p}p$) and in Fig. 2 (for $\bar{p}p \to \bar{n}n$). Interestingly the model results for the charge-exchange reaction are more or less in line with the data, while the depolarization predicted for elastic scattering is certainly too large. For fairness one should say that some of those data are already outside of the momentum range ($p_{lab} \leq 800$ MeV/c) for which the Jülich $\bar{N}N$ models were originally designed [24, 27].

In this context let us mention that a partial-wave analysis (PWA) of $\bar{p}p$ scattering has been performed by the Nijmegen Group [37] which, in principle, would allow to pin down the spin-dependence of the $\bar{N}N$ interaction. However, the uniqueness of the achieved solution was disputed in Ref. [38]. Moreover, the actual partial-wave amplitudes of the Nijmegen analysis are

not readily available and, therefore, one cannot confront the results of the Jülich models directly with those of the Nijmegen PWA. But at least the authors of [37] published partial elastic and charge-exchange cross sections. In Table 1 the results of the Jülich $\bar{N}N$ models A and D are compared with those of the Nijmegen PWA for the S- and P waves.

As one can see from the Table, qualitatively there is a good overall agreement between the two models and the Nijmegen analysis. This may be not too surprising in view of the fact that all of them reproduce the bulk properties of $\bar{p}p$ scattering rather well. But one can see also drastic quantitative differences, specifically in the P waves, where in some cases the partial cross sections of the Nijmegen analysis differ by factors of 2 or even more from those of the Jülich $\bar{N}N$ interactions. There are noticeable differences between the predictions of the models as well. Clearly those differences will be reflected in the results for the spin-dependent $\bar{p}p$ cross sections which are considered next.

The total polarized $\bar{p}p$ cross section can be written as

$$\sigma_{tot} = \sigma_0 + \sigma_1 (\mathbf{P}_B \cdot \mathbf{P}_T) + \sigma_2 (\mathbf{P}_B \cdot \hat{\mathbf{k}})(\mathbf{P}_T \cdot \hat{\mathbf{k}}) \tag{1}$$

where $\mathbf{P}_B$ and $\mathbf{P}_T$ are the polarization vectors of the beam and target, respectively, and $\hat{\mathbf{k}}$ is a unit vector in the direction of the beam [39]. In terms of the standard helicity amplitudes $M_i(\theta)$ $(i = 1, ..., 5)$ the cross sections are given by [39]

$$\begin{aligned}
\sigma_0 &= \frac{2\pi}{k} \text{Im}[M_1(0) + M_3(0)] \\
\sigma_1 &= \frac{2\pi}{k} \text{Im}[M_2(0)] \\
\sigma_2 &= -\frac{2\pi}{k} \text{Im}[M_1(0) + M_2(0) - M_3(0)],
\end{aligned} \tag{2}$$

where k is the modulus of the center-of-mass momentum of the antiproton. Note that the above equations are only valid for the purely hadronic contribution (called σ_i^h in the following) to the cross sections. The Coulomb-nuclear interference contribution to the cross sections, σ_i^{int}, has to be calculated by integration of the polarized differential $\bar{p}p$ cross section (with the Coulomb amplitudes included in the reaction amplitude) over the scattering angle within the interval $[\theta_{acc}, \pi]$, where θ_{acc} is the beam acceptance angle [9, 14]. Then the total spin-dependent cross sections σ_i $(i = 1, 2)$ are given by the sum $\sigma_i^h + \sigma_i^{int}$

Predictions of the Jülich $\bar{N}N$ interactions for the spin-dependent $\bar{p}p$ cross sections are presented in Figs. 3 and 4. Figure 3 contains results based on the purely hadronic amplitude (σ_i^h) and the Coulomb-nuclear interference term (σ_i^{int}) separately so that one can see the magnitude of the latter. In the concrete calculations the acceptance angle was chosen to be $\theta_{acc} = 8.8$ mrad [8].

At low energies, i.e. around $T_{lab} = 5 \sim 10$ MeV, the interference terms are comparable to the corresponding purely hadronic cross sections and their magnitude increases further with decreasing energy due to the $1/k$ factor, cf. Eqs. (27) in Ref. [14]. With increasing energy the relevance of the Coulomb-nuclear interference terms diminishes more and more in case of the cross sections σ_0 and σ_2. But for σ_1 the term is still significant, as one can see from Fig. 3b. Note, that the three cross sections σ_i^{int} $(i = 0, 1, 2)$ themselves are all roughly of comparable magnitude for energies from around 50 MeV onwards.

While the predictions of the two models for σ_0 are rather similar (cf. Figs. 3a), even for the Coulomb-nuclear interference cross section, this is not the case for the spin-dependent cross sections σ_1 and σ_2. For energies below $T_{lab} \approx 150$ MeV there are drastic differences between the results based on the two models. Indeed, for σ_2 at low energies even the sign differs in case of the $\bar{p}p$ channel. Obviously, here the variations in the hadronic amplitude are also reflected in large differences in the Coulomb-nuclear interference term.
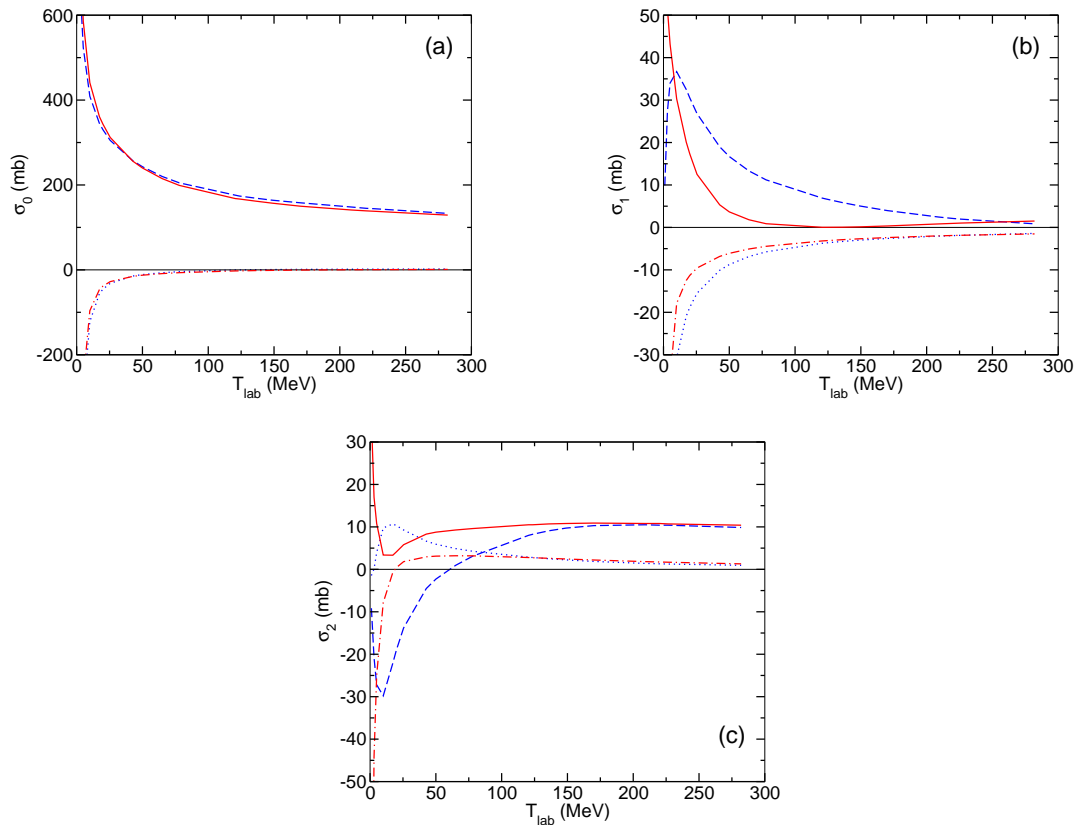
Figure 3. Total $\bar{p}p$ cross sections σ_0 (a), σ_1 (b), and σ_2 (c) versus antiproton laboratory energy T_{lab}. Results based on the purely hadronic amplitude (σ_i^h) of the models D (solid line) and A (dashed line) are shown, together with those for the Coulomb-nuclear interference term (σ_i^{int}), corresponding to the dash-dotted (D) and dotted (A) lines, respectively.
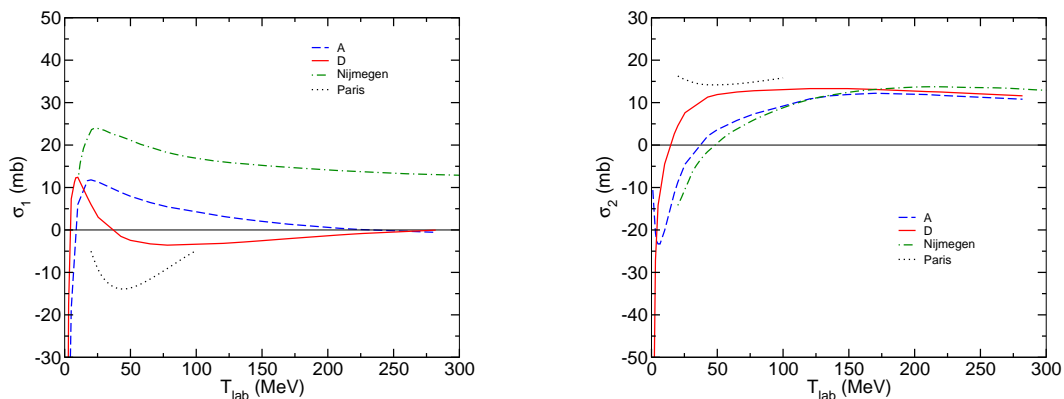

Figure 4. Spin-dependent $\bar{p}p$ cross sections σ_1 and σ_2 versus antiproton laboratory energy T_{lab}. Predictions for the total cross section ($\sigma_i = \sigma_i^h + \sigma_i^{int}$) of the Jülich models D (solid line) and A (dashed line) are shown. Corresponding results for the Nijmegen PWA (dash-dotted line) are taken from Ref. [15], while those for the Paris potential (dotted line) are from Ref. [13].

In Fig. 4 the total spin-dependent cross sections σ_1 and σ_2 are displayed. As far as σ_1 is concerned model A predicts a maximum of 12 mb at the beam energy $T_{lab} \approx 20$ MeV whereas model D yields a maximum of practically the same magnitude at $T_{lab} \approx 10$ MeV. In both cases σ_1 becomes large and negative at very low energies due to the dominance of the Coulomb-nuclear interference term in this region. For comparison, I include here also results based on the Nijmegen $\bar{p}p$ PWA, whose amplitudes were recently re-constructed by Dmitriev *et al.* [15]. Note that the displayed curves are those for $\theta_{acc} = 10$ mrad [15]. The results of Ref. [15] suggest significantly larger values for σ_1 over the whole considered energy range, cf. Fig. 4. Finally, there is also an investigation where a version of the Paris $\bar{N}N$ model [40] was employed [13]. In that calculation the largest value for σ_1 was found to be -15 mb at $T_{lab} = 45$ MeV.

With regard to σ_2 model A and D predict values around 10 mb for $\bar{p}p$ scattering at higher energies. Close to threshold large negative values are predicted for $\sigma_2^h + \sigma_2^{int}$ due to the Coulomb-nuclear interference term. One should note, however, that for beam energies below 5 MeV, say, the total Coulomb cross section becomes very large. In this case the beam lifetime turns out to be too short and the spin-filtering method cannot be used for polarization buildup in a storage ring.

The results for σ_2 based on the Nijmegen $\bar{p}p$ PWA [15] turn out to be fairly similar to the predictions of the Jülich models, in particular for energies above 100 MeV. (Please note that our definition for the cross section σ_2 differs from that in Ref. [9]: our σ_2 is equal to $\sigma_2 - \sigma_1$ as defined in Eq. (2) of Ref. [9].) The results based on the Paris $\bar{p}p$ potential are similar to those of model D, at least for the energy range covered in Ref. [13].

4. Conclusions

In this contribution I have reviewed predictions for the spin-dependent cross sections σ_1 and σ_2 using either $\bar{N}N$ potential models [24, 27, 40] or $\bar{N}N$ amplitudes from a partial-wave analysis [37]. There are significant differences in the various results – which is certainly not surprising given our incomplete knowledge of the spin dependence of the $\bar{N}N$ interaction.

The polarization buildup due to the spin-filtering mechanism is determined mainly by the ratio of the polarized total cross section σ_i (i=1,2) to the unpolarized one (σ_0) [9]. For the ratio σ_2/σ_0 all considered interactions predict values around 10% for beam energies above 50 MeV. For σ_1/σ_0 only the Nijmegen PWA yields a ratio of comparable magnitude while the potential models predict significantly smaller values, specifically for higher energies. It should be said that yields of around 10% would be sufficient for the requirements of the PAX experiment [41].

At present there are plans to investigate the polarization buildup mechanism in $\bar{p}^1$H scattering in a new experiment at CERN [42, 43]. The stored antiprotons will be scattered off a polarized ^{1}H target in that experiment [42, 43] and the polarization of the antiproton beam will be measured at intermediate energies. Besides of being a test for the feasibility of spin-filtering for antiprotons this experiment will also provide data for the spin-dependent cross sections σ_1 and σ_2. Such data will be very useful for constraining the spin dependence of the $\bar{N}N$ interaction.

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