Weak strangeness production in nucleon-nucleon scattering

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Until now the only way to study the strangeness changing baryon-baryon interaction has been through the decays of lambda hypernuclei. It would clearly be preferable to be able to study reactions such as $pn \to p\Lambda$ in free space. In order to provide some guidance concerning the feasibility of such a measurement, we investigate the energy dependence, parity violating asymmetry, and shape of the cross section for this reaction.

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The nonleptonic weak interactions have long been a topic of great interest. Until now, for experimental reasons, the study of strangeness changing, weak baryon-baryon interactions has been limited to the decays of Λ hypernuclei. (For a recent review, see, e.g., the article by Dover [1].) Fascinating as these systems are, because of nuclear structure complications, the details of the baryon-baryon interaction are difficult to extract from such data.

With the advent of new, high precision accelerators such as COSY in Jülich it may now be possible to begin the direct study of these processes, in particular the process $pn \to p\Lambda$ [2].

This paper is meant to provide an initial exploration of the size and energy dependence of the total $pn \to p\Lambda$ cross section, as well as of the basic structure of the corresponding differential cross section. The knowledge of these features is important in order to determine the feasibility of such an experiment and to decide the most suitable kinematic region.

Weak processes such as $pn \to p\Lambda$ naturally lend themselves to the distorted-wave Born approximation (DWBA) approach (which we have used previously to calculate charge symmetry breaking in np scattering [3]). In this way the strong distortion of the wave functions can be treated exactly in momentum space while the weak transition potential is treated to first order.

Our calculations are performed in the meson exchange framework. The natural starting point is the transition process in terms of pion exchange [illustrated in Fig. 1(a)], because the weak $\Lambda N \pi$ vertex, represented by an effective Hamiltonian

$$H_\pi^w = i g_\pi^w \bar{\Psi}_N (1-\lambda_\pi \gamma_5) \vec{\tau} \Psi_\Lambda \vec{\phi}_\pi + \text{H.c.}, \qquad (1)$$

is fixed empirically by the free $\Lambda \to N\pi$ decay, yielding $g_\pi^w = 0.23 \times 10^{-6}$ and $\lambda_\pi = 6.9$ [4]. Here Ψ_N and $\vec{\phi}_\pi$ are the nucleon and pion fields, respectively, while

$$\Psi_\Lambda = \begin{pmatrix} 0 \\ \psi_\Lambda \end{pmatrix}$$

is the Λ spurion field used to enforce the $\Delta T = 1/2$ rule.

Of course, the exchange of heavier mesons is also possible. However, the corresponding weak coupling parameters are not constrained empirically, as in the pion case, since heavier mesons cannot participate in the free decay of the Λ. Therefore one has to rely on theoretical estimates, which necessarily introduce considerable uncertainties [5]. Nevertheless, in order to get an impression of what can be expected from higher meson exchanges, we have also included ρ exchange [Fig. 1(b)]. The weak $\Lambda N \rho$ vertex is described by the effective Hamiltonian

$$H_\rho^w = \bar{\Psi}_N \left[f_1 \gamma^\mu + i \sigma^{\mu\nu} k_\nu \frac{f_2}{2m_N} + g_1 \gamma^\mu \gamma_5 \right] \vec{\tau} \Psi_\Lambda \vec{\phi}_{\rho,\mu} + \text{H.c.}, \qquad (2)$$

with $\sigma^{\mu\nu} = i/2[\gamma^\mu, \gamma^\nu]$ and k_ν the four-momentum of the exchanged ρ. The coupling constants f_1 $(=-1.768\times 10^{-6})$, f_2 $(=-3.112\times 10^{-6})$, and g_1 $(=-0.849\times 10^{-6})$ have been taken from the work of Nardulli [6], who used a pole model and information from weak nonleptonic and radiative decays in order to determine these couplings. [Note that in this exploratory study, and in line with Ref. [5], we have neglected a possible $\sigma^{\mu\nu} k_\nu \gamma_5$ term in Eq. (2), which according to Ref. [6] is small anyhow.] The parameters at the strong $NN\pi$ and $NN\rho$ vertices (coupling constants as well as form factors) are taken from the (full) Bonn NN potential [7]. We use the same form factors at the strong and corresponding weak ver-

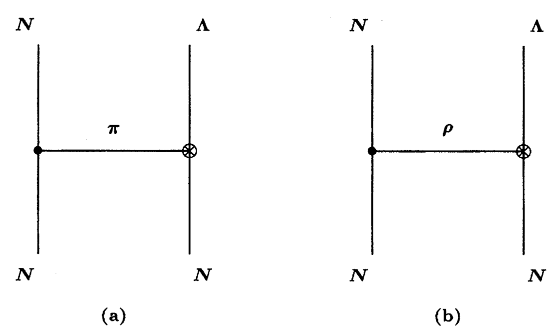

FIG. 1. (a) π exchange contribution to the reaction $NN \to N\Lambda$. (b) ρ exchange contribution. The $\otimes$ indicates the weak vertex.

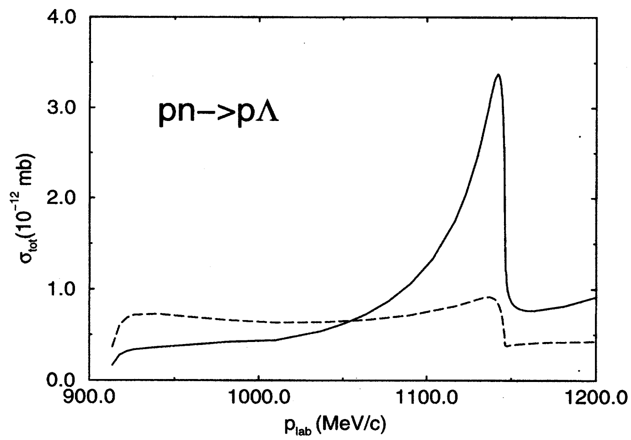

FIG. 2. Integrated cross section predicted for the reaction $pn \rightarrow p\Lambda$. Dashed line: π exchange only; solid line: π + ρ exchange.

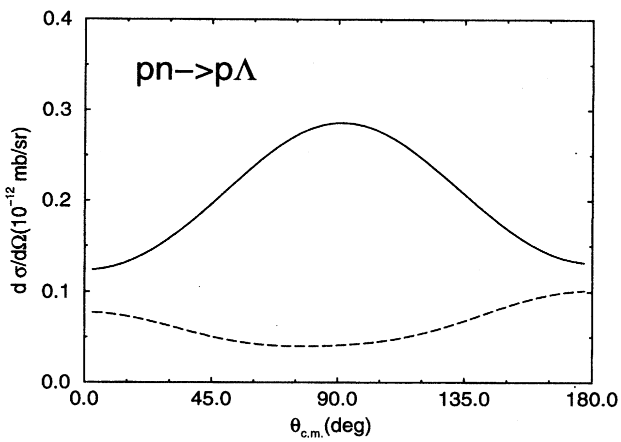

FIG. 3. Differential cross section predicted for the reaction $pn \rightarrow p\Lambda$ at $p_{\rm lab}$= 1150 MeV/c. Same description of curves as in Fig. 2.

tices. Both the initial (NN) and final ($N\Lambda$) strong interactions are likewise generated from potential models, in the one-boson-exchange (OBE) framework. For the initial state we take our model OBEPF [8], while for the final state we use our coupled channels ($N\Lambda$,$N\Sigma$) model A [9].

Resulting cross sections for the $pn \rightarrow p\Lambda$ process are shown in Fig. 2 as functions of the incoming proton's lab momentum, starting at threshold. Obviously, as a main result, a cross section of about 10^{-12} mb can be expected. Since the total np cross section at energies around the $N\Lambda$ threshold is about 30 mb the branching ratio for weak Λ production amounts to $R = \sigma_{np \rightarrow \Lambda p}/\sigma_{np} \approx 10^{-13}$.

As expected, the bulk of the cross section is already given by pion exchange. However, ρ exchange induces a sizable energy dependence; it leads to a strong enhancement of the production cross section at $p_{\rm lab} \approx 1150$ MeV/c, which is close to the ΣN threshold. This enhancement is caused by a resonance in the $N\Lambda$ interaction induced by the strong coupling to the $N\Sigma$ channel; see Ref. [9]. Since, compared with pion exchange, ρ exchange is quite short ranged the corresponding amplitude has more high momentum components and is thus more sensitive to such final state effects.

An example for the predicted differential cross section is shown in Fig. 3, in the peak region at $p_{\rm lab}$= 1150 MeV/c. These results demonstrate once more the sizable modifications caused by ρ exchange which leads to a broad bump, almost symmetric about 90°.

Analyzing our results in more detail we found that the weak Λ production is dominated by a single partial wave, namely, by $^3S_1$-$^3D_1$. This is not too surprising because this partial wave plays also a crucial role in calculations of nonmesonic decay of Λ hypernuclei [1]. Furthermore, the mentioned resonance in the $N\Lambda$ channel of our hyperon-nucleon model [9] occurs in the $^3S_1$-$^3D_1$ partial wave. In all other partial waves the main contribution is provided already by the Born term. Only in case of the $^3S_1$-$^3D_1$ is there a significant contribution from $N\Lambda$ rescattering which enhances the transition amplitude by almost 100% at energies around the $N\Sigma$ threshold. Since the $^3S_1 \leftrightarrow {}^3D_1$ transitions conserve parity it follows that in our model calculation the weak Λ production is dominated by parity conserving transitions. The parity violating contributions constitute only around 25% of the total production cross section. In order to demonstrate the extent of parity violation in the weak Λ production we show in Fig. 4 the asymmetry A,

$$A = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}, \tag{3}$$

of the total $pn \rightarrow p\Lambda$ cross section, where σ_+ and σ_- are the cross sections for positive and negative helicities of the incoming proton, respectively.

Since there is a strong coupling between the $N\Lambda$ and $N\Sigma$ channels it could be that the process

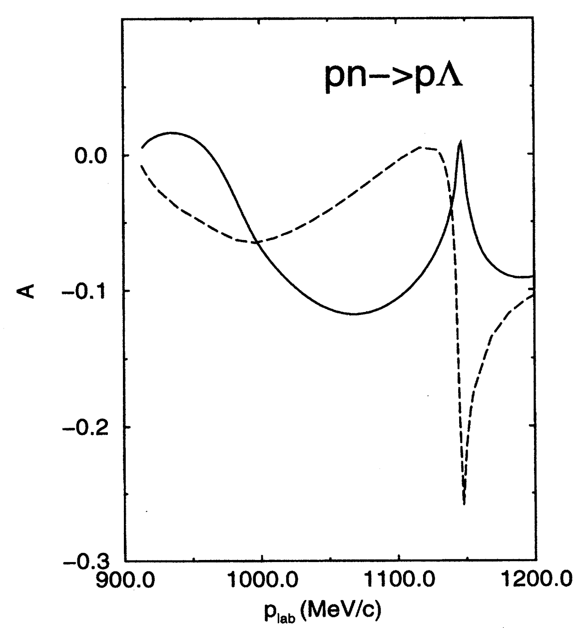

FIG. 4. Total asymmetry A predicted for the reaction $pn \rightarrow p\Lambda$. Same description of curves as in Fig. 2.

$$NN \xrightarrow{\text{weak}} N\Sigma \xrightarrow{\text{strong}} N\Lambda \tag{4}$$

gives a noticeable contribution to the weak Λ production cross section. Therefore we also calculated this amplitude, restricting ourselves to one-pion exchange for the $NN \to N\Sigma$ transition where the coupling constants of the weak $\Sigma N\pi$ vertex are known from the free $\Sigma \to N\pi$ decay [10]. It turned out that the amplitude for the process (4) is about an order of magnitude smaller than for the direct Λ production. This is partly due to the Born term, which is the dominant contribution in the direct weak Λ production but is, of course, missing here. Furthermore, the structure of the half-off-shell $N\Lambda \to N\Lambda$ and $N\Sigma \to N\Lambda$ transition amplitudes (in the important ${}^3S_1$-${}^3D_1$ partial wave) is different. The former exhibits a broad bump whereas the latter changes sign. As a consequence large cancellations occur in the integral involving the latter amplitude and the resulting rescattering term for the transition $NN \to N\Sigma \to N\Lambda$ is rather small.

It is clear from the very low cross section found here that the direct study of the strangeness changing baryon-baryon interaction will not be easy. However, with a high efficiency detection scheme a branching ratio of 10^{-13} can be determined. An ideal reaction, for which there exist high acceptance detection schemes as well as extremely clean experimental signatures for Λ production, is $dp \to pp\Lambda$. The deuteron serves as a neutron beam. In quasifree kinematics one just runs at deuteron momenta which are twice the momentum of the reaction shown in Fig. 1. One then selects the $np \to \Lambda p$ two-body reaction which is accompanied by a "spectator" proton around $0°$ with about half of the beam momentum. Maximal weak Λ production should be seen at a deuteron momentum of 2.25 GeV/c according to Fig. 2.

The occurrence of a Λ in the reaction $dp \to pp\Lambda$ has some very clean signatures. (i) The missing mass of the Λ can be verified from a measurement of the two protons. This allows the suppression of, e.g., ppn reactions. (ii) Requiring the observation of the delayed Λ decay $\Lambda \to p\pi^-$ which occurs typically 5 cm downstream from the point of Λ production rules out strong pion production events such as $ppp\pi^-$ in the target. (iii) The determination of the geometry (and/or momenta) of the $\Lambda \to p\pi^-$ decay event in a "decay spectrometer" [11] provides full information on the three four-vectors. This gives a second independent identification of the Λ mass and another consistency check for weak Λ production.

Furthermore, a $\Lambda \to p\pi^-$ spectrometer gives with high precision all Λ polarization components since the proton decay distribution depends strongly on the Λ spin. With 700 $\Lambda \to p\pi^-$ decay events one gets 10% precision on Λ polarization. Some very promising experience with Λ decay spectrometers/polarimeters exist [11].

A practical problem is that the lowest threshold for strangeness conserving $(\Lambda + K)$ production for deuterons on very heavy targets is at 1.726 GeV/c. In quasifree experiments one must therefore ensure the purity of the hydrogen target and take care that the reconstruction of the events is very precise. Since the $dp \to pp\Lambda$ reaction has a threshold at 1.54 GeV/c one can avoid background problems and run at deuteron momenta below 1.7 GeV/c.

Reactions like $pn \to p\Lambda$ contain a wealth of information on the short distance hadronic interaction, as well as the weak interaction itself. As the predicted cross section is at the edge of feasibility for modern machines and detectors it seems worthwhile to consider such experiments seriously.

After the submission of the present manuscript we became aware (through an invited talk by T. Kishimoto at the WEIN 95 Symposium in Osaka, 1995) of plans for similar experiments at KEK [12].

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