# FROM NN→NN$\pi$ TO PION PRODUCTION IN NUCLEI*

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In contrast to (p,$\pi$) reactions on nuclear targets which seem to be difficult to interpret, recent pion production experiments with systems with *two or three nucleons*, very *close to threshold*, have led to important new insights. In these studies the use of a storage ring with an internal target has been instrumental. Recent research with the Indiana Cooler is illustrated by two specific examples. In the reaction pd→pd$\pi^0$, possible *medium modifications* of pion production have been studied; while in pp→pp$\pi^0$ we have found experimental evidence for the *enhancement* of the axial current in nuclear systems.

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## 1. Introduction

With increasing bombarding energy, the interaction of nucleons with nucleons becomes inelastic at about 300 MeV because pion production becomes energetically possible. Above 1 GeV bombarding energy, inelastic processes actually dominate the NN interaction. Pion production is thus among the most important processes that can be studied in nuclear physics.

In the past, (p,$\pi$) reactions with nuclear targets have been studied extensively. Unfortunately, a description of such reactions by detailed reaction models was found to be notoriously difficult (see, *e.g.*, [1]) because of uncertainties with the reaction mechanism as well as the nuclear wave functions involved. More recently, however, there have been important contributions to our understanding of pion production from the study of systems with two or three nucleons. This development has been brought about by technical advances that have made it possible to extend measurements down

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in energy, closer to threshold than was previously possible. In this energy regime and with only few nucleons participating, the reaction is severely constrained and a comparison of near-threshold data with theory is thus more stringent since there are fewer degrees of freedom to cope with.

In the following, I will first explain the benefits one obtains when conducting experiments with internal targets in storage rings, and the consequences that result when the measurements are done close to threshold. Then, I will illustrate by two specific examples of recent research with the Indiana Cooler how such experiments have led to new physics insight.

## 2. Storage rings and pion production close to threshold

### *2.1. Stored beams with internal targets: benefits*

During the past few years, storage rings have become a new tool in nuclear physics [2]. These rings are equipped with means for phase space cooling. Cooling counteracts the growth of the phase volume of a stored beam that passes through an internal target. In most cases, so-called electron cooling is used.

Electron cooling has been demonstrated at the Indiana Cooler [3] for protons of up to 425 MeV. The limited cooling force dictates the maximum target thickness which, for hydrogen, ranges from $10^{13}$ to $10^{16}$ atoms/cm$^2$. Such targets can be realized, for instance, by crossing the stored beam with a gas jet emerging from a nozzle.

Although internal target experiments involve very thin targets, the stored beam is accumulated to several 100$\mu$A, and the resulting luminosities are comparable to conventional experiments with a one-pass beam on an external target. Cooled beams typically have small emittance, a small energy spread, and the beam energy is well known (because it is locked to the bunching RF frequency). The latter two features are especially important for measurements near threshold because of the rapid variation of the cross section with bombarding energy.

At the Indiana Cooler, several pion production measurements have been carried out [4–6]. In these experiments, only the baryons in the exit channel are observed; the parameters of the pion are then reconstructed from kinematics. As an example, Fig. 2 shows the mass of the unobserved particle in $pp \rightarrow pp\pi^0$, reconstructed event by event from the observed outgoing two protons. Close to threshold, the baryons emerge in a narrow forward cone. Thus, a detector of modest size in the forward direction is sufficient to cover all of the available phase space with the exception of a small region around the beam axis in the center of the detector. Since the target has no windows, and thus contains only the nuclei of interest, there is no competing background from (p,π) reactions on nuclei for which the threshold lab energy is much lower.

### *2.2. Constraints of NN→NNπ, close to threshold*

The typical features of pion production in few-nucleon systems have been summarized in a recent review article [7]; for the present purpose, let me just highlight the main points.

Within the first few 100 MeV above threshold of the reaction NN→NNπ, the angular momentum $L_{\mathrm{NN}}$ in the final (NN) system, as well as the angular momentum $\ell_\pi$ of the pion with respect to the NN pair, are both either 0 or 1. This restriction, together with the Pauli principle, and the conservation of angular momentum, parity and isospin greatly limits the number of partial waves that can contribute to pion production. Furthermore, the energy dependence of the cross section is well described by phase space and centrifugal barrier factors, and the final-state interaction (and, if applicable, the Coulomb repulsion) between the final-state nucleons. The partial waves with the lowest $L_{\mathrm{NN}}$ and $\ell_\pi$ have the weakest dependence on bombarding energy. Thus, as the bombarding energy is lowered, eventually a single partial wave (*e.g.*, $L_{\mathrm{NN}} = 0$, $\ell_\pi = 0$, in short, "*Ss*") will remain and thus dominate the reaction.

## 3. Nuclear targets: pd→pd$\pi^0$ close to threshold

### *3.1. Measurement of the total pd→pd$\pi^0$ cross section*

The two experiments which are discussed in Sections 3 and 4 have been carried out with the same detector system. A schematic view of the experimental setup is shown in Fig. 1. Here, I will only describe the main parts, for more detail, the reader is referred to Refs [6, 7]. A thin front scintillator (F) immediately follows the vacuum chamber that houses the deuterium or hydrogen gas jet target. Two pairs of wire planes, $(u, v)$ and $(x, y)$, are for track reconstruction, a scintillator (E) is thick enough to stop 120 MeV protons. The time of flight is measured between the F and the E detector. We require that a candidate event for pion production has no signal in the veto scintillator (V), since in this case the protons (or deuterons) have not sufficient energy to penetrate the E detector. This apparatus is then used to measure the four-vectors of the outgoing hadrons. From this, the mass of the (unobserved) pion can be calculated and used as event identification. A distribution of reconstructed masses is shown in Fig. 2.

The apparatus also detects pp elastic scattering events. In this case, a signal from the F, E, and V detectors (indicating a forward proton) is

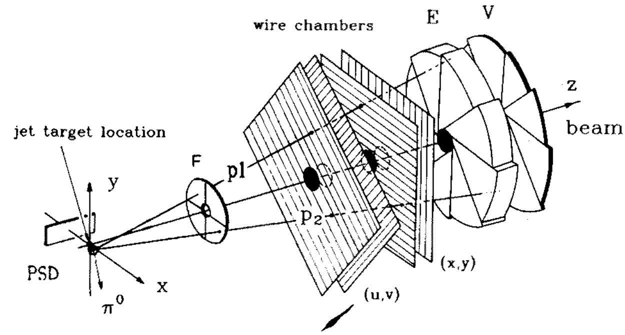


Fig. 1. Schematic view of the detector arrangement. The components are described in subsection 3.1. A typical two-prong event is shown, consisting of two protons $p_1$ and $p_2$ and an unobserved $\pi^0$. The figure is from [4].

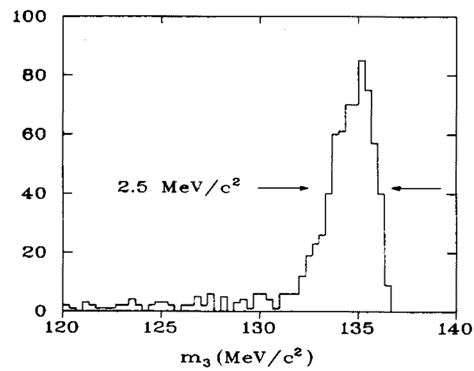


Fig. 2. Mass $m_3$ of the unobserved particle in $pp \to pp\pi^0$, reconstructed event by event from the observed outgoing two protons. The peak is at the $\pi^0$ mass (134.9 MeV/$c^2$). The bombarding energy in this case is 285.0 MeV.

required, in coincidence with a signal from position-sensitive silicon detectors (PSD in Fig. 1) caused by the corresponding, low-energy recoil proton. From the observation of pp elastic scattering (which takes place concurrent with the pion measurement and which has a known cross section) one determines the integrated luminosity. From the observed number of pion events, corrected for a number of experimental effects, then follows the total cross section. The corrections include the effect of the hole in the center of the detector, the fact that the outgoing hadrons may fall into the same detector segment, and various detector efficiencies. Also, at the higher energies the covered angular cone is not quite large enough.

The resulting cross section for $pd \to pd\pi^0$ (solid dots) is shown in Fig. 3 as a function of the customary energy parameter $\eta$. The latter is defined as the largest possible pion center-of-mass momentum (for a given bombarding energy) divided by the pion rest mass. Since threshold occurs at $\eta = 0$ in all channels, this parameter is useful when comparing observables in different channels with each other. The errors are smaller than the size of the symbols except at the highest covered energies.

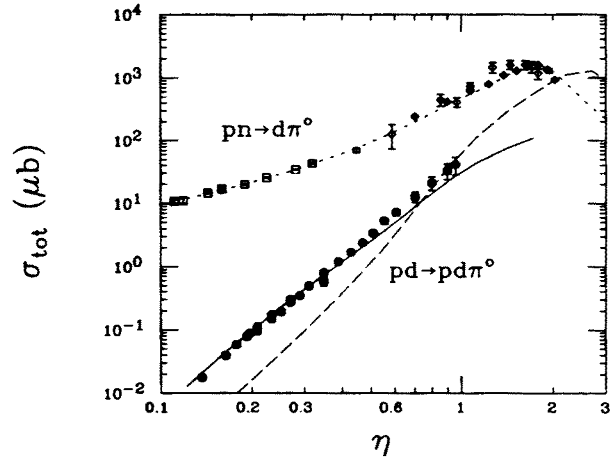


Fig. 3. Total cross section for pd→pd$\pi^0$ (solid dots: [6]) as a function of $\eta = q_{c.m.}/m\pi$. Also shown are the elementary input cross section $\sigma_{II}(\eta) = \sigma(\text{pn}\to\text{d}\pi^0)$ (dotted line), together with available data (squares [9], diamonds [16]), and the pd→pd$\pi^0$ cross section $\sigma_I(\eta)$ calculated according to Eq. (1) (dashed line). The solid curve illustrates the energy dependence with the final-state interaction included. The figure is from [8].

### *3.2. Comparison with a quasi-free pion production model*

One possible model for the reaction pd→pd$\pi^0$ is to assume that the proton in the target deuteron acts as a spectator and that the $\pi^0$ is produced by the elementary pn→d$\pi^0$ reaction, as if the neutron in the deuteron is free. The possible elementary NN channels that can contribute to pd→pd$\pi^0$ are pn→d$\pi^0$, pp→pp$\pi^0$, and pn→pn$\pi^0$. Among these, pn→d$\pi^0$ is expected to be the most important one [8].

Also shown in Fig. 3 is the total cross section for the elementary reaction pn→d$\pi^0$ (open symbols and dotted line [9]) for the same range of $\eta$. One can see that the pd→pd$\pi^0$ cross section is much smaller than the corresponding elementary pn→d$\pi^0$ cross section (at the lowest energy by three orders of magnitude!). It is certainly striking that the addition of a spectator proton should have such a large effect on the pion production cross section, and one is tempted to rule out a quasi-free reaction mechanism.

This problem was investigated in a recent study of quasi-free pion production in the three-nucleon system [8]. In this work, it is assumed that in the process $pd \to pd\pi^0$ the beam proton interacts with the neutron in the target deuteron to form the final deuteron and the $\pi^0$, *via* $pn \to d\pi^0$. It is then possible to express the total cross section $\sigma_I$ ($pd \to pd\pi^0$) in terms of the total cross section $\sigma_{II}$ ($pn \to d\pi^0$). This task can be divided into two parts. First, the amplitude for reaction I has to be related to the amplitude of the subprocess II. Second, the integration over the phase space is carried out. This leads to the expression

$$\sigma_I(\eta_I) = \frac{(2\pi)^{-2}}{\lambda(s, m_p^2, m_d^2)} \int ds_2 dt\, p_p^* \sqrt{s_2} \frac{E'_T E'_B E'_s}{E_n^* E_p^*} |\Phi_d(\vec{\kappa})|^2 \sigma_{II}(\eta_{II}) . \tag{1}$$

The ingredients in this expression arise mainly from relativistic kinematics; the interested reader should refer to [8] for details. The key point, however, is that the integrand is proportional to the deuteron momentum density probability $|\Phi_d(\kappa)|^2$. The argument $\kappa$ is bounded by energy and momentum conservation. In fact, right at threshold, $\kappa$ can have only one specific value. This is understood quite easily. Close to threshold, the reaction products are almost at rest in the center-of-mass system. The spectator proton, true to its nature, is therefore also at rest before the interaction. This determines unambiguously the required momentum $\kappa$ of the neutron in the target deuteron to about $\kappa = 200$ MeV/$c$, where the momentum density in the deuteron is about $10^3$ times lower than at $\kappa = 0$. Thus, the smallness of the $pd \to pd\pi^0$ cross section is qualitatively explained as a "trivial" medium effect, *i.e.*, as a consequence of energy and momentum conservation, and the distribution of Fermi momenta in the target deuteron. A numerical evaluation of Eq. (1) is shown as dashed line in Fig. 3.

For a quantitative comparison with the data the final-state interaction between the outgoing proton and deuteron has also to be taken into account. In a sense, this represents the most important of the true effects of the "nuclear medium". This effect can be included by modifying the matrix element in a manner described by Watson [10]. This procedure yields the energy dependence of the cross section (but not the absolute value). The result of this calculation, with an arbitrary overall normalization, is shown as solid curve in Fig. 3, and represents an excellent description of the energy dependence of the reaction.

We have thus learned that a quasi-free reaction model containing the dynamics of the deuteron provides a fair description of the data, and that, close to threshold, the final-state interaction between the outgoing hadrons is important. This study supports the idea that pion production in nuclei is mediated by short-range, elementary $NN \to NN\pi^0$ interactions, filtered by the properties of the nucleus and by the requirements of the kinematics of the reaction, and modified by distortions in the exit channel. The latter is the only medium modification that can be clearly identified. An attempt to study the effect of the extra proton on the pion production vertex would have to be based on a more careful theoretical treatment and on more detailed experimental information, such as angular distributions and energy spectra.

## 4. Pion production by nucleons

### *4.1. Measurement of the total pp→ppπ⁰ cross section*

The same technique and apparatus that has been described in subsection 3.1. was also used for the measurement of the $pp \to pp\pi^0$ total cross section. Historically, this measurement was in fact the first nuclear physics experiment carried out with the Indiana Cooler. It demonstrated for the first time, and very convincingly, the power and potential of the new technology.

The original aim of the measurement [4] was to study a possible coupling between pion production channels. Since the channels $pp \to d\pi^+$ and $pp \to pn\pi^+$ have thresholds (287.5 MeV and 292.3 MeV, respectively) that lie above the threshold of the measured $pp \to pp\pi^0$ reaction (279.7 MeV), it is conceivable that, as the bombarding energy increases, the opening of the new channels manifests itself as a "cusp", *i.e.*, a departure from a smooth energy dependence. The Cooler with its small beam energy spread ($< 50$ keV) is an ideal tool to search for such structures in the excitation function. The experimental results are shown as a function of the customary energy parameter $\eta$ as solid dots in Fig. 4. The open symbols represent the world's set of data, previous to the IUCF measurement. As can be seen from the figure, the search for a cusp turned out negative, at least on the precision level of the measurement (about 5% of the measured cross section).

These measurements are, to a large part, sufficiently close to threshold so that indeed only a single partial wave contributes. From the energy dependence as well as from the measured angular distributions of the outgoing protons, it is found [4] that this is the case below $\eta = 0.5$. In $pp \to pp\pi^0$ the lowest partial wave is "Ss" where the two final protons are in a $^1S_0$ state and the $\pi^0$ is in an s-state relative to the two protons. Parity and isospin conservation then fixes the incident wave to be $^3P_1$.

### *4.2. Comparison of pp→ppπ⁰ with theory*

For several reasons, the present, near-threshold $pp \to pp\pi^0$ data provide an very stringent test of pion production models. First, with only elementary particles involved, there is little uncertainty from the nuclear

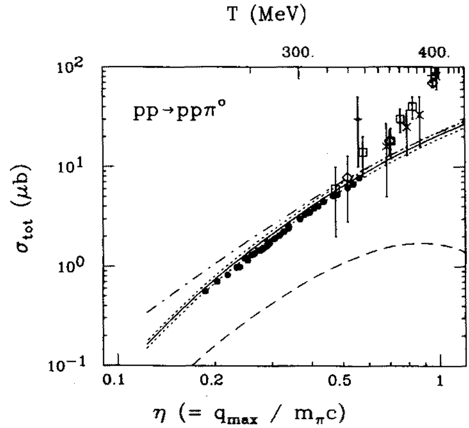


Fig. 4. Total cross section for $pp \to pp\pi^0$ (solid dots: [4]) as a function of $\eta = q_{c.m.}/m_\pi$. The open symbols mark the data from previous experiments. The dashed line shows a calculation with the one-body term (diagram a) of Fig. 5), taking the Coulomb interaction into account. The solid line in addition contains the exchange of heavy mesons (diagram c) of Fig. 5). The dotted lines represent some uncertainties in the calculation and are discussed in the text. The dash-dot line is like the solid line but without the Coulomb interaction. The figure is from [14].

wavefunctions. Second, the interaction between the nucleons can be derived with confidence from a potential model, such as the Bonn potential. Third, only a single partial wave contributes in the entrance channel, as well as the exit channel, and fourth, resonant pion production *via* an intermediate $N\Delta$ state, which is dominating in most $NN \to NN\pi$ channels, is suppressed in this case, as can be seen from the quantum numbers of the reaction.

The energy dependence of the total $pp \to pp\pi^0$ cross section is well understood in terms of phase space factors and of the contribution of the final-state interaction between the outgoing protons. Thus, the only energy dependence of the matrix element between threshold and $\eta = 0.5$ is from the NN interaction, and the "non-trivial" information contained in the data is just the size of that matrix element (a single number).

A number of calculations using the single-nucleon axial-charge operator, corresponding to diagram a) in Fig. 5, have been carried out with various choices for the NN distorting potential [4, 11–14]. Quite surprisingly, these calculations all underestimate the data by about a factor of five! An example of such a single-nucleon calculation [14] is shown in Fig. 4 as dashed line.

In an effort to explain the large discrepancy between the data and the one-body mechanism, the contributions from production mechanisms that

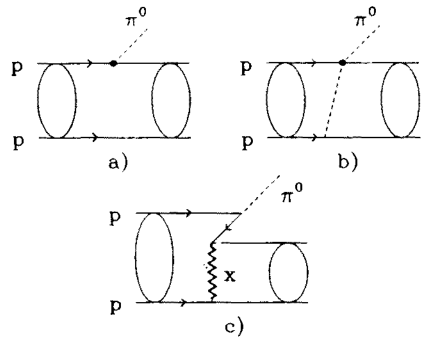


Fig. 5. Contributions to the reaction pp→pp$\pi^0$. Shown are (a) the one-body term, (b) the two-body term that arises from rescattering, and (c) the two-body term that arises from the exchange of heavier mesons. The figure is from [14].

involve both nucleons have been investigated. For instance, contributions from rescattering (diagram b) in Fig. 5) have been studied as a possible two-body mechanism. It has been found, however, that rescattering could never account for the large discrepancy, mainly due to the smallness of the iso-scalar $\pi$N amplitudes. For these studies a simple, on-shell model was used for the $\pi$N interaction. Future work will have to address the question whether off-shell effects could possibly make rescattering an important contribution to the reaction cross section.

Recently, Lee and Riska [15] have suggested that the axial charge which is responsible for $s$-wave pion production could be enhanced in nuclear system, over and above the single-nucleon contribution. Such an enhancement would be caused by the exchange of heavy mesons as shown in diagram c) of Fig. 5. This purely relativistic process is an inherently small contribution. However, the one-body part of pp→pp$\pi^0$ is suppressed due to the large momentum mismatch; in addition, rescattering and resonant production are also suppressed. Thus, heavy meson exchange can become important because it competes with a small cross section.

In a recent study of meson exchange contributions to pp→pp$\pi^0$ [14], the contributions from diagram c) in Fig. 5 were evaluated in a way that is consistent with the meson exchange parameters of the distorting Bonn potential. It was found that the main contributions to diagram c) come from the exchange of $\sigma$ and $\omega$ mesons. The amplitude that corresponds to $\sigma$ and $\omega$ exchange is even larger than the one-body amplitude. When this meson-exchange mechanism is included, an excellent description of the data is achieved (solid line in Fig. 4). The band around the solid line (indicated by dotted lines) represents the combined uncertainty from the $\pi$NN coupling constant ($0.075 \pm 0.003$), and from a possible non-zero rescattering term.

The latter depends on the $\pi$N scattering length and is constrained by pionic hydrogen data (see [14]). The dot-dash curve demonstrates the effect of neglecting the Coulomb interaction. Note, that the calculation also explains the energy dependence well, in agreement with the earlier statement that phase space and the low-energy behavior of the NN interaction are the only energy-dependent factors.

At present, heavy meson exchange is the only known physics ingredient that leads to agreement with the experiment. Provided that the study of off-shell rescattering will not change this situation, we can thus state that the near-threshold $pp \to pp\pi^0$ data constitute the first direct experimental evidence of an enhancement of the axial charge in nuclear systems.

## 5. Conclusions, future possibilities

The study of pion production is particularly interesting *near threshold*, where conservation laws severely restrict the number of participating angular momentum states, and in *few-nucleon systems* where the nuclear wave functions and the distortions are well described and where there is little freedom in the theoretical treatment.

Pion production in the bombardment of a "nucleus" by protons has been studied in the three-nucleon system $pd \to pd\pi^0$. This is an important stepping stone on the way to understand pion production (and absorption) in nuclei. The results are described well in terms of a quasi-free production model and the p+d final-state interaction. The effect of the "medium" (in this case, the presence of one spectator proton) is drastic, but it arises from conservation laws and the availability of the necessary Fermi momentum of nucleons in the target. There is no indication yet that the production vertex is sensitive to the presence of the extra nucleon, and a better understanding of the elementary NN production channels is required, before the effect of the medium on pion production can be investigated.

In the reaction channel $pp \to pp\pi^0$ where rescattering and resonant production via an intermediate $N\Delta(1232)$ state is suppressed, we have found that we become sensitive to new physics, in this case an enhancement of the axial charge in a system with more than one nucleon. Here, it seems that the imposed large momentum transfer causes a greater sensitivity to the short-range part of the NN interaction than what one would get by raising the bombarding energy. It may well turn out that pion production near threshold is one of the most important and direct tests of our understanding of the coupling of the meson field to the nucleon.

The necessary experimental accomplishment of measuring high-quality data very close to threshold has been made possible to a large part by the use of stored, electron-cooled beams with thin internal targets. Future experiments will make use of fact that this new technology not only allows the use of polarized beams, but also makes feasible the use of windowless, internal, polarized targets that are produced by an atomic beam source. To overcome the severe limits in production rate of polarized $\vec{H}$ atoms ($< 3.5 \cdot 10^{16}$ atoms/s) by such sources, a buffer cell is used to increase the dwell time of target atoms near the beam. Such targets are free of impurities and immune to radiation damage. Polarized hydrogen target thicknesses of $10^{13} - 10^{14}$ atoms/cm$^2$ have been demonstrated.

In a storage ring with only vertical magnetic fields, a vertically polarized beam is stable. Non-vertical fields do not destroy the beam polarization, but they affect the direction of the spin alignment axis at a given point along the trajectory. This can be turned to the advantage of an experiment by using longitudinal magnetic fields, produced by solenoids, to establish sideways or longitudinal beam polarization at the target location.

In the near future, measurements of polarization observables near threshold will become possible, and are in fact planned at the Indiana Cooler. This will provide additional information on individual pieces of the interaction, and hopefully will, in conjunction with a complementary theoretical effort, shed more light on this fundamental process in nuclear physics. For instance, with polarized beam and target, the spin-dependent total cross sections $\Delta\sigma_L$ and $\Delta\sigma_T$ can be measured. They are defined as the difference between the cross section with the nucleon spins antiparallel minus that with the spins parallel, with both spins either along the beam axis (L), or transverse (T). Such data, in conjunction with the unpolarized total cross section $\sigma_{\rm tot}$, provide direct information on the magnitude of next higher individual partial waves [7]. Such a measurement for pp→pp$\pi^0$ is technically within reach and is planned at the IUCF Cooler. This will allow us to separate the $(L_{\rm NN}\ell_\pi)$ Ps and Pp contributions to the pp→pp$\pi^0$ process between 300 MeV and 400 MeV bombarding energy.

In particular, the Gamov-Teller transition to a Pp final state is of interest. A possible enhancement of the axial current in Gamov-Teller transitions would affect the calculated cross section of the pp→de$^+\nu$ reaction (which is too small to measure). The temperature in the interior of the sun depends on that cross section. In turn, neutrino production depends on the solar temperature. It may thus even turn out that a study of pion production near threshold has a bearing on the solar neutrino problem.

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