Measurement of the Near-Threshold $H(\pi^+,\pi^+\pi^+)n$ Cross Section and Chiral Symmetry

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Total cross sections for the $H(\pi^+,\pi^+\pi^+)n$ reaction have been measured at pion kinetic energies of 180, 184, 190, and 200 MeV. The threshold value for the matrix element $a(\pi^+\pi^+)$ and the s-wave, isospin-2, $\pi\pi$ scattering length a_2^0 were determined. The results were found to be in agreement with chiral perturbation theory and inconsistent with the model of dominance by quark loop anomalies.

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Investigations of the underlying symmetries of quantum chromodynamics (QCD) have led to the belief that the chiral-symmetry-breaking formalism developed by Weinberg[1] is the low-energy manifestation of QCD.[2] Chiral perturbation theory (ChPT) extends the original Weinberg theory by including rescattering effects between interacting mesons. For the $\pi\pi$ system Gasser and Leutwyler[3] have made ChPT predictions for the s-wave, isospin-0 and isospin-2 scattering lengths, namely, $a_0^0=(0.20\pm0.01)m_\pi^{-1}$ and $a_2^0=(-0.042\pm0.002)m_\pi^{-1}$. Ivanov and Troitskaya[4] have used the model of dominance by quark loop anomalies (QLAD) to predict $a_0^0=0.20m_\pi^{-1}$ and $a_2^0=-0.060m_\pi^{-1}$. This model attributes $\pi\pi$ rescattering effects to σ exchange.

Experimental data for a_2^0 are very sparse. The most precise value to date was obtained from a measurement of the K_{e4} decay parameters by Rosselet *et al.*[5] and was found to be $a_2^0=(-0.028\pm0.012)m_\pi^{-1}$ (a 43% uncertainty). Near threshold, the angular momentum barrier limits the significant Feynman diagrams for the $H(\pi^+,\pi^+\pi^+)n$ reaction to virtual $\pi\pi$ scattering and the contact interaction since these are the only possible s-wave processes. As a result, at threshold the total cross section is determined by the s-wave isospin-2 scattering length a_2^0 and the contact interaction.

Olsson and co-workers[6] have derived the following relationship between a_2^0 and $a(\pi^+\pi^+)$ by means of an effective-Lagrangian model which relates the total cross section at threshold to a_2^0 (with $f_\pi=93.3$ MeV): $a(\pi^+\pi^+)=20.8a_2^0-0.243m_\pi^{-1}$, where $a(\pi^+\pi^+)$ is the reduced matrix element of the threshold value of the cross section (σ) for $H(\pi^+,\pi^+\pi^+)n$ and is given by $\sigma=a(\pi^+\pi^+)^2\times1.28\times10^{-5}T^{*2}P_{\text{c.m.}}$ μb, where T^* is the energy above threshold in the center of mass and $P_{\text{c.m.}}$ is the center-of-mass momentum of the incident pion.

In this formalism the strength of the $\pi\pi$ interaction is characterized by the chiral-symmetry-breaking parameter ξ as derived by Olsson and Turner.[6] Then a_0^0 and a_2^0 can be determined from ξ via the relations $a_0^0=(0.156-0.0560\xi)m_\pi^{-1}$ and $a_2^0=(-0.045-0.0224\xi)m_\pi^{-1}$, with $f_\pi=93.3$ MeV. When $\xi=0$, the theory is equivalent to lowest-order ChPT. Olsson and Turner believed that a single value of ξ would determine a_0^0 and a_2^0 uniquely; however, they ignored the $\pi\pi$ rescattering effects incorporated in the ChPT and QLAD approaches.[3,4] Since $\pi\pi$ scattering in the $H(\pi^+,\pi^+\pi^+)n$ reaction is purely isospin-2, one may use ξ as a phenomenological parameter to determine a_2^0. This is because both ξ and a_2^0 parametrize the strength of the $\pi\pi$ interaction, the only unknown amplitude of the $H(\pi^+,\pi^+\pi^+)n$ reaction near threshold. Thus, within the framework of effective Lagrangians, the value of a_2^0 can be determined by fitting ξ to the measured cross sections.

A more detailed microscopic model of the $H(\pi^+,\pi^+\pi^+)n$ reaction that includes the effects of Δ reaction mechanisms has been developed by Oset and Vicente-Vacas.[7] The authors confirm that the effects of Δ interactions are small below 200-MeV incident pion kinetic energy.

Recently, the OMICRON group published cross sections for $H(\pi^-,\pi^-\pi^0)p$ and $H(\pi^+,\pi^+\pi^+)n$.[8] Near threshold, both these reactions are dominated by the isospin-2 amplitude. Their results are $a_2^0=(-0.05\pm0.02)m_\pi^{-1}$ and $a_2^0=(-0.08\pm0.01)m_\pi^{-1}$ for $H(\pi^-,\pi^-\pi^0)p$ and $H(\pi^+,\pi^+\pi^+)n$, respectively. The latter measurement is inconsistent with the K_{e4} result, which is almost a factor of 3 smaller. However, if the OMICRON result of $a_2^0=-0.08m_\pi^{-1}$ were confirmed it would be a major blow for ChPT, which predicts a value some 20 standard deviations closer to 0.

The aim of this experiment was to measure the total cross section for $H(\pi^+,\pi^+\pi^+)n$ to a precision of 14% at energies where the effects of Δ interactions are small, i.e., at $T_\pi \leq 200$ MeV. This precision will easily distinguish between the OMICRON and K_{e4} results. Of course, the most direct test of ChPT would be to use ChPT to make a full prediction for $a(\pi^+\pi^+)$ rather than a_2^0. These calculations are in progress.[9]

The experiment was carried out on the M11 pion channel at TRIUMF and employed a novel technique to make this near-threshold measurement. Data were accumulated at incident pion energies of 200, 190, 184, 180, and 172 MeV. The latter energy was used to determine backgrounds since the threshold for $H(\pi^+,\pi^+\pi^+)n$ is 172.3 MeV. The beam was defined by three 2-mm-thick scintillators of cross-sectional dimensions 80×80 mm^2, 20×20 mm^2, and 80×80 mm^2, respectively, and coincidences between all three scintillators were counted as beam events. The typical beam rate was 1.7 MHz and the momentum spread of the pion beam was $\pm0.1\%$ of the central value. Pions were distinguished from positrons by their time of flight through the M11 channel. The positron contamination was typically 0.8% of the pion flux which was corrected accordingly. Another correction of $1.2\% \pm 1.2\%$ was applied to the measured beam flux to account for muon contamination as determined from previous studies of the M11 channel.[10] The target consisted of a set of 5 PILOT U plastic scintillators (chemical compound $CH_{1.1}$), each of dimensions $40\times40\times6$ mm^3 and placed in a stack along the beam. Another $80\times80\times2$-mm^3 scintillator was located behind the target and was used as a veto counter to define beam interactions in the target. The scintillator target was used to detect stopped π^+'s from the $H(\pi^+,\pi^+\pi^+)n$ reaction. A large-volume scintillator bar array was positioned 2.6 m downstream at 0° to detect the reaction neutrons. The array consisted of sixteen bars of dimensions $12.5\times10.0\times100.0$ cm^3 arranged as two rows of eight bars. The pion beam was swept away from the bars by a clearing magnet placed between the target and the array.

The experimental setup exploited the restrictive kinematics of the $H(\pi^+,\pi^+\pi^+)n$ reaction near threshold to suppress background reactions such as $^{12}C(\pi^+,\pi^+n)X$. The kinematics forced the reaction neutrons to be emitted into a narrow cone around 0° and to lie in the energy range of 15–50 MeV. Thus the neutron bars placed at 0° intercepted a large fraction of the reaction neutrons while subtending less than 1% of the solid angle around the target.

Positive pions which stopped in the target were identified by a large prompt pulse from the π^+ energy loss, followed by a second pulse corresponding to the characteristic decay sequence $\pi^+ \to \mu^+ + \nu_\mu$. Three requirements were imposed to detect these signals from the scintillators. The first employed a custom-built hardware circuit to detect the presence of two pulses closely spaced in time. This circuit could detect muons which arrived as little as 7 ns after the prompt pulse. The second method used two charge-integrating analog-to-digital converters with short (15 ns), and wide (80 ns) gates to separately view the output of each scintillator. The difference between the normalized outputs showed the presence of a decay. The third and most powerful technique was to use a Tektronics 2440 digital oscilloscope as a 500 megasample per second transient digitizer. The efficiency for detecting stopped pions was established from calibration runs during which low-energy positive pions from M11 were stopped in each segment of the active target.

The trigger for data acquisition was a pion interaction in the target in coincidence with a neutron detected in the neutron bars, a second pulse detected with the hardware circuit, and no other beam pion within 80 ns of the interaction event.

The detection efficiency of the neutron bars was determined by stopping low-energy π^- particles in liquid-deuterium and liquid-hydrogen targets thus initiating the reactions $\pi^- d \to n+n$ and $\pi^- p \to \gamma + n$. These two reactions have well measured branching ratios and therefore provide calibrated sources of monoenergetic neutrons (68 and 8.8 MeV) at energies above and below the neutron energy range of the threshold $H(\pi^+,\pi^+\pi^+)n$ reaction. We combined these two absolute calibration points with a Monte Carlo code to obtain the detection efficiency of the bars as a function of neutron energy. The weighted average neutron detection efficiency was $(33\pm3)\%$.

Another Monte Carlo code was used to determine the total acceptance of the experiment with the assumption that the reaction followed three-body phase space. This assumption is justified because the data were taken very close to threshold where s-wave processes dominate. The fraction of the full 4π solid angle intercepted by our apparatus varied as a function of energy because of the kinematics of the $H(\pi^+,\pi^+\pi^+)n$ reaction. It was determined by our Monte Carlo acceptance code to be 18.1%, 35.6%, 58.2%, and 74.6% at $T_\pi = 200$, 190, 184, and 180 MeV, respectively.

The response of the active target was calibrated with events due to single passing pions, which deposit 1.25 MeV in each 6-mm scintillator as well as beam bursts containing two pions, giving 2.5 MeV.

To analyze the data we added the energy deposited in the active target to the neutron energy, as determined by time of flight, to form the total kinetic-energy sum (T_{sum}) of the detected reaction products. T_{sum} is equal to $T_\pi - m_\pi - (m_n - m_p)$ for the $H(\pi^+,\pi^+\pi^+)n$ reaction. The yield of the reaction was given by the peak area in the T_{sum} histogram less the background contribution.

Two techniques were used to extract yields from the raw data. The first required at least one pion to be detected in the active target. This trigger has a substantial background from $^{12}C(\pi^+,\pi^+n)X$ which was suppressed by restricting the active target and neutron energies to the kinematic range allowed for the $H(\pi^+, \pi^+\pi^+)n$ reaction. The remaining background was determined by a fit of the T_{sum} spectral shape of lower-energy runs [where the yield of $H(\pi^+,\pi^+\pi^+)n$ was substantially less and different in T_{sum} than the run considered] to the regions in the T_{sum} histograms above and below the $H(\pi^+,\pi^+\pi^+)n$ peak. We found yields from this "one-pion" analysis of 742 ± 100, 700 ± 90, 580 ± 70, and 160 ± 30 events at $T_\pi=200$, 190, 184, and 180 MeV, respectively. The errors quoted are due to the estimated uncertainty in the background normalization. The total experimental acceptance was determined from the Monte Carlo code and, after including geometric effects as well as the neutron and stopped-pion detection efficiencies, was found to be 4.0%, 6.2%, 12.4%, and 13.2% at $T_\pi=200$, 190, 184, and 180 MeV, respectively.

The second analysis method required the identification of two π^+'s in two different scintillators. This extra requirement substantially reduced background events. The final yields for this "two-pion" analysis were obtained from these histograms by restricting the target-scintillator and neutron energies to the kinematic range allowed for the $H(\pi^+,\pi^+\pi^+)n$ reaction, and then subtracting background. The two-pion analysis method gave us 124 ± 11, 74 ± 8, 65 ± 8, and 8 ± 3 events at $T_\pi=200$, 190, 184, and 180 MeV, respectively. Figure 1 shows histograms for T_{sum} at $T_\pi=200$ and 184, obtained

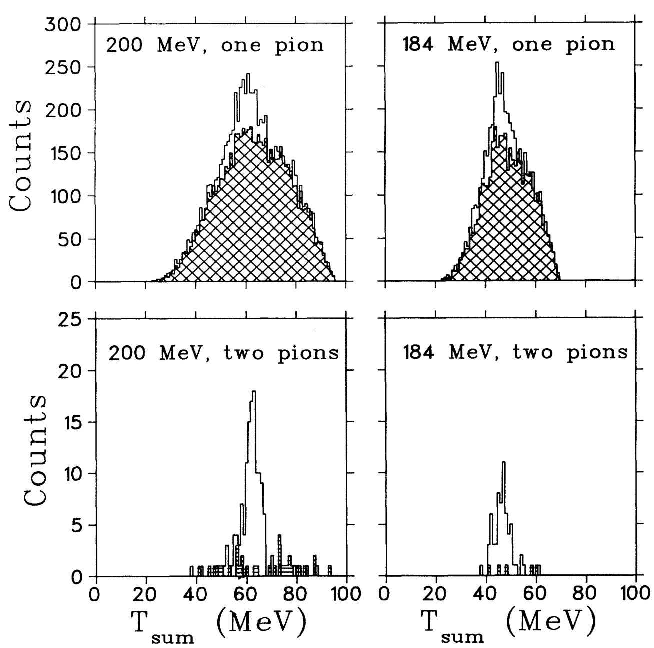

FIG. 1. The histograms for T_{sum} at $T_\pi=200$ and 184 MeV for the one-pion and two-pion analysis techniques with the neutron and target-scintillator energies required to be in the allowed ranges for the $H(\pi^+,\pi^+\pi^+)n$ reaction. Also shown superimposed as the hatched regions are background data from $^{12}C(\pi^+,\pi^+n)X$ reactions that fulfill the same requirements.

TABLE I. Total cross sections and reduced matrix elements for $H(\pi^+,\pi^+\pi^+)n$. The uncertainties quoted are the quadratic sum of statistical and systematic errors.

T_π (MeV)	One pion (μb)	Two pion (μb)	Averaged (μb)	$\lvert a(\pi^+\pi^+)\rvert$ (m_π^{-1})
200	1.4 ± 0.24	1.5 ± 0.25	1.46 ± 0.22	1.05 ± 0.08
190	0.58 ± 0.12	0.62 ± 0.12	0.60 ± 0.10	1.08 ± 0.08
184	0.29 ± 0.05	0.26 ± 0.05	0.28 ± 0.05	1.11 ± 0.09
180	0.13 ± 0.04	0.08 ± 0.03	0.11 ± 0.03	1.08 ± 0.15

from both the one-pion and two-pion analysis methods after restricting the target-scintillator and neutron energies to the allowed kinematic ranges. Also shown superimposed are the background data for each energy and analysis technique. Once again the acceptance was determined from the Monte Carlo code and was found to be 0.69%, 0.57%, 1.58%, and 1.05% at $T_\pi=200$, 190, 184, and 180 MeV, respectively. These acceptances are much smaller than for the one-pion analysis because the two-pion analysis required the detection of two pions in two different scintillators.

The yield of the reaction is extremely sensitive to T_π since the total cross section is proportional to $P_{c.m.}T^{*2}$. Consequently, care was taken to calibrate the central energy of the M11 beam line and to account for the decrease in yield as the beam lost energy through the target. We estimated the uncertainty in the M11 beam energy to be ±0.3 MeV which corresponds to effective cross-section uncertainties of 2%, 4%, 6%, and 10% at 200, 190, 184, and 180 MeV, respectively.

The total cross sections and reduced matrix elements for $H(\pi^+,\pi^+\pi^+)n$ are listed in Table I and are displayed in Fig. 2. The data have been corrected for

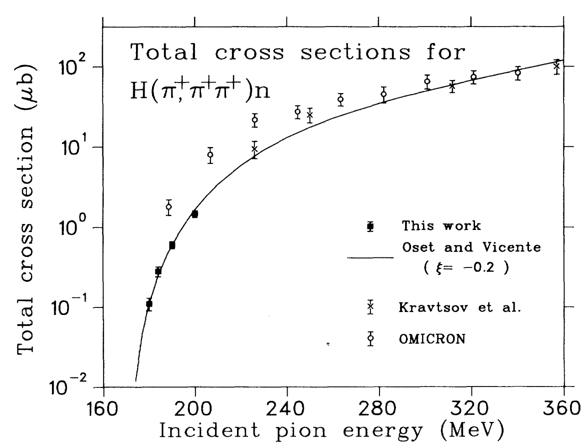

FIG. 2. Total cross sections as a function of pion bombarding energy for the $H(\pi^+,\pi^+\pi^+)n$ reaction. The curve is the Oset and Vicente calculation of the cross section with $\xi = -0.2$. The value of $\xi = -0.2$ was obtained from a fit to the data of the present experiment only.

Coulomb interactions by means of the prescription given by Bjork *et al.*[11] This increased the cross section by 5%, 7%, 8%, and 9% at 200, 190, 184, and 180 MeV, respectively. We found that the two analysis methods agree within their error bars, which lends confidence to both the Monte Carlo acceptance calculations and the π^+ detection efficiencies. For example, an error of 10% in the π^+ detection efficiency results in a 7% shift in the final cross section from the one-pion analysis but a 23% change from the two-pion analysis. The systematic uncertainties associated with the measurement were the following: neutron detection efficiency (10%), beam flux (2%), target thickness (3%), beam energy (2%, 4%, 6%, and 10% at 200, 190, 184, and 180 MeV, respectively), and experimental acceptance (5% and 10% for the one-pion and two-pion analysis methods, respectively). The experimental acceptance uncertainties include the uncertainties in the π^+ detection efficiency. The underlying matrix elements show no significant energy dependence, so the threshold value for $a(\pi^+\pi^+)$ can be obtained from a weighted average of the four values. We obtain $|a(\pi^+\pi^+)| = (1.08 \pm 0.07) m_\pi^{-1}$ and hence $a_2^0 = (-0.040 \pm 0.003) m_\pi^{-1}$. We choose this root because the other leads to $a_2^0 = 0.063 m_\pi^{-1}$, in disagreement with phase-shift analyses of $H(\pi^+,\pi^+\pi^+)n$ at higher energies that show a_2^0 is negative.[12] We also fitted our cross-section data with the model of Oset and Vicente-Vacas by treating ξ as a free parameter. The result was a value of $\xi = -0.2 \pm 0.15$ (assuming $f_\pi = 93.3$ MeV), and so $a_2^0 = (-0.041 \pm 0.003) m_\pi^{-1}$. The uncertainty of 0.15 in ξ comes from the uncertainty in the overall normalization of the cross sections.

Figure 2 shows that the extrapolated fit to our data is in good agreement with the results of Kravstov *et al.*[13] obtained from the $D(\pi^-,\pi^-\pi^-)nn$ reaction, and also with the data of OMICRON above 280 MeV. However, the lower-energy data points of OMICRON are substantially larger than both the Kravstov *et al.* data and our results. This discrepancy is much larger than the assigned uncertainties of both experiments and leads to the exceptionally large value for a_2^0 reported by the OMICRON group.

To summarize, our data give a threshold value of $|a(\pi^+\pi^+)| = (1.08 \pm 0.07) m_\pi^{-1}$ and, within the framework of effective Lagrangian models, imply a value for a_2^0 of $(-0.040 \pm 0.003) m_\pi^{-1}$. This value for a_2^0 is in agreement with Gasser and Leutwyler's prediction of -0.042 ± 0.002 and the K_{e4} measurement of -0.028 ± 0.012 and is inconsistent with the QLAD prediction of -0.060 and the OMICRON result of -0.08 ± 0.01. It will be very interesting to compare the forthcoming ChPT calculations[9] for $a(\pi^+\pi^+)$ with these measurements and so make a direct test of ChPT.

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