Systematics of proton-induced pion production at subthreshold energies

H. W. Wilschut, M.-J. van Goethem, H. Löhner, and R. W. Ostendorf
Kernfysisch Versneller Instituut, Zernikelaan 25, NL-9747 AA Groningen, The Netherlands
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A compilation of available data on proton-induced pion production is presented for the subthreshold region $E_{\mathrm{proton}} \leqslant 275$ MeV. In this energy range the transition from coherent to quasifree pion production occurs and can be studied by observing the dependence on nuclear structure and proton beam energy. Large variations in the pion cross sections were found. Within a single data set the variations can be accounted for on the basis of energy (phase space) and isospin dependence. A scaling procedure was derived to relate the production probabilities of π^+, π^0, and π^- as functions of target mass and proton beam energy. A comparison of data sets obtained by different authors shows inconsistencies that appear to a certain extent to be of experimental origin.

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I. INTRODUCTION

Pion production in proton-nucleus reactions at subthreshold energies, i.e., at energies well below the threshold for production in nucleon-nucleon reactions ($E_{\mathrm{proton}} \approx 275$ MeV), has been investigated with a variety of motivations. Initially the large momentum mismatch at subthreshold energies and the coherent production mechanism were of interest. For example, the energy dependence of pionic fusion was measured near the absolute threshold, populating specific final states [1]. With increasing proton energy a quasifree or incoherent process such as in the intranuclear cascade approach (e.g., Ref. [2]) should become dominant. By observing the cross section dependence on target mass, the yield ratios $\sigma_{\pi^+}:\sigma_{\pi^0}:\sigma_{\pi^-}$, and the dependence on beam-energy, the production mechanism at subthreshold energies can be studied in detail. Few data are available for such a program. Moreover, we will show that the existing data sets are not consistent with each other. Recently the CHIC Collaboration measured at CELSIUS the first complete excitation functions for π^+ production [3,4] on a number of targets. However, including the data on pionic fusion, we find that the combined data sets imply an energy dependence that is discontinuous. In addition, the first comparison at subthreshold energies between inclusive charged and neutral pion cross sections [5] leads to the surprising result that $\sigma_{\pi^0} > \sigma_{\pi^+}$, contrary to expectations based on isospin. In view of these unexpected results, it is necessary to consider the dependence on target and beam energy of charged and neutral pion production in more detail and to evaluate to what extent the various data available in the literature can be combined to obtain a consistent data set. This is a prerequisite for a theoretical description of pion production cross sections. In this work we consider pion production from ^{12}C and ^{14}N for which the beam energy dependence has been investigated most extensively. The mass dependence of pion production is evaluated near 200 MeV beam energy where the cross section for all pion species has been measured on a variety of targets. We find a strong dependence on the pionic fusion Q value. Together with the observed beam energy dependence of pion production, the strong target to target variations in the pion cross sections can be described empirically. Also, the isospin dependence can be described using a simple isobar model. Altogether, this provides a method to scale pion production data obtained for different targets and energies. Using this scaling it is possible to show the extent of the inconsistencies between the various data sets. A sharp dip in the π^+ cross section is found for the ^{12}C and ^{14}N targets near the absolute π^- threshold. However, the data in this energy region originate from independent measurements, which may indicate an experimental origin of this anomaly.

II. EXCITATION FUNCTIONS

First we consider the excitation function for proton-induced pion production on ^{12}C and ^{14}N targets. All data points are listed in Table I.

We start with the π^+ production. Particularly relevant are the results of Soga *et al.* [1]. These authors have measured the energy dependence of the population of final states in ^{13}C. For the lowest proton beam energies all kinematically allowed final states have been measured and the corresponding angular distributions have been obtained as well. With this the inclusive pion cross section was determined. An important aspect of the work of Soga *et al.* is that they have established the dominance of the population of $2p$-$1h$ states in the final nucleus. A particularly useful set of data was obtained by Marrs, Pollock, and Jacobs [6,7]. Their π^+ cross sections are based on the observation of μ^+ decay. This work provides the lowest energy point for π^+ production for several targets including both ^{12}C and ^{14}N. These data have the distinct advantage that they are independent of emission angles and energies of the parent pion. The most extensive excitation function was measured by the CHIC Collaboration. These data have been obtained with range telescopes to measure the pions. Two points in this energy domain were measured with a magnetic spectrograph in Orsay [8], and include π^- cross sections.

The π^0 cross section has been measured with photon spectrometers, identifying the neutral pion from its invariant mass. This is derived from the energy and angle of the two decay photons. The lowest energy point measured was just 2 MeV above the absolute threshold [9]; the two other measurements are the new TAPS data at 190 MeV [10,11] and the 200 MeV data of Bellini *et al.* [5].

A notable result is the consistent measurement of ^{13}C and

TABLE I. Collection of all the data points used for the excitation function for pion production shown in Fig. 1. The last two columns summarize the experimental method and the references, respectively.

E_p (MeV)	σ (μb)	Method	Ref.
		$p+{}^{12}C \rightarrow \pi^+$	
150.1	0.050 ± 0.025	μ-decay	[6]
151.1	0.085 ± 0.025	μ-decay	[6]
152.2	0.17 ± 0.025	μ-decay	[6]
154.7	0.65 ± 0.04	μ-decay	[7]
156	1.5 ± 0.2	magnetic spect.	[1]
159	2.4 ± 0.2	magnetic spect.	[1]
166	5 ± 1	magnetic spect. [a]	[1]
180	4 ± 1	magnetic spect.	[8]
201	63 ± 7	magnetic spect. + range telescope	[8]
		$p+{}^{12}C \rightarrow \pi^0$	
146.87	0.0732 ± 0.0032	Lead-glass array	[9]
153.5	0.192 ± 0.008	Recoil detection [b]	[12]
189	21 ± 5	BaF_2 spectrometer [c]	[10,11]
200	70 ± 7	Lead-glass telescope array	[5]
		$p+{}^{14}N \rightarrow \pi^+$	
143.5	0.075 ± 0.008	μ-decay	[6]
144.6	0.095 ± 0.010	μ-decay	[6]
147.0	0.22 ± 0.02	μ-decay	[6]
148.6	0.56 ± 0.06	μ-decay	[7]
152.2	1.9 ± 0.2	μ-decay	[6]
173.1–500	exc. fct.	range telescopes	[3]

[a]Spectrum incomplete, data for $E_x \leqslant 9.50$ MeV only.
[b]Only the ground state has been measured, i.e., this value is a lower limit.
[c]The average of two independent measurements; the error indicates the assumed systematic uncertainty.

${}^{13}N$ recoils from pionic fusion producing π^+ and π^0, respectively [12]. The ${}^{13}N$ data correspond to the population of the ground state, as this is the only bound state of ${}^{13}N$. This result has been included as a lower-limit cross section. These cross sections are also relevant because the ground states of the mirror nuclei ${}^{13}C$ and ${}^{13}N$ should be populated in accordance with isospin symmetry. This is indeed observed if one compensates for the difference in Q value by an equivalent change in the beam energy.

The excitation functions for pion production from ${}^{12}C$ and ${}^{14}N$ are shown in Fig. 1. The data for ${}^{14}N$ have been scaled by a factor $(12/14)^{2/3}$ according to the mass dependence discussed in the next section. We show the data as function of the energy available to the pion, i.e., $E_{c.m.}-E_{threshold}$, which is the center of mass energy minus the absolute threshold energy for pion production. In terms of proton beam energy T the threshold $T_{threshold}$ is given by

$$T_{threshold}=\frac{(M_{recoil}+m_{\pi^0})^2-(M_{proton}+M_{target})^2}{2M_{target}}. \qquad (1)$$

With this the available c.m. energy is given in good approximation by

$$E_{c.m.}-E_{threshold}\approx\frac{M_{target}}{M_{recoil}+m_{\pi}}(T-T_{threshold}). \qquad (2)$$

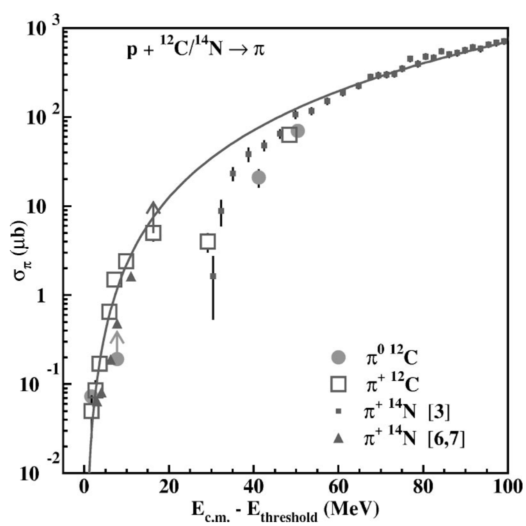

FIG. 1. The energy dependence of subthreshold pion production by protons incident on a ${}^{12}C$ target. The carbon data points are from the different sources. They are listed in Table I. The excitation function for the ${}^{14}N$ target combines the μ^+ measurements of Refs. [6,7] and the direct measurement of Ref. [3]. The two data sets are indicated separately. Both are scaled as described in the text. The solid line assumes a power law dependence with an exponent $\lambda = 2.5$. Incomplete measurements are indicated as lower limits.

With this scale one takes into account the dependence on the ground state to ground state Q value of the reaction. This procedure is well established at energies near the absolute threshold, e.g., by the comparison of the ground state population of ^{13}C (π^+) and ^{13}N (π^0) mentioned above.

At the lowest beam energies the pion cross sections show a rapid monotonic increase up to about 20 MeV available energy. Although these points are the result of individual measurements using very different techniques, the data appear to be quite consistent with each other. Above 20 MeV the cross section data again increase smoothly with only little scatter. However, to connect these two data regions the data would have to drop suddenly near 20 MeV available energy. This is observed for the data obtained both with ^{12}C and ^{14}N targets. Because the data above 20 MeV have been measured without explicit focus on very small cross sections and low pion energies, the observed discontinuity may be of experimental origin. A physical origin of the discontinuity can not be excluded: the opening of the isospin $T=3/2$ channel, where π^- production starts, occurs near the energy of the discontinuity. However, a mechanism that leads to strong absorption of the π^+ and π^0 mesons at this threshold has not been discussed in the literature. Also an enhanced π^- cross section has not been observed.

In the next section we will discuss the target mass dependence of pion production, which requires the comparison of cross sections at various beam energies and with different Q values. To eliminate to first order the dependence on available energy, we parametrize the global behavior of the excitation function, ignoring the discontinuity. We assume a smooth energy dependence of the form $\sigma_\pi = a(E_{\text{c.m.}} - E_{\text{threshold}})^\lambda$. We choose $\lambda=2.5$ and a is a free parameter adjusted to describe the π^+ excitation function at high energy. The dependence obtained this way is given by the solid line in Fig. 1. It describes the π^+ data both at low and high energy, but of course not in the energy region where the discontinuity has been found. The available π^0 cross sections also included in Fig. 1, follow closely the energy dependence found for π^+. This is to be expected as the production probability for π^0 should be at most 50% of the probability for π^+ for these targets on basis of isospin invariance. Other mechanisms will only reduce the difference (see below).

Here we do not seek further justification for the observed energy dependence. The power-law parametrization is only used to discuss the mass dependence. It removes the bias from the Q-value differences.

III. MASS DEPENDENCE

We consider the target mass dependence of the various pion production cross sections at beam energies near 200 MeV, where most experiments have been carried out. It is important to take into account the different Q values for the various pion and target combinations. Typically the variation is of the order of 20 MeV, which is significant in view of the energy dependence discussed previously. As we include targets with higher atomic number we also take the pion Coulomb barrier V_C into account. Therefore all cross sections are scaled to an equivalent energy E_0 using the scaling factor $[E_0/(E_{\text{c.m.}} - E_{\text{threshold}} - V_C)]^\lambda$. E_0 is taken to be 60 MeV, which is a typical energy over threshold when using a 200 MeV proton beam. It is well above the discontinuity in the excitation function observed in Fig. 1. In Fig. 2 we show the mass dependence of the pion production probability. We define the pion production probability as the pion cross section divided by the geometrical cross section, πR^2 using the nuclear radius $R=1.2A^{1/3}$ fm. The importance of the energy scaling can be immediately recognized from the fact that it removes the large target-to-target variation of the individual pion cross sections obtained at the same proton beam energy. This can be seen most clearly by considering the cross sections obtained for different isotopes of a certain element: the difference in the π^0 cross section for ^{118}Sn and ^{124}Sn is 13% [5] and the difference for the isotope combination of ^{58}Ni and ^{64}Ni is 16% for the π^+ and 72% for the π^- cross sections, respectively [13]. Using the energy scaling with $\lambda=2.5$ these differences are reduced by an order of magnitude. It has been found that the range of λ for which a smooth mass dependence can be obtained is between 2.0 and 3.5. Therefore, the uncertainty in the excitation function does not affect the conclusions in the following.

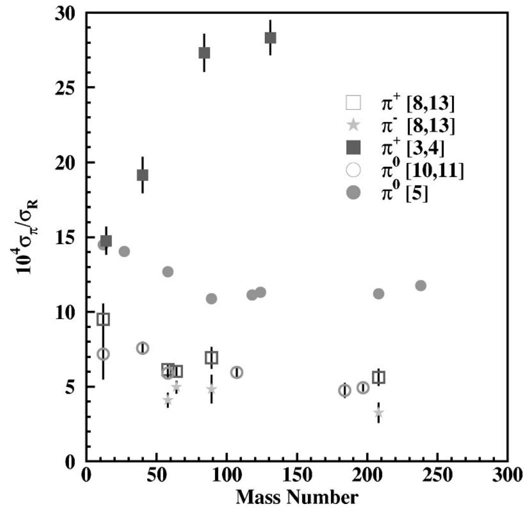

FIG. 2. Pion-production probabilities for proton-induced reactions at 200 MeV, scaled to equivalent energy $E_0=60$ MeV (see text). The π^+ and π^- cross sections were scaled according to the isobar model to yield equivalent π^0 cross sections (see text). The π^0 data are from Ref. [5] (full circles) and from the TAPS Collaboration [10,11] (open circles). The π^+ data are from the CHIC Collaboration [3,4] (full squares) and from measurements at Orsay, [8,13] (open squares). The latter measurements are also the source of the π^- data (stars).

The data in Fig. 2 have also been scaled for isospin dependence. The probabilities in Fig. 2 are given as the equivalent π^0 probability, $P_{\pi^0\text{eq}}$, by applying the isobar model of Sternheim and Silbart [14], i.e.,

$$P_{\pi^0\text{eq}}(\pi^+) = \frac{2Z+4N}{10Z+N} P_{\pi^+}$$

and

$$P_{\pi^0\mathrm{eq}}(\pi^-) = \frac{2Z+4N}{N} P_{\pi^-}.$$

This model assumes first-chance quasifree pion production. Using this isospin scaling gives a basis for the comparison of the small π^- cross sections with the much larger π^0 and π^+ cross sections.

We now discuss the differences between the various data sets. Most striking in Fig. 2 is the difference between the π^+ data obtained by the CHIC Collaboration [3,4] (full squares) and the data obtained with the ''Mathusalem'' spectrometer at Orsay [8,13] (open squares). The CHIC Collaboration made use of range telescopes for the pion measurements. In both cases pion spectra have been extrapolated to account for the slow pions that could not be detected. The systematic error in the pion production probability of the CHIC Collaboration could be as large as 50% in this energy region [15]. The high energy end of the differential cross sections from Orsay [13] were compared to data measured elsewhere, e.g., Ref. [16]. It appears that this absolute normalization is satisfactory. Therefore, any missing cross section in the Orsay result should be associated with the low-energy pions that could not be measured. Comparison with the model of Scholten *et al.* [17], which predicts a pion spectrum that reflects phase space and the density of $2p$-$1h$ final states, shows that the shape of the extrapolated spectrum in Ref. [13] is consistent with the shape of the model spectrum; at most a 30% increase of the cross section could be argued. Therefore, the difference between the Orsay and CHIC results due to systematic errors is probably at most 80%. This is still insufficient to explain the large differences between the two data sets. In view of the good comparison of the Orsay pion energy spectrum with those in Ref. [16], this points towards large experimental uncertainties of the CHIC data in the subthreshold energy region.

Next, we compare the π^0 and π^+ cross sections: taking the energy scaling into account the difference between the π^0 data of Bellini *et al.* [5] and the Orsay measurements of π^+ [8,13] remains unexplained, i.e., the π^0 production is stronger than the π^+ production. In contrast, it appears that the set of π^0 cross sections of the TAPS Collaboration and those obtained at Orsay [8,13] are consistent, i.e., the equivalent π^0 production probabilities fall within a narrow band. Of course, this observation depends on the validity of the isobar model. The isobar model works well to explain the π^+/π^- ratio observed by the Orsay group. Note that the isobar model predicts the largest possible difference in the pion production probabilities; it ignores charge exchange reactions and the absorption of pions in the target medium. These processes will play a role, especially for heavy target nuclei and with increasing beam energy. They have been observed at energies [14,2] above the free pion threshold where the pion production ratios are smaller than predicted by the isobar model.

Note that with the present energy and isospin scaling the π^0 probabilities of Bellini *et al.* [5] are too large by a factor of 2 as compared with the Orsay and TAPS data. This discrepancy may indicate a systematic error in the π^0 detector acceptance or efficiency for the data in Ref. [5]. The efficiency calulation is non-trivial in this energy domain, requiring a method to estimate the yield where the set of photon detectors does not cover the pion distribution [10].

IV. CONCLUSION

In conclusion, we have considered the systematic dependence of proton-induced pion production at subthreshold energies. Combining data from different authors obtained with different methods, we notice large inconsistencies in the published cross sections. Nonetheless, these data illuminate the crucial role of the available phase space for the pion yield. To obtain a smooth target mass dependence of the pion production cross section, it is necessary to take into account the large differences in Q value between different targets. By evaluating the beam energy dependence of the pion cross section, an empirical energy scaling was found, which allows one to scale for the cross section differences due to Q value. The isospin dependence can be explained with a simple isobar model. Within this empirical framework and considering the energy region near 200 MeV beam energy, the only two independent measurements that appear to be consistent with each other are the recent TAPS results and the spectrometer data of Orsay [8,13]. New and more accurate charged and neutral pion production cross sections are needed to provide a systematic consistent set of data. Of particular importance is to clarify whether the excitation function near 20 MeV available energy behaves anomalously or if this anomaly is a symptom of the experimental problems identified in this work. An improved excitation function would allow the study of the threshold behavior in more detail, in particular with respect to nuclear structure and the transition from a coherent to an incoherent production mechanism, and illuminate the role of absorptive processes.

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