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Search for a narrow resonance structure in pion production from $p+\mathrm{Cu}$ near 350 MeV

V. Aseev, Yu. Gavrilov, F. Guber, M. Golubeva, T. Karavicheva, A. Kurepin, K. Shileev, and V. Tiflov
Institute for Nuclear Research, Russian Academy of Sciences, Moscow, Russia

A. Badalà, R. Barbera, A. Palmeri, G. S. Pappalardo, F. Riggi, and R. Turrisi
Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Catania, Catania, Italy
and Dipartimento di Fisica dell'Università di Catania, Catania, Italy

L. Bimbot
Institut de Physique Nucleaire, Orsay, France

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The excitation function of positive pions produced at 90° by protons on Copper has been studied to get information on the long-standing problem of the existence of a narrow resonance near 350 MeV incident energy. Momentum spectra of π^+ were measured by the CLAMSUD magnetic spectrometer. A narrow resonance has been indeed observed, in agreement with previous results obtained in different laboratories during the past years. [S0556-2813(97)50108-7]

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After the first experiment made by Krasnov *et al.* [1], who observed at the JINR synchrocyclotron an enhancement of the π^+ yield at 350 MeV, different investigations of the proton induced π^+ production on Copper have been carried out over the past decade in order to confirm or reject that result [2–4]. Julien *et al.* [2] measured at Saturne energy spectra of π^+ with a range telescope in steps of 12 MeV around 350 MeV, confirming the existence of a narrow structure for low-energy pions. Another experiment by the same group [3] reported an enhancement of 5% near 350 MeV with a FWHM around 5 MeV. A search was also done using the reaction $\mathrm{Cu}(p,\pi^\circ)$ [3], but no definite evidence was found for any structure around 350 MeV. Additional experiments performed at Dubna [4] have observed an enhanced yield of low-energy (20–60 MeV) to high-energy (60–100 MeV) π^+'s at angles of 90°, 115°, and 125°, and a spin-parity assignment $J^\pi=2^+$ was extracted [5].

A more recent experiment [6], performed at TRIUMF, searched for an enhancement of 40 MeV charged pions to 100 MeV charged pions using a magnetic spectrometer and only an upper limit of 2.7% for π^+ and 9.1% for π^- was set. Even if this experiment did not give a convincing evidence for the existence of the resonance under discussion, some structure was anyhow observed close to 350 MeV.

Several origins have been proposed for such a resonance. The first proposed explanation was related to the possible excitation of the ${}^3F_3$ dibaryon state ($M=2220$ MeV) almost at rest, with subsequent three body decay $\pi^+ + p + n$ [1]. It was also suggested that the enhanced production of low-energy pions near 350 MeV could be due to the formation of a resonant nuclear state near 350 MeV excitation energy with a small width, which decays predominantly by emission of two pions. This interpretation was based on the experimental observation that the anomaly was seen only for pion energies below about 70 MeV, together with the fact that in such a process on a heavy nucleus, the maximum energy of a pion would be 350 MeV$-2\ m_\pi \simeq 70$ MeV. Alternative possibilities were discussed in terms of an apparent transparency of nuclei to low-energy pions [7] or of the existence of bound two-pion Cooper pairs in nuclei [8].

Due to the interest related to these different possibilities, more experimental work is needed in order to get an unambiguous evidence for such a process and, possibly, to study it under different conditions (different targets, angles, and pion charge states, ...). To reach all these goals the experiment should provide very careful tuning of the incident proton energy and precise measurements of pion spectra down to low energies.

The present paper reports new results on this problem, obtained within a research program on pion production in proton-nucleus reactions.

The experiment was carried out at the proton linear accelerator of the Moscow Meson Factory. A special experimental area near the end of the linac was built to transport the main proton beam at a reduced intensity, downstream to a shielded Faraday cup. The beam spot on the target had a diameter of 3 mm. The time structure of the beam had 65 μs macropulses with a repetition rate of 50 Hz. The duty factor was only 0.3%. For such reason the average beam current was reduced to about 100 pA, in order to keep the background as low as possible. The beam energy was varied with about 2 MeV steps by means of a special tuning procedure of the linac. A time-of-flight measurement with two detectors placed along the linac channel was carried out to get the absolute value of the beam energy. This gave a precision of less than 1 MeV, whereas the energy spread was estimated to be about ± 1 MeV.

Several checks were made concerning the beam position on the target. A luminiscent foil inserted at the target position allowed one to observe the beam spot by a TV camera before and after data taking at each proton energy. During data taking the beam transmission was monitored by the neutron background along the proton channel and near the magnetic spectrometer. Correction methods were used during off-line data analysis according to the following procedure. The beam flux was monitored by a Faraday cup (F) inserted

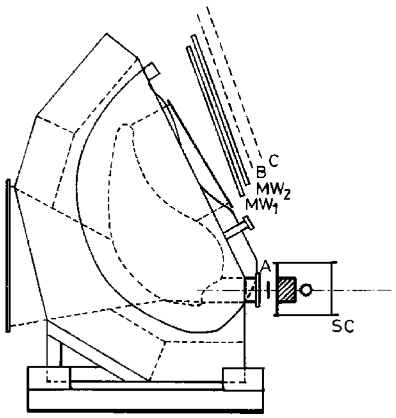

FIG. 1. Sketch of the magnetic spectrometer CLAMSUD, which has been used in the present experiment to detect protons and charged pions. A: Start Detector. B,C: Two planes of plastic scintillators for ΔE and TOF measurements. MW_1, MW_2: Two sets of multiwire X-Y drift chambers. SC: Scattering Chamber.

at the end of the beam line and by a counter telescope (M) of three scintillation detectors placed at 90° with respect to the beam direction (on the opposite side of the CLAMSUD spectrometer), and looking at the target. A four-elements hodoscope (A) of plastic scintillators was used at the entrance side of the spectrometer. This detector is also used to provide a start signal for the time-of-flight measurement of the particles entering the spectrometer. The information from detectors M and A, together with that from the Faraday cup (F) was stored on tape buffer by buffer. Each buffer contained approximately 30 events, and was filled in about one second. All these informations collected along each run were used to check the beam quality as a function of the time. As an example, the distributions of the quantities A/M and F/M were extracted during each run and it was found that these distributions are Gaussian with a narrow width, reflecting the degree of stability of the beam position on the target. The results were studied without any condition on these A/M and F/M ratios, and also by excluding those events for which A/M (or F/M) lie outside one or two standard deviations from the mean value. It was found that the results were the same within statistical errors.

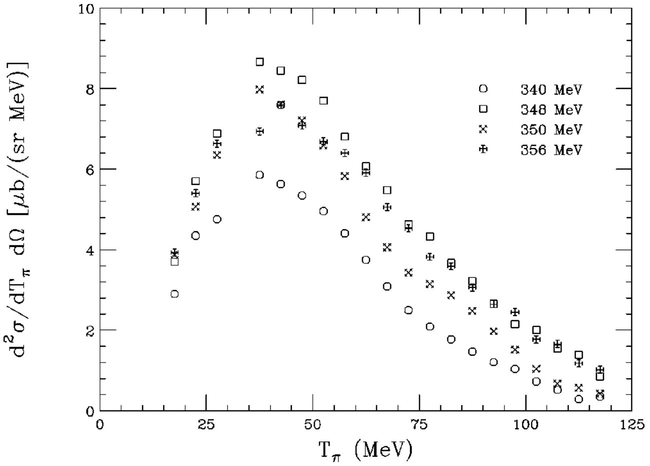

FIG. 2. Double differential π^+ production cross section versus pion kinetic energy for different proton energies.

A vacuum chamber with a large Mylar window was used to insert and rotate targets. A Cu target with a thickness of 134 mg/cm^2 was used, tilted by 45° with respect to the beam direction. Charged pions were detected by the CLAMSUD magnetic spectrometer [9,10]. This is a compact dipole magnet with nonparallel poles (see Fig. 1), installed on a platform which allowed detection angles from 32° to 150° with respect to the beam direction. The momentum range of detected pions extends up to about 250 MeV/c. The solid angle of the spectrometer was about 12 msr. A hodoscope of four plastic scintillators was used at the entrance of the spectrometer as a start detector. The focal plane detector of the CLAMSUD spectrometer was equipped with two planes of segmented plastic scintillators [for time of flight (TOF) and energy loss (ΔE) measurements] and two multiwire drift chambers with X- and Y-coordinate information. The particle momentum was determined from the X coordinates in the two chambers by single wire readout, with a resolution of about 300 μm. The overall energy resolution of the detector setup was about 0.2%. The main trigger was generated selecting only the coincidences between the start detectors and the two segmented planes of scintillators which can be originated from the physical tracks of the particles.

Charged pions were identified by their TOF and ΔE. Low-energy protons were also detected for the highest magnetic field settings, but they were easily discriminated against pions, due to their larger TOF. Due to the compactness of the CLAMSUD spectrometer, pion flight paths are limited to about 2 m, causing approximately only 20% of pion decay in flight for 60 MeV pions. All cross sections reported here have been corrected for the in-flight decay. Off line, radial and axial angles of the particles, as determined from X and Y coordinates in the two chambers, were used, together with the relevant TOF information, to eliminate muons coming from pion decay, following GEANT simulations [9].

Measurements of π^+ from $p+$Cu reactions were done at 90° in the lab system, for several proton energies, from 340 MeV to 364 MeV in small (about 2 MeV) energy steps. For each energy the pion momentum spectrum was measured up to the maximum momentum which can be reached by the CLAMSUD spectrometer. Figure 2 shows the double differential absolute cross section of π^+ at four incident proton energies. Spectra were measured also at several other energies, but they are not reported here to improve the clearness of the figure. A maximum near a pion energy of 40 MeV is observed at all incident energies, with a different behavior at 348 MeV, as compared to lower and higher incident energies.

Error bars are not shown in Fig. 2 to make the figure more clear. They are about 2% on the top of the spectra and reach 3–4% on the low- and high-energy tails of the spectra. Approximately, 15 000 pions were collected for each spectrum.

Several methods of analysis have been used in past experiments to get evidence of such resonance effect. Since such effect was mainly observed as an enhancement of low-energy pions, a preliminary analysis of the measured spectra has been carried out here by looking at the ratio of low-energy to high-energy pions. Pion spectra at low and high bombarding energy are expected to have a different slope, due to the influence of phase space, which results in a larger yield of pions of higher energy when the bombarding energy

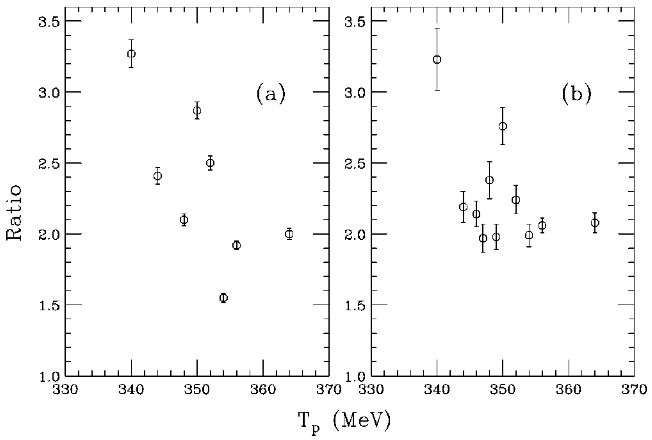

FIG. 3. Ratio of low-energy to high-energy pion yield versus incident proton energy, measured at $\vartheta_{\rm lab}=90°$ in the p+Cu reaction. (a) The integrated cross section between 30 and 60 MeV was divided by the corresponding value obtained for the region between 75 and 120 MeV. (b) The low- (75–97 MeV) and high-energy (97–120 MeV) sides of the same portion of spectrum (fixed field of the spectrometer) were considered to build up the ratio as a function of the incident energy (see text).

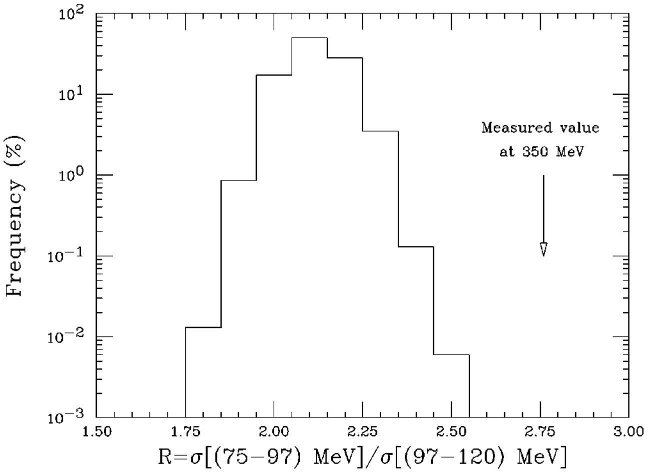

FIG. 4. Distribution of the quantity $R=\sigma(75\text{–}97\ \text{MeV})/\sigma(97\text{–}120\ \text{MeV})$ as simulated in a series of Monte Carlo generated energy spectra containing the same number of pions actually measured at 356 MeV. Comparable results were also obtained from simulations carried out by the use of the spectra measured at 344, 346, 347, and 354 MeV (see text). The arrow shows the value which was extracted from the spectrum at 350 MeV.

is raised. The ratio of low-energy to high-energy pions in a spectrum is then expected from simple considerations to vary monotonically with the bombarding energy. While the absolute value of this quantity depends on the particular choice of the energy regions, this regular trend is indeed observed in all measurements of pion energy spectra. As an example, Julien *et al.* [3] extracted a ratio $R=\sigma(20\text{–}50\ \text{MeV})/\sigma(75\text{–}100\ \text{MeV})$ which goes from about 1.0 at 310 MeV to about 0.5 at 425 MeV. For this reason, most of the experiments concerned with the study of this resonance have searched for deviations from this regular trend near 350 MeV.

Figure 3(a) shows for the present experiment the ratio between the integrated cross sections in two different regions of the spectrum, namely 30–60 MeV and 75–120 MeV, as a function of the bombarding energy. A clear structure is seen at energy around 350 MeV, with a very narrow width, which can be estimated in the order of 5 MeV. The statistical error bars for this set of data are in the order of 3–4% and usually of the order of the size of the points, except at 340 MeV where the error bar is larger. The deviation of the measured yields from the average regular behavior is in the order of 25%. Since each spectrum is obtained by a superposition of different (five) field settings of the spectrometer, systematic errors due to relative normalization could be a source of problems within each spectrum. To exclude this possible source of errors, the ratio between the low-energy and the high-energy parts of a portion of spectrum, measured at a given field setting, was studied as a function of the bombarding energy. This spectrum is obtained for a region of pion momentum of approximately ±15% with respect to the central momentum. This corresponds to a constant efficiency as a function of the momentum. Also in this case a bump was observed, consistent with that extracted from the analysis of the overall shape of the spectrum. As an example, Fig. 3(b) shows the result for the ratio between the cross section in the region 75–97 MeV and that in the region 97–120 MeV, extracted from a single field setting.

It is of course important for a critical experiment like that described in this paper, to check the reproducibility of the results. The data for this experiment were actually taken during three different periods, several months apart. Full measurements of pion spectra between 15 and 120 MeV (5 field settings of the spectrometer) were obtained in the first two experimental runs. Data from these runs are reported in Fig. 3(a). The points at 356 MeV and 364 MeV are from the first run, the point at 340 MeV from the third run, all the other points belonging to the second run. Several points were measured twice for comparison. In the third run, two field settings of the spectrometer were used, to cover the pion energy ranges 35–60 MeV and 75–120 MeV, and a smaller energy step (1 MeV) was chosen around the resonance. Part of these data, which are independent of the previous ones, are reported in Fig. 3(b). For some of the points it was also possible to make a direct comparison to the corresponding data measured in a different period, and a good agreement was found. For the data reported in Fig. 3(b) an increase of the cross-section ratio is also observed at 348 MeV with a lower value at 349 MeV; however it should be remembered that the beam energy in this experiment is only known to a precision of about 1 MeV, which can explain this behavior. Also the data reported in Fig. 3(b) show an enhancement of the cross section near 350 MeV which is outside the statistical fluctuations; if we compare the value of R obtained at 350 MeV (2.76 ± 0.13) with values outside the resonance (for instance 2 ± 0.08), a difference around 5 standard deviations is extracted. To make a more quantitative significance test, the following procedure was adopted [11]. An energy spectrum of pions was simulated by a Monte Carlo procedure, according to the shape observed at 356 MeV, i.e., outside the resonance; this spectrum contained the same number of pions as measured in the experiment (about 15 000). For this spectrum the ratio between the integrated cross section in the two regions 75–97 MeV and 97–120 MeV was evaluated, as in Fig. 3(b). This procedure was repeated several times, in order to get the distribution of this quantity. The result is reported in Fig. 4; according to this distribution, the probability to obtain a value of R around 2.4 is only 0.13%, and correspondingly smaller for larger values of R.

The idea behind the statistical test applied to the data was to check whether a large deviation of R from the expected value could come from fluctuations compatible with the shape of the spectra. In order to be of some significance, however, an input spectrum at energies not too far from the resonance must be chosen. If a very low bombarding energy is chosen (for instance 340 MeV or lower, as in previous experiments), the ratio R under investigation will have a value even larger than that observed near 350 MeV, but this only reflects the regular change of the shape of the spectrum. What is then important is that this ratio is found significantly higher than the surrounding points. The same analysis applied to the spectrum at 356 MeV was then carried out also for the spectra measured at 344, 346, 347, and 354 MeV (i.e., at energies which lie at least ±3 MeV outside the expected resonance). For these spectra the average value of the ratio R was found to be 2.06. A negligibly small probability to get a value of R as high as 2.76 (as measured at 350 MeV) was obtained in all cases. Even for the spectrum at 344 MeV, which has the larger value of R (2.18) among these spectra, this probability is smaller than 0.001%. These confidence limits are clearly the result of the high statistics which was used in the present experiment.

In conclusion, the already observed structure is thus confirmed and an estimation of the width of this reasonance gives a value which is comparable to that estimated before [3]. Further work is presently in progress to analyze all the data in more detail with several methods of analysis.

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