Measurement of $\pi^0\pi^0$ Production in the Nuclear Medium by π^- Interactions at 0.408 GeV/c

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We report on an investigation of the $(\pi^-, \pi^0\pi^0)$ reaction by means of measurements of the $\pi^0\pi^0$ invariant mass distributions from π^- interactions on H, D, C, Al, and Cu targets at $p_{\pi^-} = 0.408$ GeV/c. The sharp, strong peak in the $\pi^+\pi^-$ invariant mass near $2m_\pi$ reported by the CHAOS Collaboration is not seen in our $\pi^0\pi^0$ data. However, we do observe a change in the shape of the $\pi^0\pi^0$ invariant mass spectrum for the different targets, indicating that the $\pi^0\pi^0$ interaction diminishes in the nuclear medium as represented by nuclei D, C, Al, and Cu, compared to hydrogen.

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The reaction $A(\pi, \pi\pi)X$ has attracted much attention in recent years because it is expected that the nuclear medium causes major modifications of the π-π interaction. The $\pi\pi$ system in the $J = I = 0$ state in vacuum is only mildly attractive at low energy and there is no bound $\pi\pi$ state. In a nuclear medium, the π-π interaction could have *increased* strength and Schuck *et al.* [1] have even considered the possibility of a $\pi\pi$ bound state in matter. Recently, Hatsuda *et al.* [2] have promoted the notion that a peak in the $\pi\pi$ invariant mass near $2m_\pi$ could be an indication of partial restoration of chiral symmetry, which is the first step to achieving the quark-gluon plasma. There are many discussions in the literature [3–7] about medium modifications, in particular, about a possible major *reduction* in the mass of the "σ" meson. The σ is a complicated system of correlated $J = I = 0$ pion pairs. It is considered to be the chiral partner of the π meson. The σ is listed in the Review of Particle Physics as the $f_0(400-1200)$ [8].

The recent interest in the $\pi\pi$ system in a nuclear medium was stimulated by the unexpected features of the $\pi\pi$ data published by the CHAOS group [9–12]. Specifically, CHAOS reported that the $A(\pi^+, \pi^-\pi^+)X$ reaction measured at $p_{\pi^+} = 0.399$ GeV/c has a strong, sharp, A dependent enhancement in the $\pi^+\pi^-$ invariant mass spectrum close to $2m_{\pi^\pm}$, while no such sharp enhancement is found in the $A(\pi^+, \pi^+\pi^+)X$ channel.

In this Letter we present novel measurements of the $A(\pi^-, \pi^0\pi^0)X$ reaction. The study of the $\pi^0\pi^0$ channel instead of $\pi^+\pi^-$ has several advantages. For instance, the $\pi^0\pi^0$ system cannot be in a P state, it cannot have odd isospin, and there are no Coulomb corrections. From the experimental point of view, the advantage of the $\pi^0\pi^0$ system is the four-gamma final state that allows for two additional constraints, namely, the mass of the two π^0's. On the other hand, a $\pi^+\pi^-$ pair of low invariant mass could result from misidentification of a $\gamma \to e^+e^-$ conversion. The experimental setup for studying the π^0-π^0 interactions should fulfill several conditions such as the following: (i) a nearly 4π solid angle acceptance, (ii) good energy resolution, (iii) π^0 acceptance down to zero pion energy, and (iv) a smooth behavior of the acceptance for the full $\pi^0\pi^0$ invariant mass spectrum.

The Crystal Ball multiphoton spectrometer readily fulfills the above conditions. The Crystal Ball (CB) was built at SLAC. It is constructed of 672 optically isolated NaI(Tl) crystals that cover 93% of 4π sr. Electromagnetic showers in the spectrometer are measured with an energy resolution $\sigma_E/E \sim 1.7\%/[E\ (\mathrm{GeV})]^{0.4}$; the angular resolution for photon showers at energies 0.05–0.5 GeV is $\sigma_\theta = 2°–3°$ in the polar angle and $\sigma_\phi = 2°/\sin\theta$ in the azimuthal angle. The targets were located in the center of the CB in a thin aluminum cradle surrounded by a veto barrel made of four sections of plastic scintillation counters which covered the active volume of the CB. The main purpose of the veto barrel was to select neutral final states over charged ones. Here we report only on neutral final states. For the Monte Carlo simulation of our experiment, we have implemented the GEANT 3.21 package available from CERN. The CB acceptance calculated for H and C is shown in Fig. 1(a). The $2\pi^0$ production for both targets was simulated as the $p(\pi^-, \pi^0\pi^0)n$ reaction by using only three-body phase space. For the carbon target, the proton was given a uniform Fermi momentum in the interval ± 0.22 GeV/c. The acceptance is a smooth function of the invariant mass, $m_{\pi^0\pi^0}$ in both cases. Figure 1(b) shows the mass resolution of the CB for the $\pi^0\pi^0$ system. The mass resolution is about 1.2% at $m_{\pi^0\pi^0} = 2m_{\pi^0}$ and reaches a plateau of 2.2% at $m_{\pi^0\pi^0} \simeq 0.3$ GeV/c^2. Even a π^0 with zero kinetic energy is detected in the CB spectrometer with large acceptance.

The experiment was performed in the C6 beam line of the Brookhaven AGS. The data presented here were obtained at $p_{\pi^-} = 0.408$ GeV/c; the centroid of the beam is known to better than 1%. We used five targets: CH_2 (1.67 g/cm^2), CD_2 (1.47 g/cm^2), C (3.44 g/cm^2), Al (1.69 g/cm^2), and Cu (1.51 g/cm^2). Data were collected for an integrated beam flux of $\sim 5 \times 10^8$ pions on each target. Further details on the experiment and analysis can be found in [13].

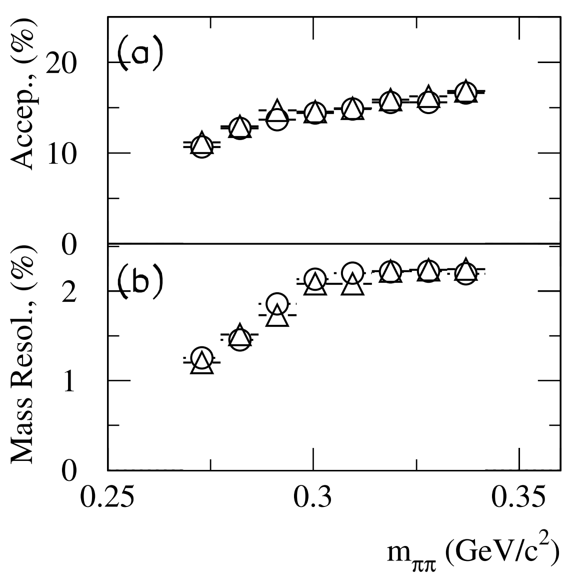

FIG. 1. (a) The $2\pi^0$ acceptance at 0.408 GeV/c as a function of the $2\pi^0$ invariant mass $m_{\pi^0\pi^0}$, calculated by a Monte Carlo simulation. (b) Invariant-mass resolution of the CB detector at 0.408 GeV/c calculated by using Monte Carlo. The triangles show the values for the hydrogen target, the circles for the carbon target.

The following procedure was used to select good $A(\pi^-, \pi^0\pi^0)X$ events: (i) We assume all clusters to be photons. A cluster consists of 13 neighboring crystals in the CB with at least 0.015 GeV deposited in the central crystal, and the timing signal associated with the cluster is within 20 ns of the beam particle signal. Only neutral final-state events with four clusters were analyzed. The fraction of events with a neutron detected in the CB is less than 5% of the total number of events and may be ignored. (ii) There are three possible combinations of two-cluster pairs to form $2\pi^0$ event candidates from four clusters. We tested all three combinations. An event candidate was used when one combination satisfied the $2\pi^0$ hypothesis at the 95% confidence level. The fraction of events with more than one solution is less than 6%.

The resolution of the $m_{\pi^0\pi^0}$ distribution obtained from the four photons alone was only about 5%. The resulting $m_{\pi^0\pi^0}$ spectrum shows no peak near $m_{\pi^0\pi^0} = 2m_{\pi^0}$ for any of the five targets. We can improve the resolution of $m_{\pi^0\pi^0}$ by making a kinematical fit to the known mass of both π^0's. We fit the measured four photon clusters to the hypothesis that the production occurs on a single proton that is not at rest but moves with the Fermi momentum ("quasifree" production). We have made extensive investigations into the suitability of the quasifree production model and have found it to be good. For instance, we find good agreement between the measured and Monte Carlo missing-mass spectra for hydrogen as well as the "effective-missing-mass" spectra for nuclear targets assuming quasifree production. The resolution obtained with this conventional kinematical fit technique is shown in Fig. 1(b).

The $\pi^0\pi^0$ invariant mass spectrum measured for H and C targets and evaluated by applying the kinematical fit is shown in Fig. 2. We have compared the shapes of the $m_{\pi^0\pi^0}$ spectra evaluated with and without the kinematical fit and found them to be statistically the same. We prefer to use the kinematical fit method because of its better $m_{\pi^0\pi^0}$ resolution. The solid line in Fig. 2 for the H data is the invariant mass distribution assuming a pure three-body phase space. The dashed line is the $m_{\pi^0\pi^0}$ distribution calculated for the sequential process $\pi^- p \to \Delta^0\pi^0 \to \pi^0\pi^0 n$. Neither agrees with the H data. The solid line in Fig. 2 for the C data is the distribution for pure phase space calculated for the quasifree production on a proton that has a Fermi momentum in the range ± 0.22 GeV/c.

The $m_{\pi^0\pi^0}$ spectra obtained in our experiment for five targets and corrected for Crystal Ball acceptance are shown in Fig. 3. The uncertainty introduced due to acceptance correction is estimated to be less than the statistical

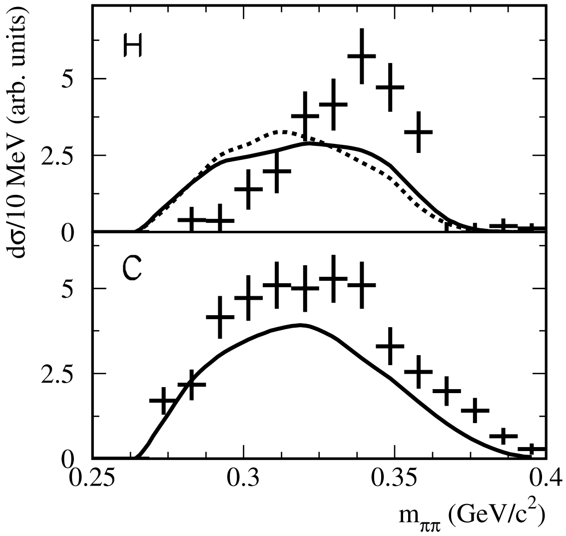

FIG. 2. Experiments results for the $2\pi^0$ invariant mass distributions (crosses) for H and C targets uncorrected for acceptance. The solid line is the Monte Carlo calculated $m_{\pi^0\pi^0}$ assuming pure phase space; see text for details. The dashed line is the spectrum based on a Monte Carlo calculation of the sequential process $\pi^- p \rightarrow \Delta^0\pi^0 \rightarrow \pi^0\pi^0 n$.

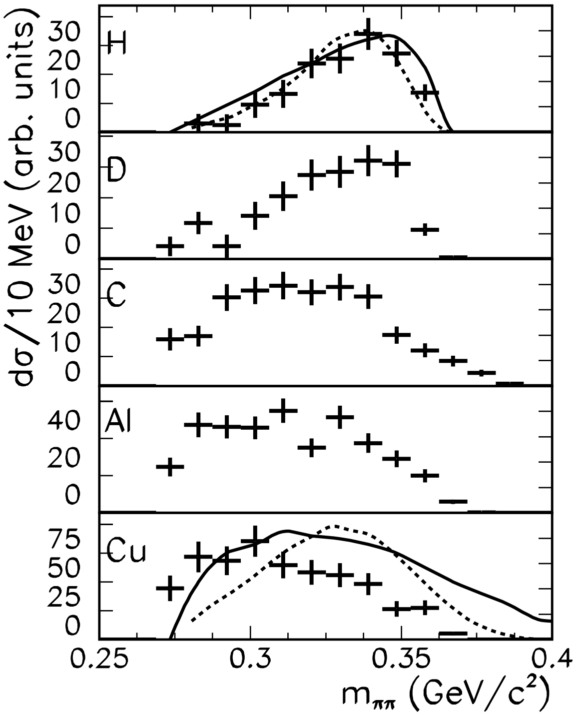

FIG. 3. Experimental results for the $2\pi^0$ invariant mass distributions obtained for the H, D, C, Al, and Cu targets corrected for Crystal Ball acceptance. The vertical scale is in arbitrary units. The solid lines show the results of calculations made by Rapp [18], and the dashed line is the prediction by Vicente Vacas [16].

uncertainty of the data. No evidence for a sharp peak near $2m_{\pi^0}$ is seen.

It is apparent from Fig. 3 that there is a change in the shape of the $m_{\pi^0\pi^0}$ distributions as a function of A that reflects the medium modification of the π^0-π^0 interaction. To obtain a measure of this change, consider the $m_{\pi^0\pi^0}$ distribution for the H target. Define ρ to be the parameter that represents the degree of agreement of the $m_{\pi^0\pi^0}$ spectral shape between data and pure phase space: $\rho \equiv m_{\pi^0\pi^0}(\text{data})/m_{\pi^0\pi^0}(\text{phase space})$, where the $m_{\pi^0\pi^0}$ distributions are normalized to have equal areas. Thus, $\rho = 1$ for all values of the $m_{\pi^0\pi^0}$ spectrum would show that the data have the same distribution as pure phase space. The results of the ρ distributions for our five targets are shown in Fig. 4. For the H target, there is a large deviation of ρ from unity. This deviation is expected for a π^0-π^0 interaction that increases with energy, a fact that was already observed by Lowe *et al.* [14]. We have fitted the distribution of ρ for H by a second order polynomial. The result of the fit is shown by the solid line for all targets in Fig. 4 for comparison with the H spectrum. In calculating ρ for the complex targets, the $m_{\pi^0\pi^0}$ phase-space distribution was simulated by assuming the quasifree $2\pi^0$ production. We conclude from Fig. 4 that nuclear medium as represented by nuclei D, C, Al, and Cu changes the π-π interaction in such a way that the $\pi^0\pi^0$ invariant mass distribution from complex targets is closer to the phase-space distribution than is the same distribution from H.

When interpreting $2\pi^0$ production data on nuclei, one must also consider the effects of the propagation of the pions through the nuclear medium. The average energy of the outgoing pions in our experiment is 0.05 GeV. This value corresponds to a mean free path of the pion in the nucleus of about 10–15 fm [15]. The pion rescattering on the spectator nucleons is small even in the case of our heaviest target, Cu, and should not distort the $m_{\pi^0\pi^0}$ spectrum outside the statistical accuracy. This assessment is supported by a full calculation of the $(\pi, \pi\pi)$ cross section made by Vicente Vacas and Oset [16]; see below. It is also supported by the general treatise on pion absorption by Hüfner and Thies [15] based on the use of a pion-nucleon optical potential and the Boltzmann equation, by our sequential-model Monte Carlo calculation, and by the pion transport calculations of Mashnik *et al.* [17].

A numerical evaluation of the $(\pi, \pi\pi)$ process on complex nuclei has been made by Rapp *et al.* [18]. This calculation is based on a model of the coherent sum of single pion exchange and the excitation of the Roper resonance with its subsequent decay into a nucleon and two pions. The production amplitude is modified by the final-state interaction between the pions for which the chirally improved, meson-exchange Jülich model is employed. The agreement of this calculation with our data on hydrogen and copper targets (where we have used the available ^{40}Ca calculation) is quite good (see Fig. 3).

Also shown in Fig. 3 is the calculation by Vicente Vacas and Oset [16] that is based on a microscopic model for pion production and a standard chiral Lagrangian pion-pion

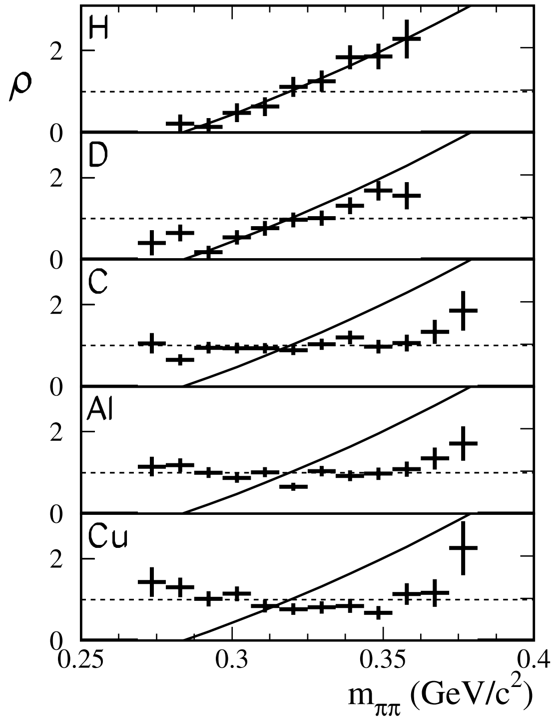

FIG. 4. Illustration of the change in the $\pi^0\pi^0$ invariant mass spectrum as expressed by the ratio $\rho = m_{\pi\pi}(\text{data})/m_{\pi\pi}(\text{phase space})$. The ratio is calculated for each of our five targets. The solid line is a second-order polynomial fit to the data on H. The dashed line represents $\rho = 1$.

final-state interaction. It includes pion absorption, Pauli blocking, Fermi momentum, and the strong modification of the π-π interaction in the nuclear medium. It agrees well with our measured $m_{\pi^0\pi^0}$ distribution on hydrogen; however, it does not describe the shape of our data for the copper target.

We summarize our results as follows: the data on $2\pi^0$ production by π^- on complex targets at $p_{\pi^-} = 0.408$ GeV/c show that the $m_{\pi^0\pi^0}$ distribution is smoothly varying. All of our $m_{\pi^0\pi^0}$ spectra for complex targets show that there is no sharp, strong peak near $m_{\pi^0\pi^0} = 2m_{\pi^0}$ of the magnitude reported by the CHAOS group. Our data are statistically consistent with the nonexistence of a peak. However, our data reveal a major change in the shape of $m_{\pi^0\pi^0}$. For the hydrogen target, ρ increases with increasing $m_{\pi^0\pi^0}$. This change is consistent with a π^0-π^0 interaction that is gaining strength rapidly as the invariant mass of the pair increases. The magnitude of this effect diminishes in complex targets as A increases. Complex targets give $\pi^0\pi^0$ invariant mass distributions which are nearer to the expectations based on phase space.

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