Evidence for ρ^o mass modification in the ^{3}He(γ,ρ^o)ppn reaction

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We have observed a modification of the ρ^o mass in the nuclear medium via the $^3He(\gamma,\pi^+\pi^-)X$ reaction using the Tokyo tagged photon facility and TAGX magnetic spectrometer. The tagged photon energies were mostly below the ρ^o production threshold on a free nucleon and the bound nucleon's Fermi momentum was utilized to produce the ρ^o. The mass shift observed is significantly larger than theoretical model predictions for this nuclear matter density. An extension of this study to other vector mesons at Jefferson Lab is required to distinguish between competing explanations for this finding.

It is widely expected that the ρ^o mass is modified in the nuclear medium, however, there is little experimental evidence directly supporting such modification. Several heavy ion experiments at CERN leading to dilepton production, indicate an enhanced production cross section in the lower dilepton invariant mass range of 200-600 MeV/c^2, which can be explained if the vector meson masses are reduced, but this is not conclusive. For a recent review of the field, the reader is referred to reference [1].

There is a clear need to determine the medium modifications in a simpler nuclear system, where the interpretation of the results is more straightforward. Our experiment was formulated to investigate the hadronic decay $\rho^o\to\pi^+\pi^-$ in the $^3He(\gamma,\pi^+\pi^-)$ reaction. The nearly 100% branching ratio for $\rho^o\to\pi^+\pi^-$ is advantageous, and the complication of πN final state interactions is reduced by choosing the light ^3He target. The tagged photon energy range of 800 to 1120 MeV is also advantageous. First of all, the ρ^o is produced with small Lorentz boost with respect to the nuclear medium, thus increasing the probability of its decay within the ^3He nucleus. Secondly, by photoproducing the ρ^o mostly below the free threshold of 1083 MeV (assuming a nominal m_{ρ^o} = 768 MeV/c^2), the coherent ρ^o photoproduction process is greatly suppressed, and the probability of ρ^o photoproduction on a single nucleon inside the nucleus is enhanced by taking advantage of the bound nucleon's Fermi momentum. We refer to this process as "subthreshold production". The experimental apparatus is described in reference [2], and the results of our analysis in references [3–5].

Two different methods were employed to identify any ρ^o mass shift. The simpler of the two methods reconstructs the emission angle of one of the pions in the dipion center-of-mass frame. If the $\pi^+\pi^-$ pair comes from the decay of a $J=1$ meson, their angular distribution will carry the unique $l=1$ signature of the final state. This technique has been extensively used in many ρ analyses, as there is no other pion production process which can mimic this signature in this energy regime [6]. In our experiment, any modified ρ^o contribution will manifest itself as a $cos^2\theta^*_{\pi^+}$ component in the angular distribution in the invariant mass range well below the free ρ^o mass.

There is an additional kinematical condition that any events from $\rho^o\to\pi^+\pi^-$ decay must follow; it is a unique two body decay in which the two pions are emitted back-to-back in the rest frame of the ρ^o. The boost to the lab frame preserves this correlation in the sense that the two pions must have a large opening angle. In contrast, $\pi^+\pi^-$ from background processes such as $\Delta^{++}\pi^-$ and $\Delta\Delta$ decay are uncorrelated. Accordingly, the results shown in figure 1 have a cut to eliminate events whose lab opening angle is too small to have been the outcome of back-to-back production at a single reaction vertex, and they indicate a substantially reduced ρ^o mass beyond the apparent lowering due to the kinematical constraint of probing the lower tail of the ρ^o mass distribution near threshold.

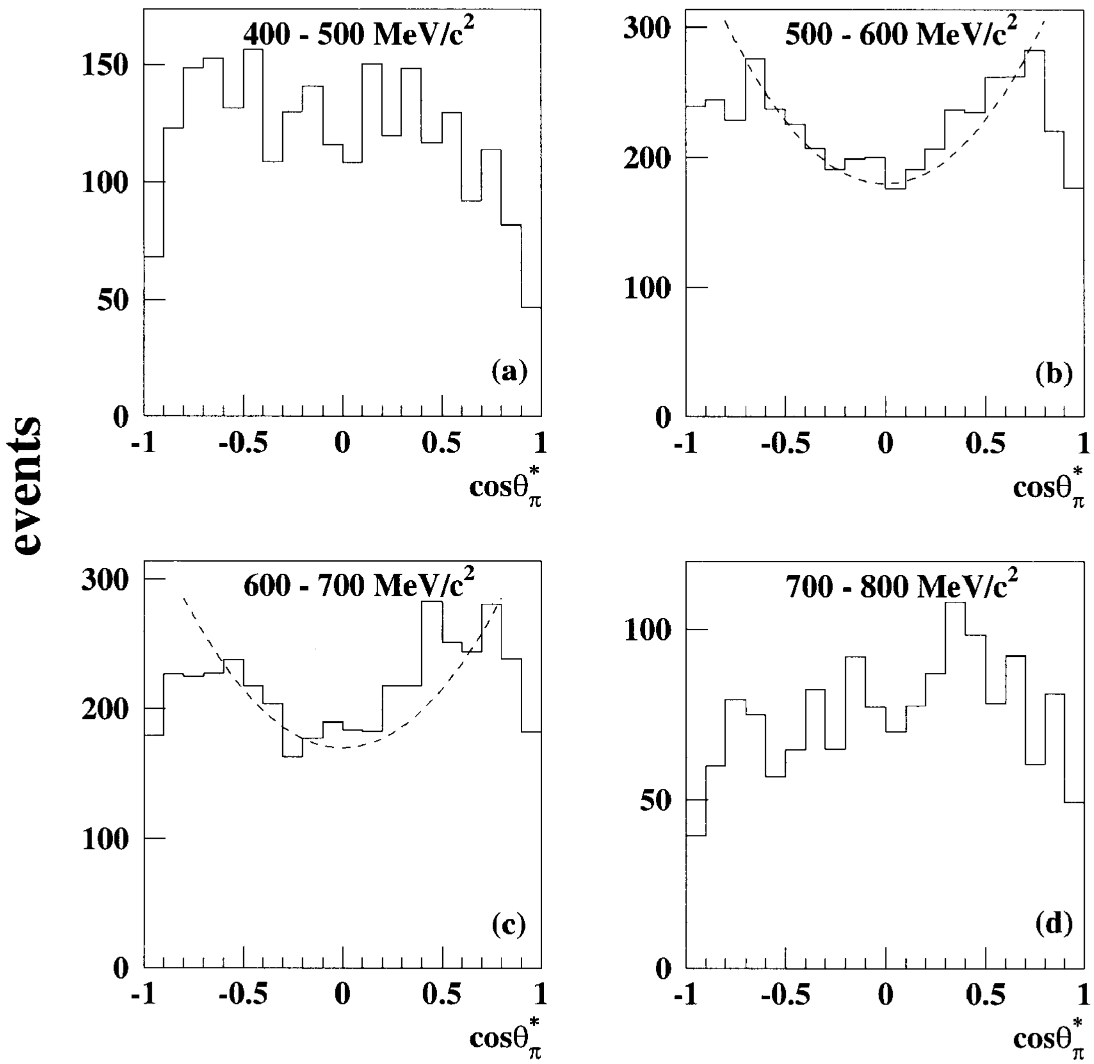

FIG. 1. $cos\theta^*_{\pi^+}$ distribution of the data for different dipion invariant mass regions from 400 to 800 MeV/c^2, subject to the requirement $\theta_{\pi\pi} > 70^o$. Panels b) and c) display the $cos^2\theta^*_{\pi^+}$ dependence (dashed curve) characteristic of the decay of a $J = 1$ vector meson, but at significantly lower mass than allowable for nonmodified ρ^o decay.

The second, more comprehensive method of extracting the modified ρ^o mass relied heavily on Monte Carlo simulations of the foreground and background processes. The processes that can result in a $\pi^+\pi^-$ pair at these energies, over and above ρ^o production, include quasifree $\Delta\pi$ production, $N^*\pi$ production, $\Delta\Delta$ production, and s-wave correlated pion production. In addition, pions with kinetic energies in the Δ_{1232} resonance region can experience final state interactions (FSI) via elastic scattering, $\pi N \rightarrow \pi' N'$ after production. All of these processes were modelled in order to understand the experimental data distributions. Each simulation assumed a constant matrix element, so the shapes of the resulting particle distributions are defined solely by their appropriate (kinematical) phase space. In order to assure the constancy of the matrix elements of the data, they should be divided into bins of photon energy which are as narrow as possible. We found that a division of the data into photon energy bins of 80 MeV width allowed meaningful statistics of the data in these bins.

Six kinematic variables were studied: dipion invariant mass $m_{\pi\pi}$, missing mass m_{miss}, missing momentum p_{miss}, dipion opening angle in the lab frame $\theta_{\pi\pi}$, scattering angle of the dipion system in the lab frame θ_{im}, and the pion emission cosine $cos\theta^*_{\pi+}$. The simulated data from the competing $\pi^+\pi^-$ channels were tracked through the TAGX spectrometer, including the experimental threshold, acceptance, and resolution, and analyzed in the same manner as the experimental data.

First, exploratory fits of the simulated data to the experimental distributions were performed, assuming that the ρ^o mass is not modified. In this case, only a small contribution of the nonmodified process $\rho^o \to \pi^+\pi^-$ is expected, as the experiment is below the energy threshold for most of the broad m_ρ distribution. The number of events attributed to each simulated process was common to all of the kinematic spectra, and so the fits were multipli constrained in angle, energy, momentum, and invariant mass for each process. This imposes a far more stringent criterion than an analysis based on only the invariant mass distribution, as in the case of the CERES data [1]. In addition, the estimated cross section for each process, based on an extrapolation of data from p and d targets, was used to verify that the fitting procedure had arrived at a physically reasonable solution.

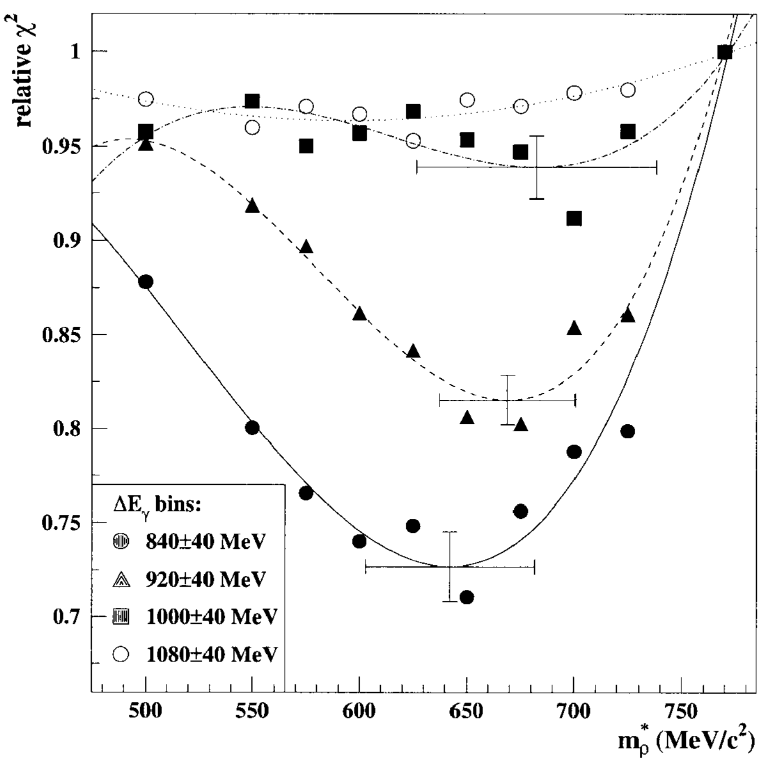

FIG. 2. Quality of fit of the simulated processes to the data when a modified ρ^o mass is assumed, compared to when only the free ρ^o mass is assumed. Results are shown for the four ΔE_γ=80 MeV bins, and the mass with the best fit is 642± 40 MeV/c^2, at E_γ=840± 40 MeV, 669±32 MeV/c^2, at $E_\gamma = 920 \pm 40$ MeV, and 682±56 MeV/c^2, at E_γ = 1000± 40 MeV.

The procedure was then repeated with the addition of a ρ^o wi· ·nodified mass. Separate Monte Carlo generators were written for a number of $m^*_{\rho^o}$ between 500 and 725 MeV/c^2, in steps of 25 MeV/c^2, because of the nontrivial dependence of the kinematic distributions upon $m^*_{\rho^o}$. Fits were performed using each modified ρ^o mass, in addition to the nonmodified ρ^o contribution, the goodness of fit recorded for each case, and compared to the χ^2 obtained when only the free ρ^o mass was assumed. The resulting comparison versus $m^*_{\rho^o}$ is shown in figure 2. We see that the quality of fit is substantially improved when a medium modified ρ^o with mass in the vicinity of 650 MeV/c^2 is added to the fit. This finding corroborates the angular correlation analysis, which found the distinctive $J = 1$ signature of $\rho^o \rightarrow \pi^+\pi^-$ decay in an invariant mass region far below that expected for the free ρ^o mass distribution.

Our results indicate that the ρ^o meson has a surprisingly large mass reduction in nuclear matter. For example, a calculation carried out specifically for this experiment, based on the quark-meson coupling model with a realistic ^3He density distribution, predicts a reduction to only $m^*_{\rho^o}$=730 MeV/c^2 [7]. One explanation put forward to account for such a large mass shift is related to the subthreshold nature of the experiment, where the ρ^o is created essentially at rest with respect to the hit nucleon. In this case, the ρ^o is sensitive to the high hadronic density of the nucleon, resulting in a very large modification [8]. Another possibility is that the ρ meson is deeply bound in the nuclear scalar potential [9].

It will take considerably more investigation to discern the correct explanation for this effect. An extension of this experiment to ^2H and ^{12}C nuclei at TAGX is still under analysis. Further work at Jefferson Lab to see if there is any modification of the ω^o and ϕ^o mesons will likely also be required.

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