PHYSICAL REVIEW C, VOLUME 63, 054601

Coherent ρ^0 production in the (p,p') reaction

Swapan Das and B. K. Jain
Nuclear Physics Division, Bhabha Atomic Research Centre, Mumbai 400 085, India
(Received 22 September 2000; published 29 March 2001)

Cross sections for coherent rho production in the (p,p') reaction on ^{12}C have been calculated in the beam energy range 1.8−2.5 GeV. The rho meson produced at the pp' vertex is brought on-shell by the coherent effect of the target nucleus through an optical potential. The latter is constructed using the high energy ansatz with the elementary ρN scattering amplitude coming from the vector dominance model and the resonance model, and the coupled channel calculations on the meson-nucleon scattering. The cross sections are found to be significant and sensitive to the strength of the potential and the beam energy. The rho mesons are found to come mostly in the forward direction.

DOI: 10.1103/PhysRevC.63.054601 PACS number(s): 25.40.Ve, 24.50.+g, 24.10.Ht

I. INTRODUCTION

Recently, there has been much interest in the medium modification of hadron masses. Brown and Rho [1] suggested that the masses of vector bosons, such as ρ,ω, etc. (and also baryons), scale as

$$\frac{m_V^*(\varrho)}{m_V} \sim \frac{f_\pi^*(\varrho)}{f_\pi}, \tag{1}$$

where the asterisk denotes the in-medium quantities. f_π is the pion weak decay constant. If the decay constant f_π^* decreases, as it does at higher nuclear densities/temperatures due to restoration of the chiral symmetry, the vector boson masses decrease. At the nuclear saturation density (ϱ_0) the decrease in mass for $\rho(770)$ and $\omega(782)$ mesons is thought to be around 20% or so. At densities/temperatures ($\sim 3\varrho_0$/150 MeV) achievable in relativistic heavy-ion collisions, the decrease is estimated to be around a factor of 2. This decrease in vector meson mass, linked to the modification of quark condensates in the medium, is also corroborated by the effect obtained by using QCD sum rule techniques in the medium [2]. Decreases in hadron masses are also seen in the relativistic mean field calculation by Walecka *et al.* [3]. A model calculation by Herrmann *et al.* [4] of the density dependent two pion self-energy in nuclear matter suggests a strongly increased decay width, but, unlike others, only a negligible change of the in-medium ρ mass. At high densities, ($\varrho = 2-3\varrho_0$), they also find another peak in the ρ meson spectral distribution function at the invariant mass $\approx 3m_\pi$. This branch corresponds to the decay of the ρ meson into a pion and a Δ-hole state. Using the π-N-Δ-ρ configurations distinct medium modification of the rho-meson spectral function has also been found in several other calculations [5], starting with those due to Chanfray and Schuck. Using the quark-meson coupling model a detailed calculation on light nuclei has been reported by Saito *et al.* [6] recently. They find that the average mass of a ρ meson gets reduced by about 50 MeV in ^{12}C nucleus.

Experimentally, the indication of a large medium effect on the rho meson is believed to have been seen in the enhanced dilepton yield in CERES and HELIOS relativistic heavy-ion reaction data taken at CERN-SPS [7]. Theoretically these data have been found to be compatible with both the ‘‘dropping’’ mass scenario as well as the more conventional ρ-meson spectral function modification due to coupling of ρ,π,Δ, and nucleon dynamics [8].

Thus, with so much interest in the vector-meson mass modification and no such conclusive evidence emerging for it from the heavy-ion reactions, attention has been shifted of late to look for it somewhere else. Plans are in place to measure the photoproduction ρ^0 cross section by measuring the dielectron yield at CEBAF and $\pi^+\pi^-$ at the 1.3 GeV Tokyo Electron Synchrotron [9]. The e^+e^- measurements have an advantage in that they do not interact with the medium strongly, and therefore preserve the information about the ρ mass modification. But the cross section for this channel is very small, because the dielectron partial decay width of the ρ meson is only 6.77 keV ($\Gamma_\rho \sim 150$ MeV).

Yet another potential tool to explore the above issue is through proton scattering on nuclei at intermediate energies. In the past, (p,n) and $(^3\mathrm{He},t)$ reactions have been used successfully to explore the medium effect on pi-meson and delta isobar [10]. The experience with these measurements had been very rich and rewarding. The same reactions should be quite useful to study the rho production if ^{3}He beams at intermediate energy or the neutron detection at these energies were available. In the absence of them at present, we have explored the $(p,p'\rho^0)$ reaction to study the rho production in nuclei. Like pion production in the $(^3\mathrm{He},t)$ reaction, we visualize that the beam proton emits rho mesons. These rho mesons, of course, are virtual as the four-momenta carried by them correspond to the dispersion relation obeyed by protons. It is the nuclear medium which scatters them coherently and brings them on shell to be detected in experiments. Naturally, the measure of these cross sections should have a direct bearing on the medium modification of rho meson masses in nuclei. The experiment envisages the coincident measurement between p' and ρ^0 for different four-momenta of p'. This provides a handle for studying the medium effects on the rho meson at different four-momenta. The ρ^0 can be identified through the invariant mass of its decay products $\pi^+\pi^-$ or dileptons. Alternatively ρ^0 can be identified by detecting p' in coincidence with the recoiling nucleus, which remains the target nucleus in the coherent production case, and then constructing the missing

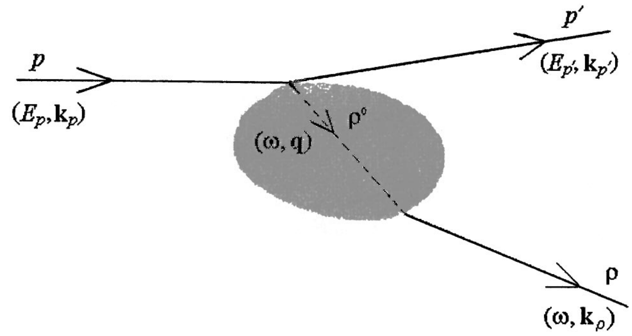

FIG. 1. A pictorial representation of the coherent rho production mechanism.

mass spectrum. It is true that all these measurements have to be done against the nonresonant background of events which give the same missing mass. However, considering the present sophistication in the experimental measurements it should be possible.

It may, however, be mentioned that, compared to pion production, the cross section for coherent rho-meson production in proton scattering on nuclei is expected to be much smaller due to larger momentum mismatch. For example, the cross section for coherent π^+ production in (p,n) reaction at forward direction, as estimated by Fernández *et al.* [11], is around 80 μb on ^{12}C at 800 MeV beam energy, while, as shown later in Fig. 4, we estimate for similar settings a cross section of about 1 μb for ρ^0 production at 2 GeV beam energy.

In Sec. II we give the formalism for the coherent ρ production in the (p,p') reaction. In Sec. III we present the calculated cross section for different ρ optical potentials.

II. FORMALISM

The cross section for the $(p,p'\rho^0)$ reaction, as shown in Fig. 1, is given by

$$d\sigma=[\mathrm{PS}]\langle|T_{\mathrm{coh}}|^2\rangle, \tag{2}$$

where the phase-space factor [PS] is written as

$$[\mathrm{PS}]=\frac{\pi m_p^2E_A}{(2\pi)^6}\frac{k_{p'}k_\rho^2}{k_p[k_\rho(E_i-E_{p'})-(\mathbf{k}_p-\mathbf{k}_{p'})\cdot\hat{k}_\rho E_\rho]}\times S(m^2)dm^2dE_{p'}d\Omega_{p'}d\Omega_\rho, \tag{3}$$

with $E_i=m_A+E_p$. E_ρ and k_ρ denote the energy and momentum of the rho meson, respectively, corresponding to its mass m. $S(m^2)$ is the free space rho mass distribution function which is given by

$$S(m^2)=\frac{1}{\pi}\frac{m_\rho\Gamma_\rho(m)}{[(m^2-m_\rho^2)^2+m_\rho^2\Gamma_\rho^2(m)]}, \tag{4}$$

with $m_\rho=770$ MeV. The width, $\Gamma_\rho(m)$, of the rho meson, which is energy dependent, is taken as

$$\Gamma_\rho(m)=\Gamma_{\rho\to\pi\pi}(m_\rho)\left(\frac{m_\rho}{m}\right)\left(\frac{k(m)}{k(m_\rho)}\right)^3, \tag{5}$$

where $\Gamma_{\rho\to\pi\pi}(m_\rho)=150$ MeV and $k(m)$ is the pion momentum in the rest frame of decaying rho meson of mass m.

The T matrix T_{coh} is given by

$$T_{\mathrm{coh}}=(\chi_{\mathbf{k}_{p'}}^{(-)*},\Psi_{\mathbf{k}_\rho}^{(-)*}\langle p',\rho^0|\mathcal{L}_{\rho NN}|p\rangle\chi_{\mathbf{k}_p}^{(+)}), \tag{6}$$

where χ's denote the distorted waves for the incoming and outgoing protons. However, in the energy region of interest for rho production the distortion effects are mainly absorptive. Therefore, the proton distorted waves above can be replaced by plane waves for the present purpose. The effect of absorption is included by multiplying the plane wave cross section by the square of an attenuation factor $\mathcal{N}$. This factor, for the above purpose, has been estimated using the relation [12]

$$\mathcal{N}=\frac{\int d\mathbf{b}dzf(\mathbf{b},z)\exp[-\frac{1}{2}\sigma_T^{pN}\varrho_0L(\mathbf{b})]}{\int d\mathbf{b}dzf(\mathbf{b},z)}, \tag{7}$$

where $L(\mathbf{b})[=\int_{-\infty}^{+\infty}f(\mathbf{b},z)dz]$ is the length of the path travelled by the proton in the medium. ϱ_0 and σ_T^{pN} are the typical nuclear density and the total proton-nucleon cross section, respectively. $f(\mathbf{b},z)$ is the shape of the radial distribution for the nuclear density.

$\Psi_{\mathbf{k}_\rho}^{(-)*}$ is the ρ-meson scattering wave function with asymptotic momentum $\mathbf{k}_\rho$. It has the form

$$\Psi_{\mathbf{k}_\rho}^{(-)*}=e^{-i\mathbf{k}_\rho\cdot\mathbf{r}}+\Psi_{\mathrm{scat}}^*. \tag{8}$$

In the absence of any dispersive nuclear distortion of p and p', the first term in this equation does not contribute to T_{coh} because $\mathbf{k}_\rho\neq\mathbf{k}_p-\mathbf{k}_{p'}$. In other words, as stated before, the rho meson produced at the proton vertex is off shell. It cannot be seen in the detector without incorporating the medium effects on it. Ψ_{scat} is the part of the wave function which includes this effect. If we associate a self-energy $\Pi(=2\omega V$, where V is the corresponding optical potential) with the ρ meson, Ψ_{scat} is given by

$$\Psi_{\mathrm{scat}}^*=\chi_{\mathbf{k}_\rho}^{(-)*}\Pi G_\rho(t), \tag{9}$$

where $\chi_{\mathbf{k}_\rho}^{(-)*}$ is the scattering solution of the potential V. $G_\rho(t)$ is the ρ-meson propagator, and is given by

$$G_\rho(t)=-\frac{1}{m_\rho^2-t-im_\rho\Gamma_\rho(t)}. \tag{10}$$

$t(=\omega^2-\mathbf{q}^2)$ is the four-momentum transfer squared to ρ meson at the production vertex. The recoil effects are included in our calculations by using the four-momenta $(\omega,\mathbf{q})$ obtained after considering the full three-body kinematics in the final state.

For the ρ production Lagrangian in Eq. (6) we have taken

$$\mathcal{L}_{\rho NN}=\frac{fF(t)}{m_\rho}N^\dagger(\sigma\times\mathbf{q})\tau N\cdot\boldsymbol{\rho}, \tag{11}$$

with ρNN coupling constant, f, equal to 7.81, and the off-shell extrapolation form factor

$$F(t)=\frac{\Lambda^2-m_\rho^2}{\Lambda^2-t}, \tag{12}$$

with $\Lambda=1.3$ GeV/c. These values are consistent with the nucleon-nucleon potentials such as the Bonn potential [13].

III. RESULTS AND DISCUSSION

With the above formalism we calculate the ρ production cross section for the ^{12}C target nucleus. The only quantity required for the calculation is the description of the optical potential V of the ρ meson, which, currently, is of much debate internationally. Some estimates exist for it in the literature [14,15]. One of them, which also gives the energy dependence of V, is by Kondratyuk *et al.* [15]. They use the high-energy ansatz for V and write

$$U=-\alpha\left[\frac{1}{2}v_\rho\sigma_T^{\rho N}\varrho_0\right] \tag{13}$$

and

$$W=-\left[\frac{1}{2}v_\rho\sigma_T^{\rho N}\varrho_0\right], \tag{14}$$

where

$$V=[U+iW]f(r). \tag{15}$$

$f(r)$ gives the radial shape of V. α in the above is the ratio of the real to imaginary part of the elementary ρN scattering amplitude and $\sigma_T^{\rho N}$ is the total cross section for it. ϱ_0 is the typical nuclear density. They use the vector dominance model (VDM) at high energies and resonance model at low energies to generate the ρN scattering parameters. However, as emphasized by Friman *et al.* recently [16], these potentials might have large uncertainties at low energies because of the lack of any constraint on the input quantities at these energies. Going further, following a coupled channel approach to meson-nucleon scattering at low energies, they have given an estimate for the rho-nucleon scattering amplitude. This amplitude is constrained by the fact that their calculations reproduce the pion-nucleon scattering data around the rho-meson production threshold. In our calculations we have used V at low energies arising from the ρN scattering amplitude due to Friman *et al.* [16], while at higher energies we use potentials by Kondratyuk *et al.* [15]. Some representative values of the self-energies used in our calculations are shown in Fig. 2. Up to $s^{1/2}$ 1.8 GeV they are due to Friman *et al.* and beyond from Kondratyuk *et al.* The bumps at low energies in the self-energy, as mentioned by Friman *et al.*, are due to the coupling of rho meson to resonances below the threshold, similar to the $N^*(1520)$.

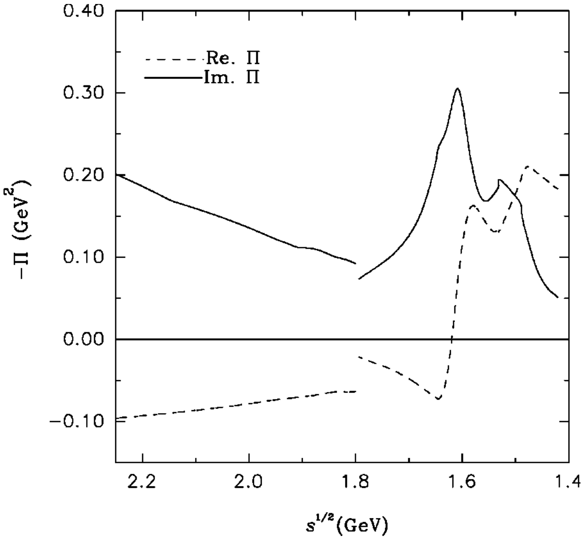

FIG. 2. Representative values for the self-energies obtained from the available ρN scattering amplitudes in Refs. [15,16].

The radial shape of the density distribution $f(r)$ for the ^{12}C nucleus is taken as

$$f(r)=[1+a(r/c)^2]e^{-(r/c)^2}, \tag{16}$$

where the values of a and c are 1.247 and 1.649 fm, respectively [17]. The attenuation factor $\mathcal{N}$ is obtained with the above radial density distribution and an appropriate value for $\sigma_T^{\rho N}$.

In Fig. 3 we plot the calculated outgoing proton energy

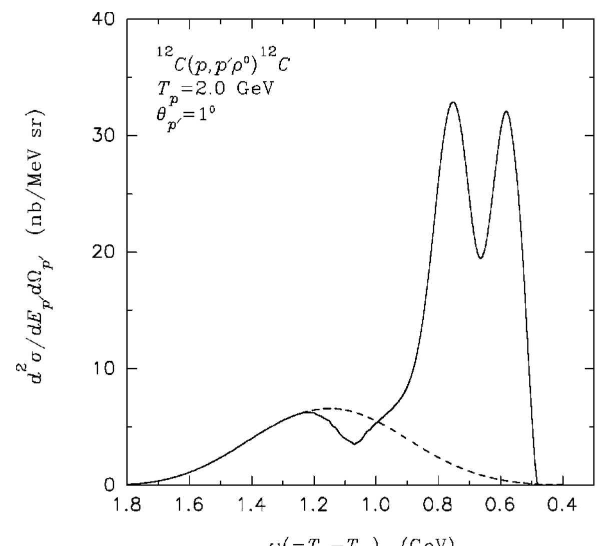

FIG. 3. Calculated energy spectrum for the outgoing proton near forward angle as a function of the energy transfer $\omega(=T_p-T_{p'})$ for ^{12}C$(p,p'\rho^0)^{12}$C reaction integrated over all emission angles of the ρ^0 meson. The beam energy is 2 GeV. The dashed curve uses Ref. [15] potential throughout.

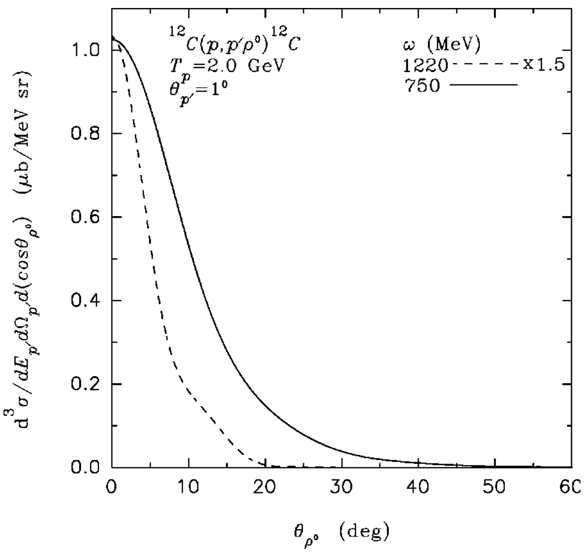

FIG. 4. Calculated angular distribution of the ρ^0 meson for the energy transfer (ω) at first two peaks in Fig. 3.

spectrum for p' going very near to the forward direction against the energy transfer $\omega(=T_p-T_{p'})$. This energy transfer and the corresponding momentum transfer $\mathbf{q}(=\mathbf{k}_p-\mathbf{k}_{p'})$ are shared between the rho meson and the recoiling nucleus through the interaction of the rho meson with the target nucleus. The beam energy is taken to be equal to 2 GeV. We see in the figure that the calculated distribution (continuous curve) has several peaks. This peak structure is the reflection of the structure in the self-energy shown in Fig. 2. The peak cross section is around 32 nb/(MeV sr). The dashed line corresponds to results if we had used the Kondratyuk *et al.* potentials throughout.

In Fig. 4 we show the angular distribution of the above rho mesons at the first two peaks positions in Fig. 3. It is observed that most of the rho-meson flux gets emitted in the forward direction only. Very little is seen beyond 30° or so.

To show the variation of the cross section with the beam energy, in Fig. 5 we plot the calculated cross sections at two other energies, i.e., 1.8 and 2.5 GeV, along with the 2 GeV results. As we see, the general structure of the cross sections remains the same at all the energies. The magnitude, however, increases with the beam energy. The cross section at the broad peak, for example, increases to 33.3 nb/(MeV sr) at 2.5 GeV from 2.4 nb/(MeV sr) at 1.8 GeV. This increase is mainly due to the reduction in the magnitude of the momentum mismatch $(\mathbf{q}-\mathbf{k}_\rho)$ between the momentum of the virtual and the real rho meson with the increase in the beam energy.

The above results are given for a certain choice of the ρ-meson optical potential. However, we expect them to be sensitive to the change in this potential. In Fig. 6 we have investigated this sensitivity. The optical potential for this purpose has been taken to be purely real, and different values for the depth of it are fixed through different mass-shifts of the ρ meson in the medium using the relation

$$\Pi = m^{*2} - m^2 \tag{17}$$

or

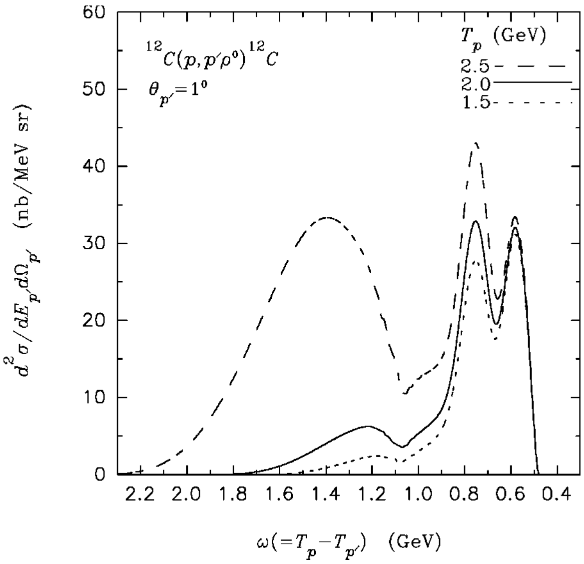

FIG. 5. Calculated energy spectrum for the outgoing proton near forward angle as a function of the energy transfer $\omega(=T_p-T_{p'})$ for the different values of beam energies.

$$U \approx \frac{m}{E_\rho}(m^* - m), \tag{18}$$

where m^* is the medium modified mass of the ρ meson. The dependence on the nuclear density distribution is incorporated, as done earlier, by multiplying U by $f(r)$.

In Fig. 6, we show the calculated proton energy spectrum for $\Delta m(=m-m^*)$ taken to be equal to 50, 100, and 150 MeV. The beam energy is 2.0 GeV. We observe in these results that, with the increase in the strength of the potential, the magnitude of the cross section increases and the peak position shifts towards lower values of ω. In increasing

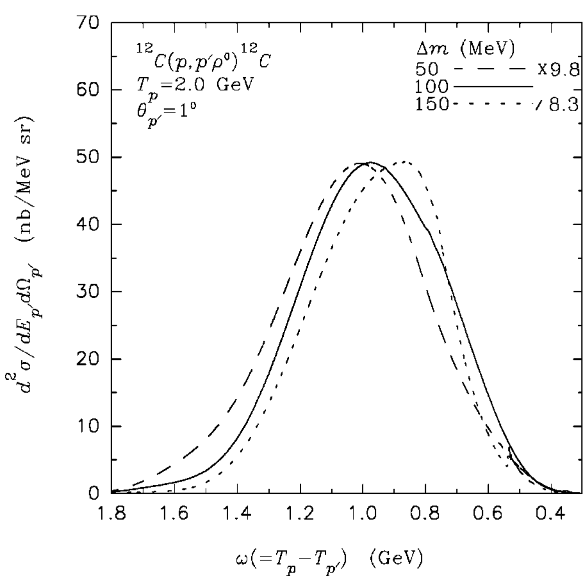

FIG. 6. Calculated energy spectrum for the outgoing proton near forward direction as a function of the energy transfer $\omega(=T_p-T_{p'})$ at 2.0 GeV beam energy for different values of ρ-meson mass shift.

Δm from 50 to 150 MeV the increment factor in the peak cross section is around 80 and the shift in the peak position is around 145 MeV.

Finally, before concluding it may be mentioned that the decay of rho meson takes place all along its path. The relative probability of its decay inside and outside the nucleus depends upon its speed, size of the nucleus, and the rho decay length. A rigorous calculation, similar to that done by Jain and Kundu [18] for the Δ propagation in the nucleus, should take this aspect into account. This would involve the spectral function $S(m^2)$ inside and outside the nucleus and the distortion of rho meson as well as its decay products. This task would be a lot more involved. Considering the exploratory nature of the present work we have not attempted this here. If we go by the work on delta decay, this extra feature may result in a further reduction in cross section by a factor of about 3/2.

IV. CONCLUSIONS

We find that in proton scattering on nuclei a measurable cross section exists for ρ meson production due to coherent effect of the target nucleus. The actual magnitude of the cross section depends sensitively on the strength of the ρ meson optical potential which is related to the rho-mass modification in the nuclear medium. The cross section increases with the increase in the potential strength and the beam energy. The angular distribution of the emitted rho-mesons is such that most of them go in a forward cone of about 30°.

ACKNOWLEDGMENTS

The authors thank Shashi Phatak for many useful discussions.

[1] G. E. Brown and M. Rho, Phys. Rev. Lett. **66**, 2720 (1991).

[2] T. Hatsuda and S. H. Lee, Phys. Rev. C **46**, R34 (1992).

[3] J. D. Walecka, Ann. Phys. (N.Y.) **83**, 491 (1974); B. D. Serot and J. D. Walecka, Adv. Nucl. Phys. **16**, 1 (1986); Int. J. Mod. Phys. E **6**, 515 (1997); H. Shiomi and T. Hatsuda, Phys. Lett. B **334**, 281 (1994).

[4] M. Herrmann, B. L. Friman, and W. Nörenberg, Nucl. Phys. **A560**, 411 (1993).

[5] G. Chanfray and P. Schuck, Nucl. Phys. **A545**, 271c (1992); **A555**, 329 (1993); M. Asakawa and C. M. Ko, Phys. Rev. C **48**, R526 (1993); M. Asakawa, C. M. Ko, P. Lévai, and X. J. Qiu, *ibid.* **46**, R1159 (1992); F. Klingl and W. Weise, Nucl. Phys. **A606**, 329 (1996).

[6] K. Saito, K. Tsushima, and A. W. Thomas, Phys. Rev. C **56**, 566 (1997).

[7] A. Drees, Nucl. Phys. **A610**, 536c (1996); CERES Collaboration, Th. Ullrich, *ibid.* **A610**, 317c (1996): HELIOS-3 Collaboration, M. Masera, *ibid.* **A590**, 93c (1995); NA50 Collaboration, E. Scomparin, *ibid.* **A610**, 331c (1996).

[8] G. Q. Li, C. M. Ko, and G. E. Brown, Phys. Rev. Lett. **75**, 4007 (1995); W. Cassing, W. Ehehalt, and C. M. Ko, Phys. Lett. B **363**, 35 (1995); G. Chanfray, R. Rapp, and J. Wambach, Phys. Rev. Lett. **76**, 368 (1996); R. Rapp and J. Wambach, hep-ph/9909229; E. L. Bratkovskaya and W. Cassing, Nucl. Phys. **A619**, 413 (1997); W. Cassing and E. L. Bratkovskaya, Phys. Rep. **308**, 65 (1999); W. Cassing, E. L. Bratkovskaya, R. Rapp, and J. Wambach, Phys. Rev. C **57**, 916 (1998).

[9] CEBAF Proposal No. PR 89-001, ''Nuclear mass dependence on vector meson masses using the photoproduction of lepton pairs,'' D. Heddle and B. M. Preedom, spokespersons (unpublished); CEBAF Proposal No. PR 94-002, ''Photoproduction of vector meson off nuclei,'' P. Y. Bertin, M. Kossov, and B. M. Preedom, spokesmen (unpublished); Report Nos. INS-ES-134 and INS-ES-144, LBL-91 revised, UC-414, 1994 (unpublished), p. 108; K. Maruyama, *Proceedings of the 25th International Symposium on Nuclear and Particle Physics with High Intensity Proton Accelerators* (World Scientific, Singapore, 1998).

[10] T. Ericson and W. Weise, *Pions and Nuclei* (Clarendon, Oxford, 1988); C. Gaarde, Annu. Rev. Nucl. Part. Sci. **41**, 187 (1991); B. K. Jain and A. B. Santra, Phys. Rep. **230**, 1 (1993); in *Proceedings of RIKEN International Workshop on Delta Excitation in Nuclei*, Wakoshi, Japan, 1993, edited by H. Toki, M. Ichimura, and M. Ishihara (World Scientific, Singapore, 1994).

[11] P. Fernández de Córdoba, E. Oset, and M. J. Vicente-Vacas, Nucl. Phys. **A592**, 472 (1995).

[12] B. K. Jain, J. T. Londergan, and G. E. Walker, Phys. Rev. C **37**, 1564 (1988).

[13] R. Machleidt, Adv. Nucl. Phys. **19**, 189 (1989).

[14] B. Friman, Nucl. Phys. **A610**, 358c (1996); V. L. Eletsky and B. L. Ioffe, Phys. Rev. Lett. **78**, 1010 (1997); V. L. Eletsky, B. L. Ioffe, and J. I. Kapusta, Eur. Phys. J. A **3**, 381 (1998).

[15] L. A. Kondratyuk, A. Sibirtsev, W. Cassing, Ye. S. Golubeva, and M. Effenberger, Phys. Rev. C **58**, 1078 (1998).

[16] B. Friman, M. Lutz, and G. Wolf, nucl-th/9811040; in *Baryon 98, Proceedings of the 8th International Conference on the Structure of Baryons*, Bonn, 1998, edited by D. W. Menze and B. Metsch (World Scientific, Singapore, 1999), p. 663.

[17] H. De. Vries and C. W. De Jager, At. Data Nucl. Data Tables **36**, 495 (1987).

[18] B. K. Jain and Bijoy Kundu, Phys. Rev. C **53**, 1917 (1996).