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Title: Quasifree ($\vec{p}$, $\vec{n}$) Reactions and Enhancement of Pionic Processes

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Submitted to: *Future Directions in Particle & Nuclear Physics at Multi-GeV hadron Beam Facilities, March 4-6, 1993, Upton, New York*

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Quasifree $(\vec{p}, \vec{n})$ Reactions and Enhancement of Pionic Processes

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Abstract

Results from a complete set of polarization-transfer observables for quasifree $(\vec{p}, \vec{n})$ scattering at 495 MeV are reported. Measurements were carried out on CD_2, carbon, and calcium targets at a laboratory scattering angle of 18° using the new Neutron Time-of-Flight facility at LAMPF. The ratio of spin-longitudinal to spin-transverse responses at a momentum transfer of approximately 1.72 fm^{-1} is extracted from the data, as well as the separated responses, and compared to distorted-wave calculations incorporating a Random-Phase Approximation description of the nuclear response. The spin-transverse response is compared to (e,e') measurements. The spin-longitudinal response represents new information available from hadron scattering.

The investigation of collective spin-isospin excitations in nuclei has been a rich field for observation of new phenomena.[2] At low excitation energies ($\omega < 20$ MeV) and small momentum transfers ($q \approx 0$) the spin-isospin particle-hole interaction is strongly repulsive, leading to collective excitations such as the giant Gamow-Teller resonance. The quenching of measured Gamow-Teller strengths relative to a model-independent sum rule has led to extensive theoretical studies of possible mechanisms, ranging from conventional configuration mixing to underlying sub nucleonic degrees of freedom.

At higher excitations ($\omega \approx$ 30-160 MeV) and momentum transfers ($q \approx$ 1-2 fm^{-1}), the spin-longitudinal interaction, taken to be driven by one-pion exchange, is expected to become mildly attractive, while the spin-transverse interaction mediated by rho exchange continues to remain repulsive due to the larger mass of the rho compared to the pion. Although signatures of shell structure, such as discrete states and giant resonances, disappear in this sector, the nucleus should continue to respond collectively through the action of the residual particle-hole interaction. The very dissimilar momentum dependence of the spin-longitudinal and transverse interactions should give rise to different phenomena in the corresponding nuclear spin isospin responses. For example, relative to a noninteracting Fermi gas, the spin-transverse response (R_T) is predicted to be quenched and pushed to higher energy loss, while the spin-longitudinal response (R_L) is predicted to be enhanced and shifted to lower energy loss due to an enhanced pion field within the nucleus.[3] The very (non)existence of such collectivity is directly connected to the form and magnitude of the spin isopin dependent parts of the residual interaction, and hence to the basic underlying degrees of freedom in the nuclear system.

Quasifree scattering can provide detailed information on the nuclear response. At intermediate energies (incident particle energies of several hundred MeV) and moderate momentum transfers ($q \geq 0.5$ fm^{-1}), quasifree scattering is a dominant part of the nuclear excitation spectrum. A broad structure is seen with a peak near $\omega \approx q^2/2m$ (m being the nucleon mass) and a width determined by the Fermi momentum. At momentum transfers above about 1 fm^{-1}, this region of excitation is well separated from the low lying discrete states and resonance region and can be identified with quasifree scattering. Shifts in the position of the quasifree peak with respect to free scattering have been observed for several

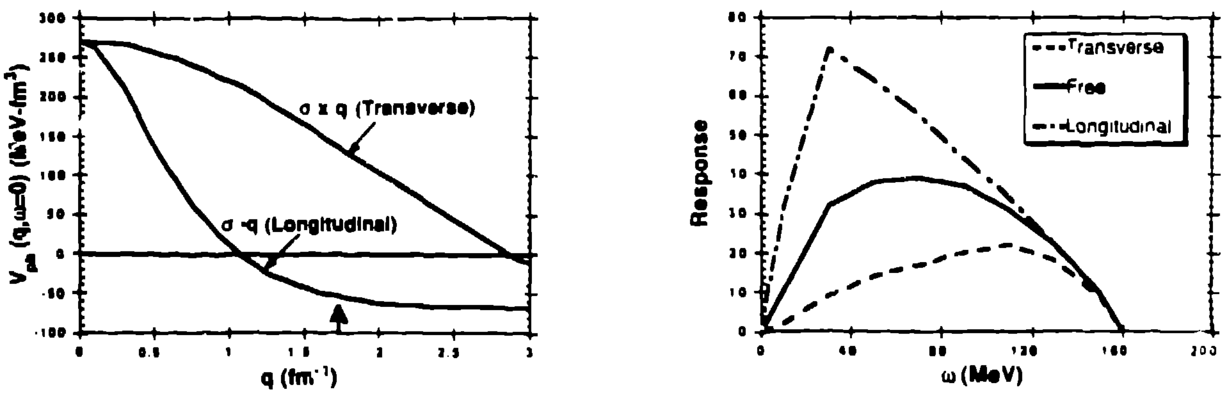

Figure 1: Particle-hole interaction (left) given by Eq. 1 with the Landau-Migdal parameter $g' = 0.6$ and the nuclear matter calculation (right) of the spin responses at q=1.75 fm^{-1}.

reactions. Attempts to explain these shifts have invoked the changing character of the underlying spin-isospin responses as a function of momentum transfer.[4, 5]

The form of the effective particle-hole interaction is generally taken to be

$$
\begin{aligned}
V(q,\omega) \;=\; & \left(\frac{f^2}{m_\pi^2}\right)\left\{\left[g' + \frac{q^2}{\omega^2 - (q^2 + m_\pi^2)}\Gamma_\pi^2(q,\omega)\right](\sigma_1 \cdot \hat{q})(\sigma_2 \cdot \hat{q})\right. \\
& \left. + \left[g' + C_\rho \frac{q^2}{\omega^2 - (q^2 + m_\rho^2)}\Gamma_\rho^2(q)\right](\sigma_1 \times \hat{q})(\sigma_2 \times \hat{q})\right\}\tau_1 \cdot \tau_2 \qquad (1)
\end{aligned}
$$

where m_π and m_ρ are the pion and rho masses respectively, ω is the energy transfer, C_ρ is the ratio of the ρ and π coupling, f^2 is the πNN coupling constant, and Γ_π and Γ_ρ are the vertex (monopole) form factors of the π and ρ respectively. A contact interaction governed by the Landau-Migdal parameter g' takes into account the short-range repulsive nature of the interaction. This interaction is shown in Fig. 1 (left) as a function of momentum transfer. In nuclear matter calculations, a very large enhancement of the ratio of R_L to R_T is predicted near 1.7 fm^{-1}, as seen in Fig. 1 (right), due to the collectivity introduced by Eq. 1.[3] Observation of such an enhancement should therefore provide a sensitive test of particle-hole correlations in the nucleus. Effects due to finite nucleus geometry and distortions can in principle reduce the size of the effect. However, most calculations retain a significant signature of the enhancement when these effects are included.[4, 5]

Several reactions provide information on the spin-isospin nuclear response. Deep inelastic electron scattering is sensitive to R_T, but this reaction does not excite the spin-longitudinal modes. Access to R_L requires a probe which couples longitudinally to the nucleonic spins such as the (p,n), (n,p), (p,p'), $(^3He,t)$, $(d,2p)$ reactions or semi-hadronic processes such as $(e,e'\pi)$. The (p,n) reaction provides several unique advantages as a probe of R_L owing to its purely isovector nature, close connection of polarization transfer (PT) observables for this reaction to the responses of interest, as well as important experimental considerations. By measuring complete sets of PT observables for quasifree nucleon-nucleus scattering, the responses R_L and R_T can be extracted.[6, 7, 8] The transverse spin response R_T can be compared to the isovector part of the response obtained from electron scattering, while the longitudinal spin response R_L represents new information. Previous analysis of PT data taken at LAMPF for the (p,p') reaction at 500 MeV and q 1.75 fm^{-1} provided no evidence for the predicted enhancement in the ratio R_L/R_T; however, uncertainties in the isoscalar contribution and distortion effects complicated the interpretation.[9, 10] It has been recognized that the (p,n) reaction is the most promising method of observing the predicted enhancements in R_L/R_T. Until recently, however, only limited PT data for the (p,n) reaction were available, none above incident energies of 200 MeV. The new Neutron Time-of-Flight (NTOF) facility[11] at LAMPF now provides the capability of precision PT measurements for (p,n) reactions up to 800 MeV, opening the possibility of detailed studies of the nuclear continuum.

A complete set of PT observables for quasifree scattering in the (p,n) reaction on ^{2}H, C, and Ca at a laboratory scattering angle of 18° (the momentum transfer varies from about 1.6 to 1.9 fm^{-1} over the excitation range of interest, with the peak of the quasifree at $q \approx 1.72$ fm^{-1}) was measured at 495 MeV with the new NTOF facility at LAMPF. All three proton beam polarization directions (normal to the scattering plane, along the beam direction, and sideways) were provided at the NTOF target. Details of the experimental apparatus and procedures have been published.[12, 13] The experiment spanned the range of neutron energy loss from 30 to 160 MeV, corresponding to quasifree scattering at this momentum transfer.

In order to extract further information from the data, it is necessary to make the connection of PT observables to the nuclear response functions. It has been shown[8] that if the effect of distortion is simply represented by a common attenuation factor due to absorption in both channels, then the ratio of the spin-longitudinal to spin-transverse reponses for the kinematics of this experiment is given by

$$\frac{R_L(q,\omega)}{R_T(q,\omega)} = \frac{D_q/|\delta|^2}{D_p/|\varepsilon|^2} \tag{2}$$

where the center of mass observables D_q and D_p are obtained from the laboratory polarization transfer observables according to

$$\begin{aligned} D_q &= \frac{1}{4}[1 - D_{NN} + (D_{SS'} - D_{LL'})\cos(2\theta_p - \theta_{lab} - \Omega) \\ &\quad - (D_{LS'} + D_{SL'})\sin(2\theta_p - \theta_{lab} - \Omega)] \\ D_p &= \frac{1}{4}[1 - D_{NN} - (D_{SS'} - D_{LL'})\cos(2\theta_p - \theta_{lab} - \Omega) \\ &\quad + (D_{LS'} + D_{SL'})\sin(2\theta_p - \theta_{lab} - \Omega)] \end{aligned} \tag{3}$$

where the nucleon-nucleus center of mass coordinates $\mathbf{p}$ and $\mathbf{q}$ are given by

$$q = \frac{\vec{k}_f - \vec{k}_i}{|\vec{k}_f - \vec{k}_i|}, \quad n = \frac{\vec{k}_i \times \vec{k}_f}{|\vec{k}_i \times \vec{k}_f|}, \quad p = q \times n \tag{4}$$

and

$$N = \frac{\vec{K}_i \times \vec{K}_f}{|\vec{K}_i \times \vec{K}_f|}, \quad L = \vec{K}_i, \quad S = N \times L \tag{5}$$

and θ_{lab} are the laboratory quantities. The relativistic rotation angle Ω is defined in Ref. 8, θ_p is the angle that $\mathbf{p}$ makes with respect to the initial beam direction, and k_i and k_f (K_i and K_f) are the initial and final momenta respectively in the center of mass (laboratory) frame. The D_{ij} are the measured laboratory PT observables. The spin-longitudinal and spin-transverse amplitudes δ and ε are defined in the nucleon-nucleon charge exchange scattering matrix

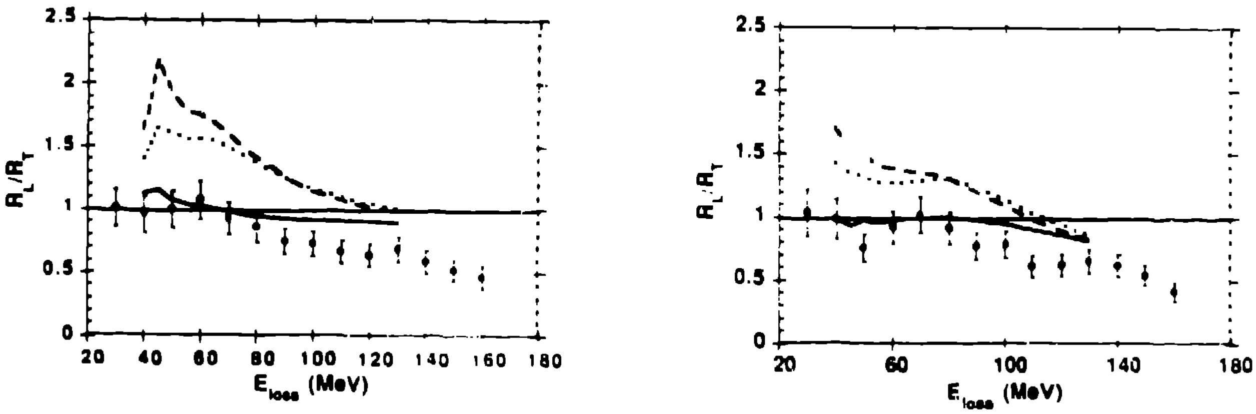

Figure 2: Ratio of spin-longitudinal to spin-transverse responses defined in Eq. 2 for 495-MeV quasifree (p,n) scattering at a laboratory scattering angle of $18°$ ($q \approx 1.72$ fm^{-1}) for carbon (left) and calcium (right). Curves are DWIA-RPA calculations described in the text.

$$
\begin{aligned}
M(q) &= \alpha - i\gamma\{(\sigma_1 \cdot \hat{n}) + (\sigma_2 \cdot \hat{n})\} \\
&\quad +\beta(\sigma_1 \cdot \hat{n})(\sigma_2 \cdot \hat{n}) + \delta(\sigma_1 \cdot \hat{q})(\sigma_2 \cdot \hat{q}) + \varepsilon(\sigma_1 \cdot \hat{p})(\sigma_2 \cdot \hat{p})
\end{aligned} \tag{6}
$$

where σ_1 and σ_2 are the Pauli matrices for the projectile and target nucleons, respectively.

The assumption of distortion effects providing only a common attenuation factor in both the spin-longitudinal and -transverse channels appears to be supported by Distorted-Wave Impulse Approximation (DWIA) calculations for the (p,n) reaction with the kinematics of this experiment.[14] These calculations predict an overall reduction in the responses due to distortion effects, with essentially no change in the shape as a function of energy loss as compared to plane-wave calculations with the same interaction. The calculated distortion effects for the (p,n) reaction are not as great as in the (p,p') reaction at the same energy and momentum transfer, where both a reduction and a drastic reshaping of the responses, primarily in the spin-transverse channel, is predicted by the same calculation. In addition, only the isovector responses contribute to the present (p,n) results, whereas the (p,p') reaction mixes the isoscalar and isovector channels and requires model dependent corrections to the data in order to extract the isovector responses. The (p,n) reaction at 500 MeV therefore appears to be well suited for investigation of the nuclear spin response.

Fig. 2 shows our results for the ratio of spin longitudinal to spin transverse response functions for carbon and calcium as defined in Eq. 2. The ratio of $|\delta|^2$ to $|\varepsilon|^2$ was determined empirically from scattering measurements from deuterium, which is taken to be the free scattering case. Also shown are DWIA calculations from Ref. 15 for the same quantities with and without Random Phase Approximation (RPA) correlations, which take into account the collectivity introduced by the particle-hole interaction given in Eq. 1. The dashed curve is for a value of $g' = 0.6$ and the dotted curve is for a value of 0.8. These values for g' span a reasonable range of this parameter as determined from the spectra of unnatural parity states at lower momentum transfers and excitations. The solid curve is the same calculation with no RPA collectivity.

The implication of the present data can be further emphasized by comparison of the separated responses to the RPA predictions. In Fig. 3, we show the experimental spin longitudinal and spin transverse responses for carbon (left) and calcium (right) compared to the RPA responses ($g' = 0.6$)

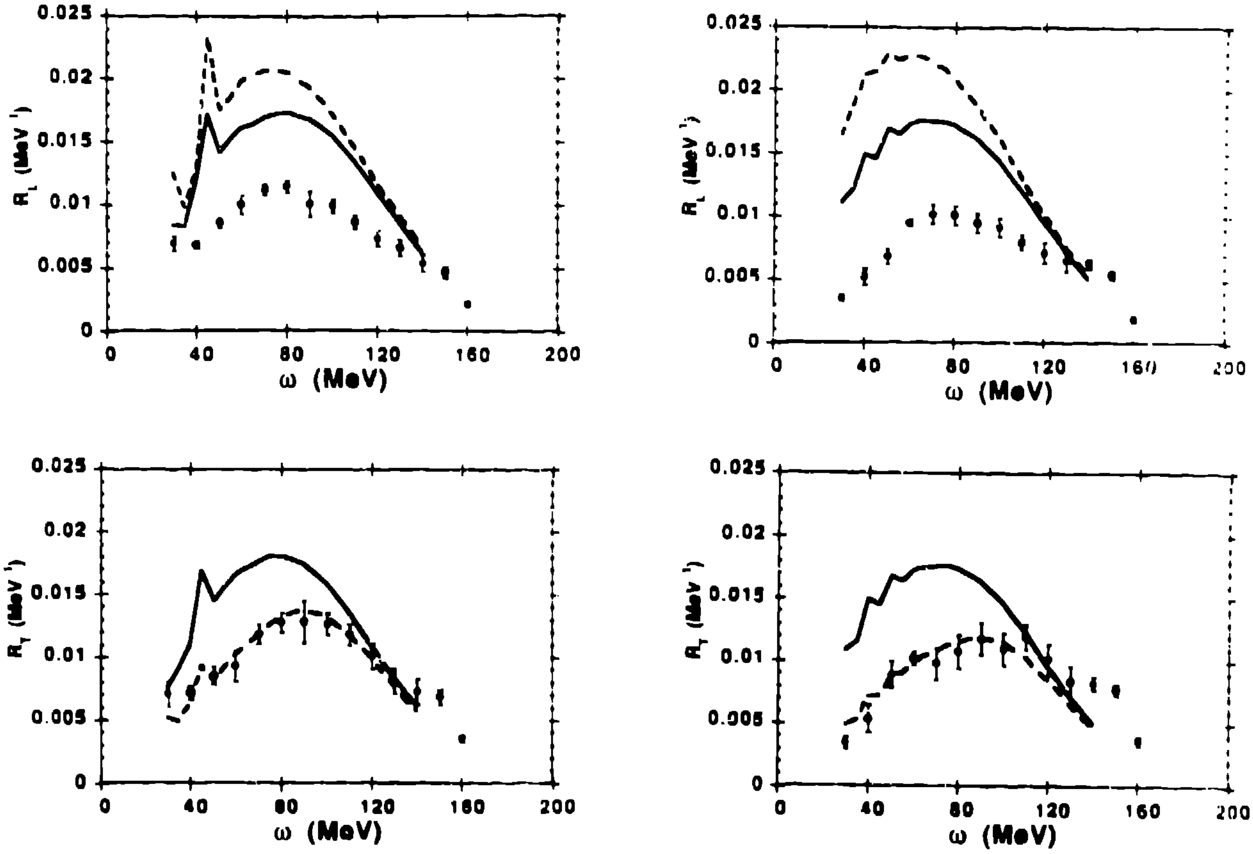

Figure 3: Separated spin-longitudinal (top) and spin-transverse (bottom) responses for carbon (left) and calcium (right). Curves are DWIA-RPA calculations described in the text.

provided by Ichimura and Kawahigashi.[15] The full line in the the figure represents the free response (no RPA correlations), while the dashed lines indicate the responses when the residual particle hole interaction of Eq. 1 is turned on. In the case of the spin-transverse response, the agreement of the correlated RPA calculation with the data is surprisingly good. In the spin-longitudinal channel, however, the RPA correlated response is in marked disagreement with the data. No evidence for the predicted enhancement is observed in the data. In fact, the data show a quenching with respect to the free response in this channel, much the same as the spin transverse response. Comparison of the shape of the (p,n) spin-transverse response with the transverse response measured in electron scattering is remarkable, while the normalization agrees to within 20-25%. Several factors, such as surface vs. volume responses and attenuation factor uncertainties could very well account for this difference in magnitude.

Brown, Osnes, and Rho[16] have argued that g' should take on larger values at higher momentum transfers, perhaps as large as 1.0-1.55 at the momentum transfer of this experiment, which would bring the calculations more into agreement with our data. Other interactions which allow for medium modifications of Eq. 1 may be able to account for the apparent lack of enhancement seen in the data. Brown and Rho[17, 18] have proposed a scaling of the vector meson masses and coupling constants according to

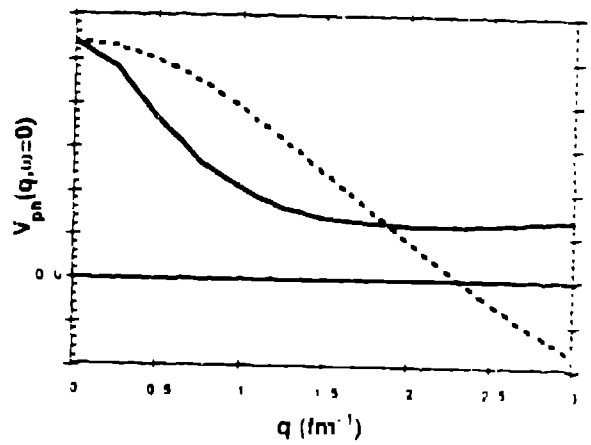

Figure 4: Schematic momentum dependence of medium-modified interaction of Brown and Rho (ref. 17 and 18) with s=0.8 and large g'.

$$s^2 = \frac{(m_\rho^*)^2}{m_\rho^2} \approx \frac{C_\rho}{C_\rho^*} \approx \frac{(m_N^*)^2}{m_N^2} \tag{7}$$

where the asterisk denotes a medium modified quantity and m_N is the nucleon mass. s depends on the nuclear density, with s=1 corresponds to the free space interaction. Using this interaction, an almost complete cancellation of the attractive pion force by the rho tensor force can take place for values of s close to 0.8, leading to a predicted ratio of R_L/R_T close to unity, in agreement with the observed experimental ratio. As seen in Fig. 4, in addition to the spin-transverse and spin-longitudinal channels being nearly equal at the momentum transfer measured in this experiment, both are repulsive due to the large value of g'. This would, therefore, also account for the observed quenching with respect to the uncorrelated prediction. This form of the interaction should have a very different momentum dependence as compared to the conventional form in Eq. 1 and Fig. 1. Additional measurements at 1.1 fm^{-1} have been taken on carbon and deuterium and are under analysis. Further measurements at 2.5 fm^{-1} are being planned for this summer and will provide a more comprehensive data base with which to define the appropriate form of the interaction.

We wish to thank Professors M. Ichimura and K. Kawahigashi for stimulating discussions and for supplying us with their calculations and Professor G. E. Brown for his suggestions for inclusion of medium effects into the calculations.

This work supported in part by the U.S. Department of Energy and the National Science Foundation.

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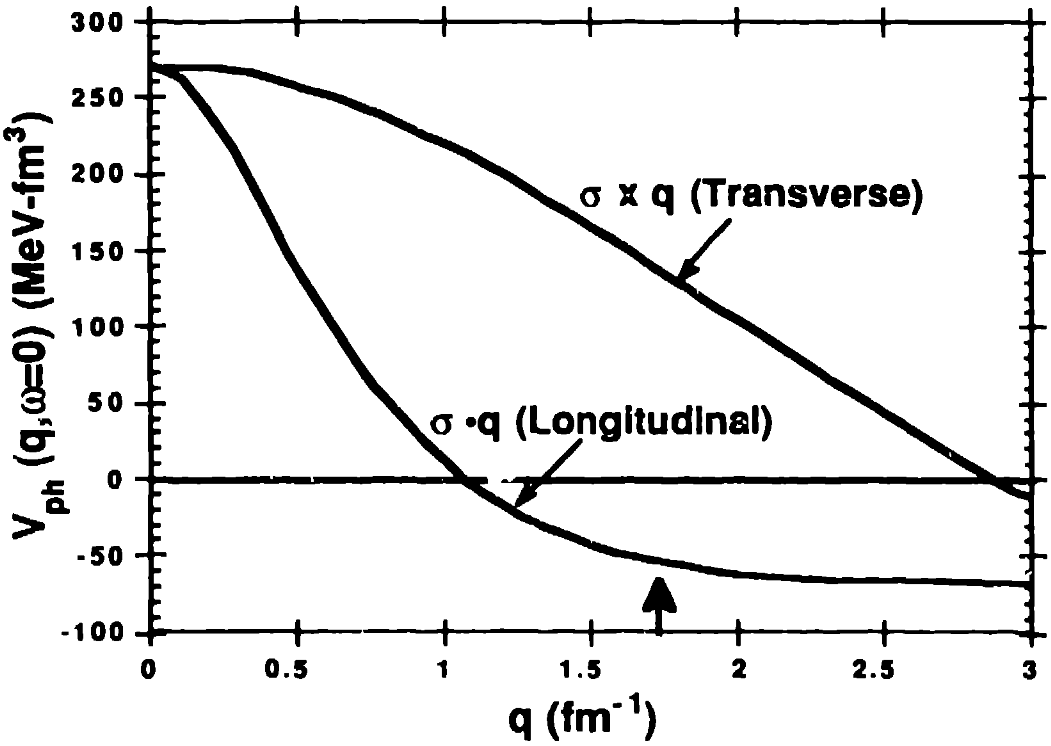


300
250
200
150
100
50
0
-50
-100
V_{ph} (q,ω=0) (MeV-fm^3)
σ x q (Transverse)
σ ·q (Longitudinal)
0
0.5
1
1.5
2
2.5
3
q (fm^{-1})

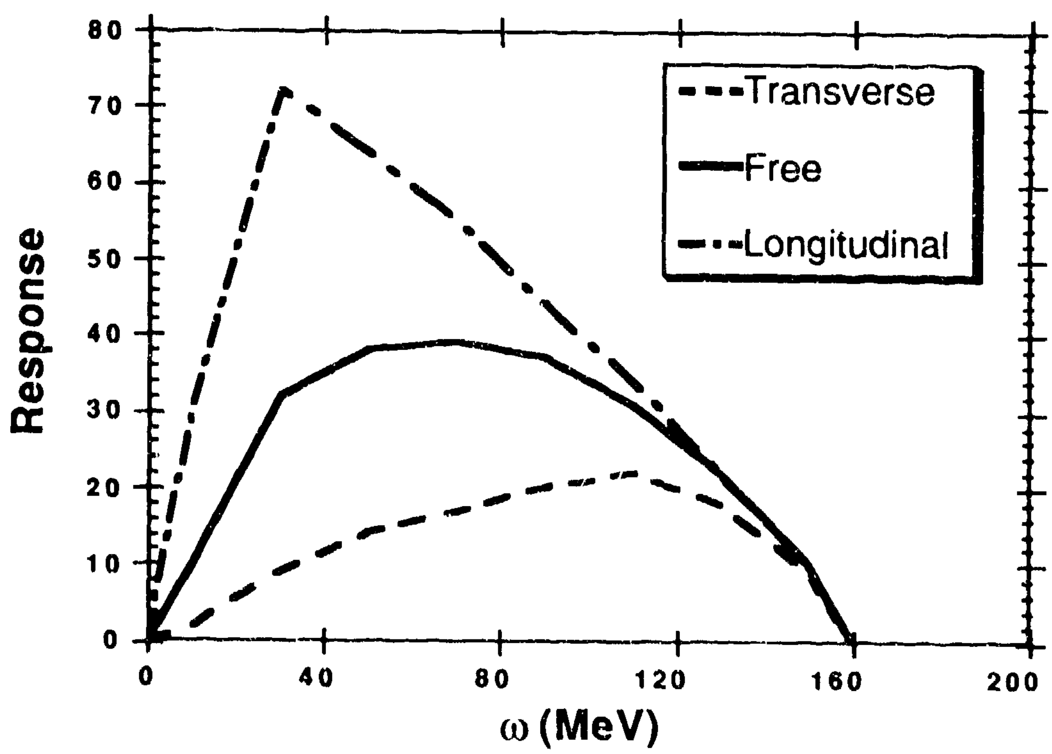
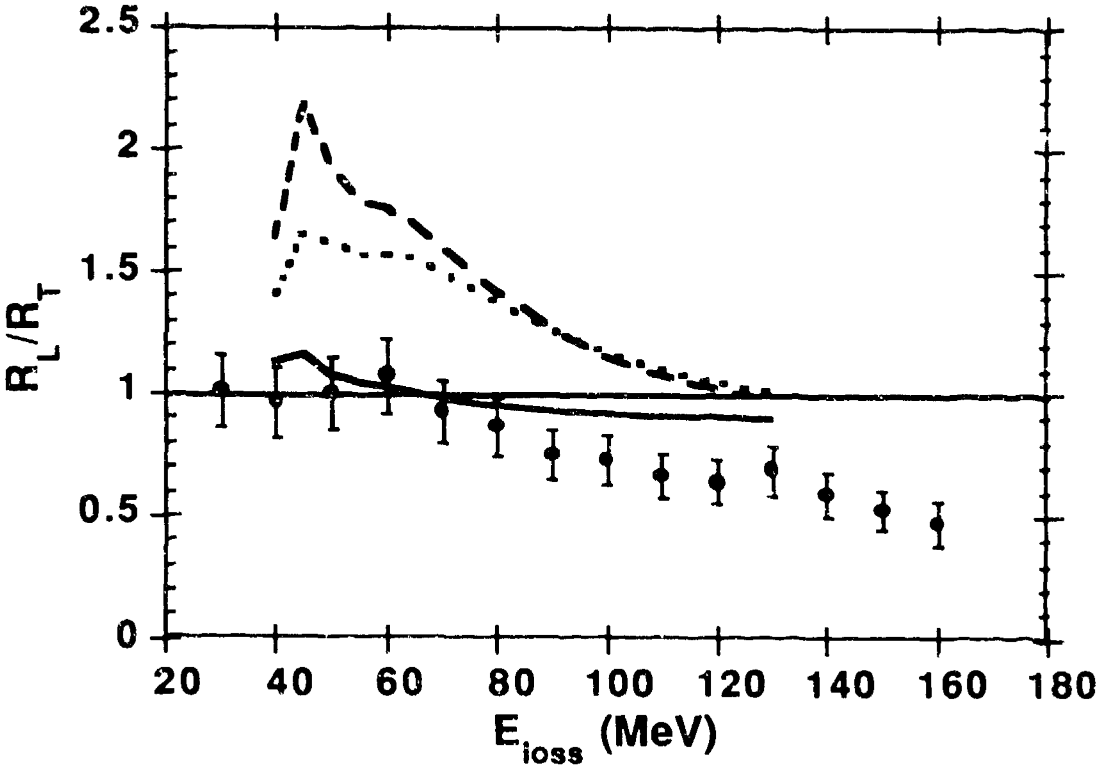
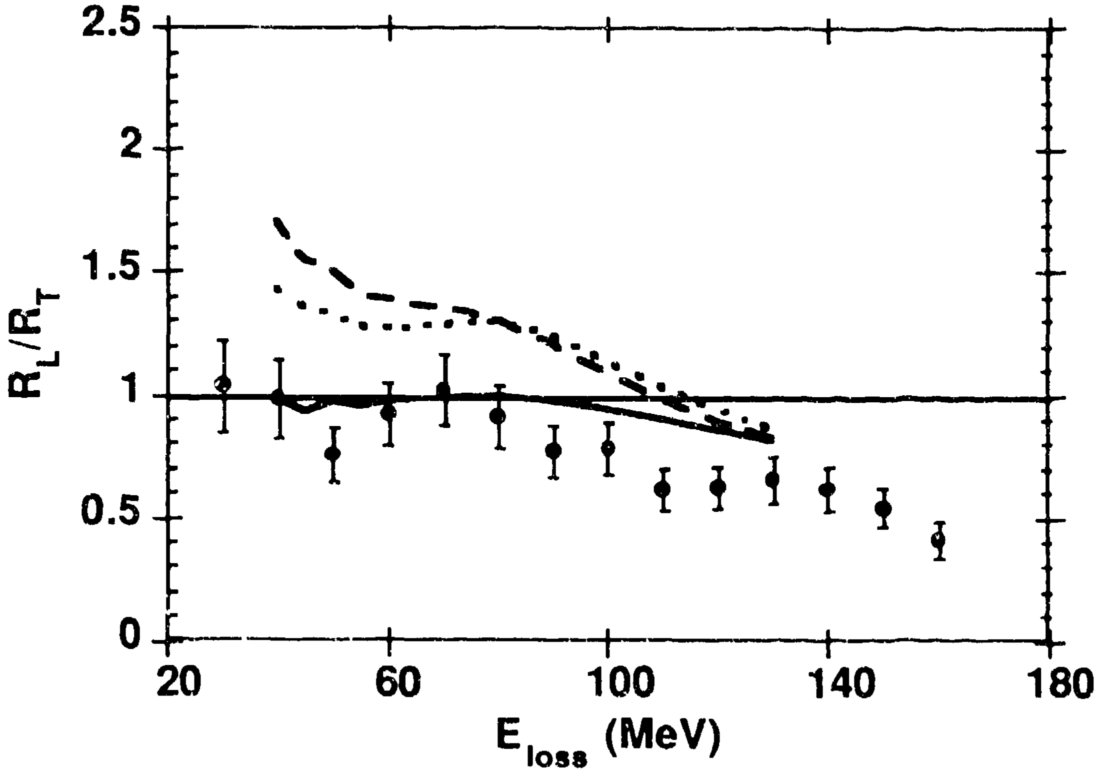


Figure 1 (right)


2.5
2
1.5
1
0.5
0
R_L/R_T
20
40
60
80
100
120
140
160
180
E_{loss} (MeV)



2.5
2
1.5
1
0.5
0
20
60
100
140
180
R_L/R_T
E_loss (MeV)

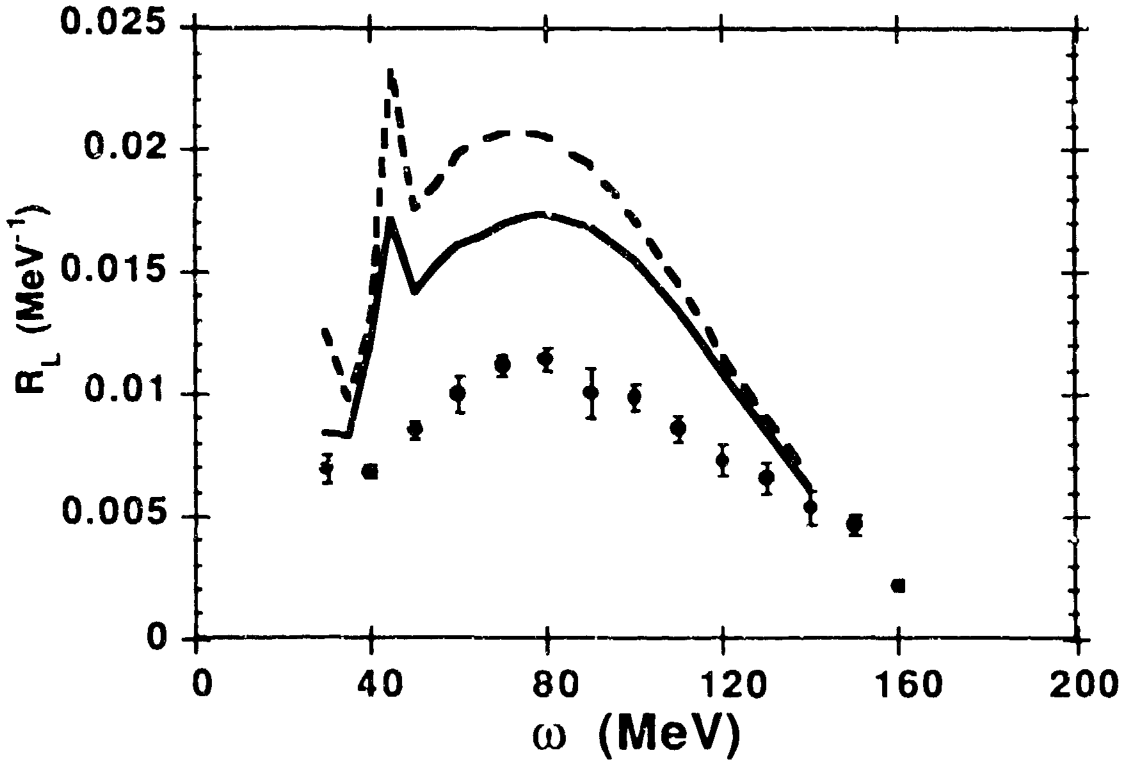


Figure 3 (Top Left)

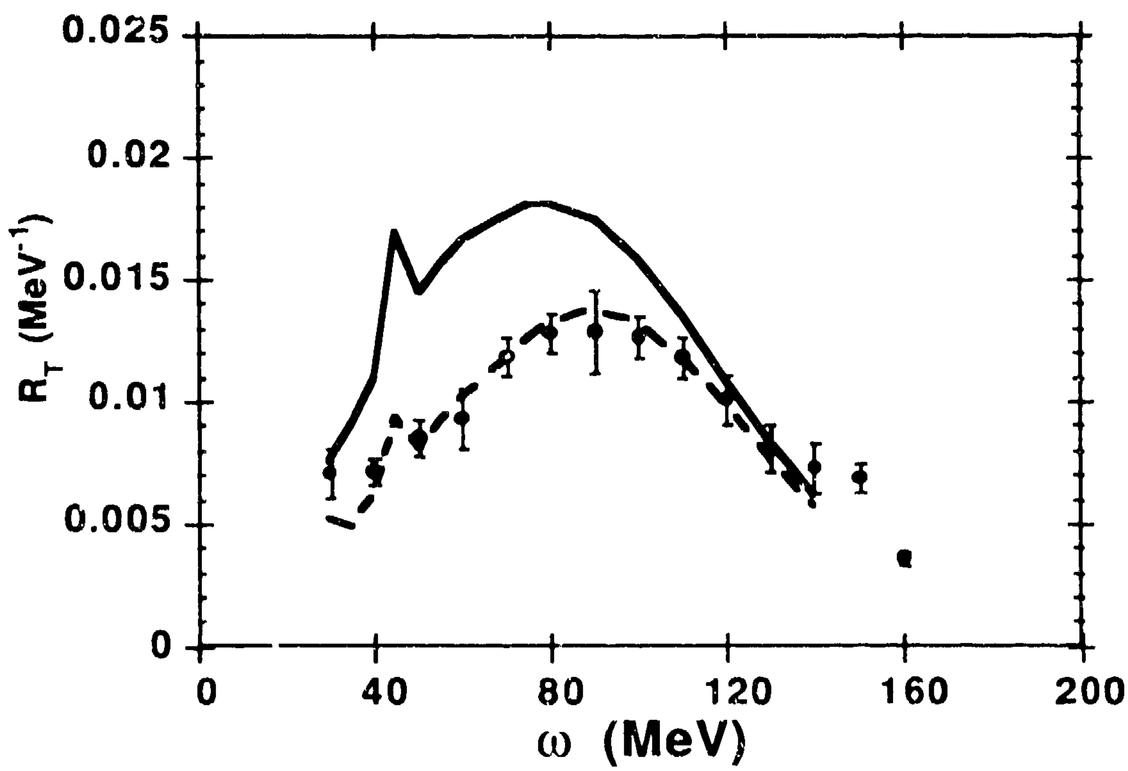
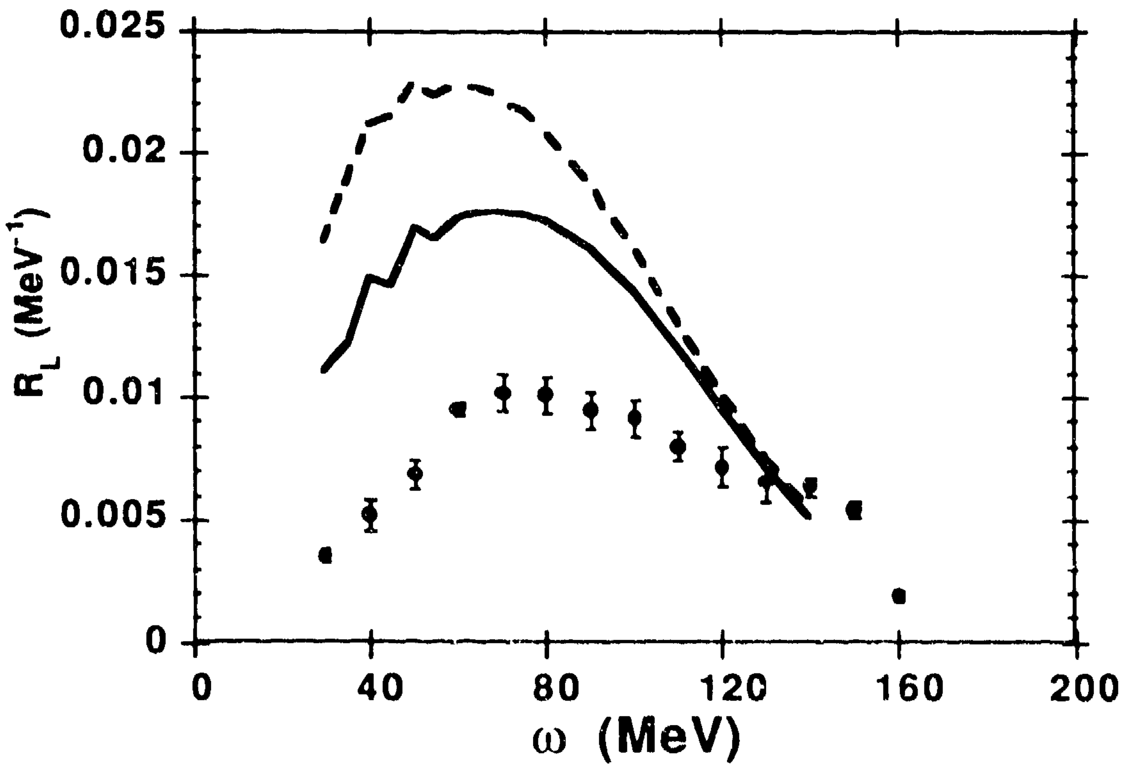


Figure 3 (bottom left)



Fi... 3 (Top right)

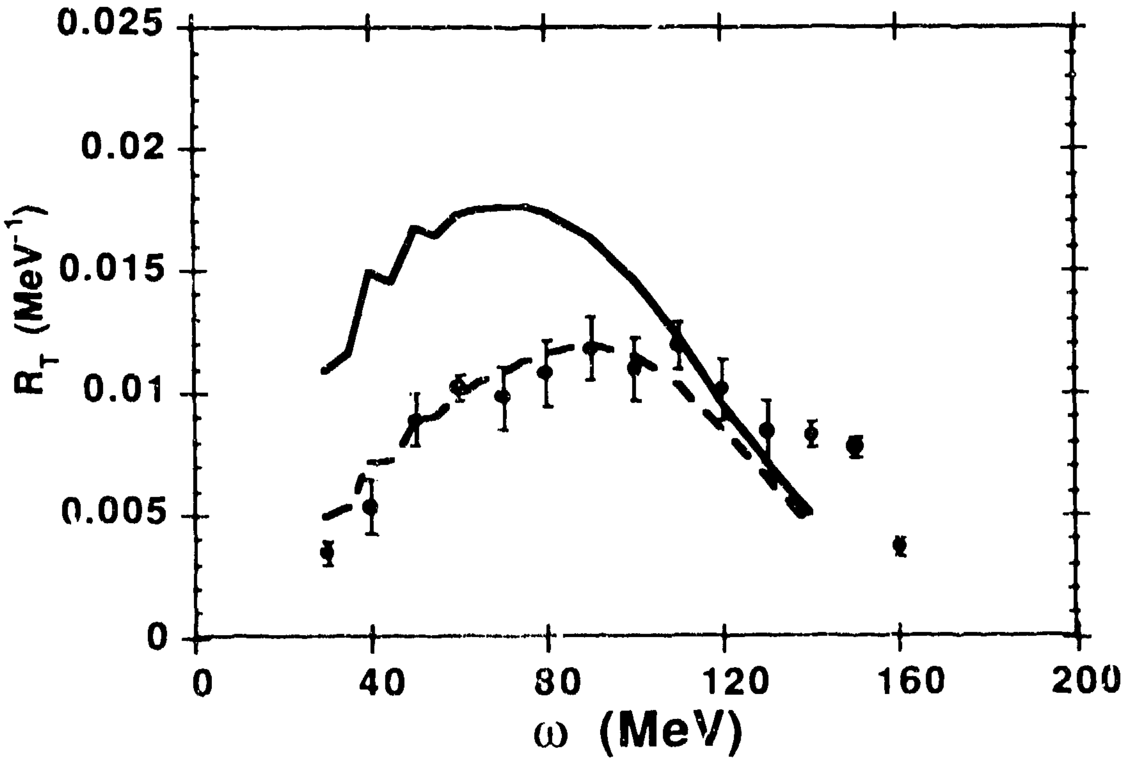


Figure 3 (bottom right)

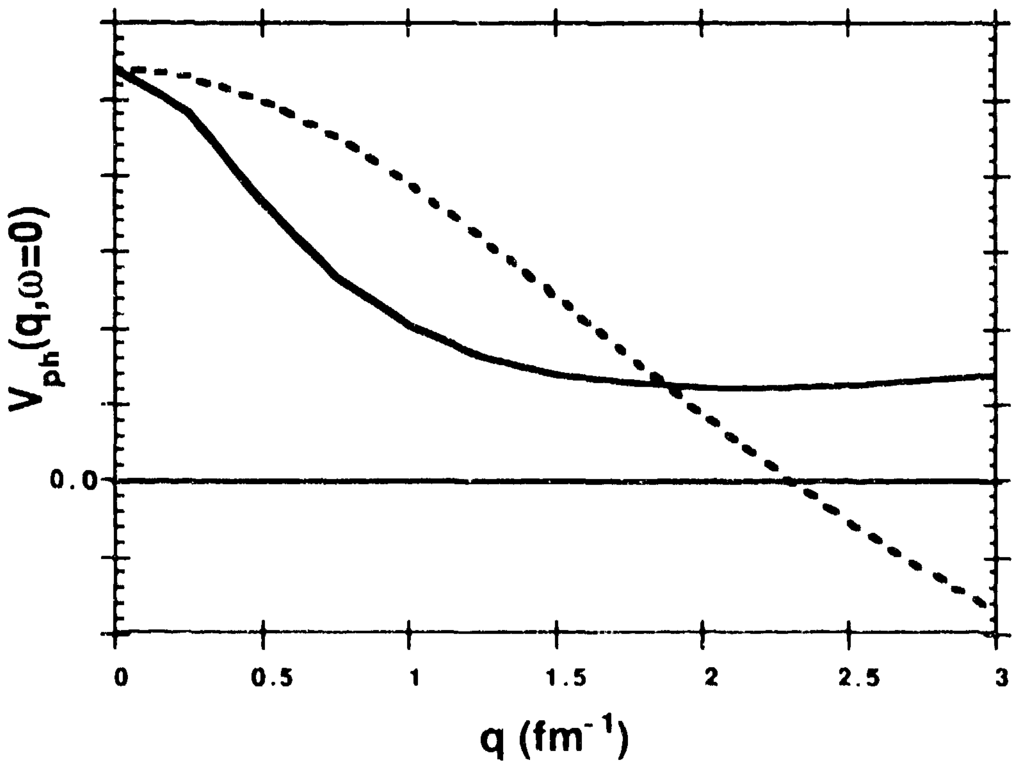


Figura 4