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TITLE: INTERMEDIATE ENERGY NEUTRONS AT WNR

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INTERMEDIATE ENERGY NEUTRONS at WNR

Spin-isospin and energy dependence of the NN interaction and the nuclear response

The major focus of experiments with intermediate energy (50–800 MeV) neutron probes for the next five years will be to explore fundamental details of the spin-isospin and energy dependence of the NN interaction and the nuclear response.

To achieve this goal, the WNR white neutron source will be used for nucleon-nucleon and nucleon-nucleus interaction studies over a broad continuous range of incident neutron energy. Measurement of polarization observables using polarized targets or polarized beam should be possible, and will add an important extra dimension to these studies.

Experimental initiatives:

- elastic np scattering in selected kinematic regions
- inelastic np scattering:

  np bremsstrahlung

  $np \rightarrow pp\pi^-, np\pi^0, nn\pi^+$

  $np \rightarrow d\gamma$
- elastic n-nucleus scattering
- (n,p) reactions: continuum and giant resonance region

Recent Accomplishments in Nucleon Physics at Los Alamos:

LAMPF

- Separation of longitudinal and transverse spin responses for ^{2}H, ^{12}C, and ^{40}Ca
- Observation of medium modification of the tensor interaction at $q = 0$.
- Tests of the isovector content of Dirac optical potentials using (p,n) IAS reactions
- np elastic observables from 300–800 MeV

WNR

- inclusive γ spectrum from np bremsstrahlung
- excitation function for isovector resonances in (n,p) reactions
- energy dependence of the isovector tensor interaction

The 1989 Long-Range Plan

During the development of the last long-range plan in 1989, two Town Meetings were held on the topic of "Light Hadronic Probes." The first meeting was April 23–24 in Bloomington, IN, and the second was May 22-23 in Santa Fe, NM.

The following general theme concerning nucleon probes was expressed in the workshop report from the Santa Fe meeting:

> *The major focus of work with nucleon probes in the next five to ten years can be broadly described as the determination and understanding of the spin-isospin nuclear response function. ... To achieve this goal spin observables will be measured for elastic, inelastic, and charge-exchange scattering to discrete and continuum final states up through the Delta resonance.*

In the Appendix to this report, the experimental thrusts in nucleon physics for the following five years (1989–1994) were outlined:

a. *Investigate medium modification of the free NN interaction, particularly in the charge-exchange channel.*

b. *Understand the dynamics of quasifree charge exchange and Delta production*

c. *Study meson production on nucleons and nuclei, particularly near threshold*

d. *Provide decisive data for comparison of the best relativistic and non-relativistic descriptions of scattering and structure*

Recent Accomplishments and Near-term Plans

Recent progress in the study of intermediate energy (50–800 MeV) nucleon-nucleon (NN) and nucleon-nucleus reactions at Los Alamos has been driven by experiments using the Neutron Time-of-Flight (NTOF) Facility and Optically-Pumped Polarized Ion Source (OPPIS) at LAMPF and the "white" neutron source at the Weapons Neutron Research (WNR) facility. Of these facilities, only the white source at WNR remains in operation.

The key feature of experiments with the NTOF facility and the nucleon physics facility (Area-B) at LAMPF was the measurement of polarization transfer. Such experiments were made possible by the high intensity polarized beam provided by OPPIS. The key feature of experiments performed with the WNR white neutron source was the ability to obtain the energy dependence of observed reactions in the range from 50–600 MeV in a single measurement.

Experiments at the WNR will continue to take advantage of the wide neutron energy spectrum provided by this facility. Experiments involving neutron-proton and neutron-nucleus reactions will continue or are being planned. In addition, plans are being formulated to measure the polarization of the WNR neutron beams. It is likely that in certain energy regions the neutron polarization could be as high as 15–30%. If this can be verified and accurately measured, then experiments involving polarization observables will become possible.

Polarization transfer in (p,n) reactions

The collective response of a nucleus to the influence of an external probe is intimately linked to the character of the mesonic fields in the nuclear medium. Collective behavior is manifested as enhancement or quenching of the nuclear response in specific spin-isospin channels and a shift of the responses toward higher or lower excitation energy. The isovector spin responses are expected to show an enhanced ratio between spin-longitudinal $(\sigma \cdot q)$ and spin-transverse $(\sigma \times q)$ response functions for momentum transfers near 1.5 fm^{-1}, as predicted by the $\pi + \rho + g'$ mesonic-exchange models of the nuclear mean field.

Over the past four years the NTOF facility at LAMPF has been used to measure the isovector spin responses in quasifree (p,n) reactions on ^2H, ^{12}C, and ^{40}Ca. Measurements have been carried out for three momentum transfers ($q = 1.2, 1.7, 2.5$ fm^{-1}) at 494 MeV incident proton energy, and for one momentum transfer ($q = 1.7$ fm^{-1}) at 795 MeV. The experimental technique involves measurement of a complete set of polarization-transfer observables, in which the polarization of both the incoming proton and outgoing neutron are completely determined.

The spin-transverse responses obtained from these measurements can be compared to those measured in deep inelastic electron scattering. The spin longitudinal response represents new information not accessible by electromagnetic probes. Analysis of the separated responses reveals reasonable agreement between the longitudinal response and random phase approximation (RPA) structure calculations, but the transverse response is greatly enhanced relative to both the RPA predictions and the transverse responses observed in electron scattering. This result is contrary to early interpretations of response ratios, which attributed a lower-than-expected longitudinal/transverse ratio to a deficit in the longitudinal response.

Excitation of the Delta resonance in nuclei via (p,n) and $(^3He,t)$ reactions reveals a considerable downward energy shift of the resonance peak position compared to that measured on the proton. These reactions excite both the isovector spin-longitudinal $(\vec{S}\cdot\hat{q})$ and spin-transverse $(\vec{S}\times\hat{q})$ nuclear responses. In contrast, electromagnetic probes, which excite the Delta through a predominantly spin-transverse coupling, show little shift in the Delta peak in nuclear targets compared to the proton. This observation led to the suggestion that nuclear correlations in the spin-longitudinal (pion) channel could be responsible for the shift seen in the $(^3He,t)$ and (p,n) reactions. This interpretation has been supported by a number of calculations indicating that much of the observed shift is due to a strong collective pion mode in the spin-longitudinal channel.

The NTOF facility has been used to measure polarization transfer for Delta production in ^{2}H(p,n) and ^{12}C(p,n) reactions at 0° and 795 MeV incident energy. From these measurements, the spin-longitudinal, spin-transverse, and non-spin partial cross sections have been obtained. Fair agreement is observed between the experimental cross sections and theoretical predictions for the spin-longitudinal channel. In contrast, the cross section in the spin-transverse channel is much larger than expected.

The results of the quasifree nucleon and quasifree Delta measurements present a consistent picture of nuclear isovector spin responses. In both regions the longitudinal response is fairly well described by theoretical calculations that include an attractive residual interaction in the pion channel. On the other hand, in both excitation regions there is an excess of cross section in the transverse channel. This consistent effect that spans both nucleon and subnucleon regions of excitation should stimulate some reevaluation of the respective roles played by mesonic fields in the nucleus.

Some open questions remain that are intimately linked to the interpretation of the quasifree nucleon and Delta data. Extraction of the "bare" spin responses from the measured spin cross sections requires a well understood reaction model. The usual framework in which these data are interpreted is the distorted-wave impulse approximation (DWIA) or, with some simplifying assumptions, the plane-wave impulse approximation (PWIA) with eikonal distortions. In both these models, it is important to have accurate free nucleon-nucleon amplitudes as input, and to understand the role of the nuclear medium in modifying these amplitudes. There are indications that the present nucleon-nucleon data base does not sufficiently constrain NN phase shift solutions in the kinematic regions relevant to the quasifree data. Some new measurements of np elastic scattering in specific kinematic regions may therefore be valuable. Relativistic (Dirac) formulations of the PWIA model implicitly modify the NN amplitudes in the nuclear medium and thereby affect polarization and cross section observables. These relativistic formulations for quasifree scattering are closely connected to relativistic models of elastic nucleon scattering. Calculations by Ichimura and collaborators have shown that spin-dependent distortion of the projectile waves may have large effects on certain polarization transfer observables. It is therefore important to refine current models and arrive at a consistent relativistic description of both elastic and inelastic nucleon-nucleus scattering. Because the (p,n) data are sensitive to the isovector components of the distorting fields, additional data such as neutron elastic scattering may be crucial to the development of such models.

The random phase approximation (RPA) has been used to generate the nuclear structure amplitudes used in studies of the nuclear quasifree spin responses. Recent theoretical work has pointed out deficiencies in this approach, and has suggested that studies of light systems such as ^{2}H or ^{3,4}He may help refine the theoretical framework necessary to understand the response of heavier nuclei. Plans are moving forward to continue quasifree polarization transfer studies on light nuclides with the (p,n) reaction at IUCF. The NTOF detector system and several key magnets required to precess the outgoing neutron polarization have been moved to IUCF in a major upgrade of the neutron time-of-flight facility at that laboratory. WNR physicists are collaborating on this project.

np bremsstrahlung

Nucleon-nucleon bremsstrahlung examines directly the fundamental nucleon-nucleon force through coupling of the strong and electromagnetic (EM) components of the interaction. Bremsstrahlung is the lowest energy inelastic reaction that occurs in nucleon-nucleon scattering and the only inelastic reaction that occurs below the pion production threshold. Neutron-proton bremsstrahlung (npb) and proton-proton bremsstrahlung (ppb) probe entirely different aspects of the nucleon-nucleon interaction. The EM interaction couples to the charge of the exchanged meson. In ppb only neutral mesons are exchanged. Thus, meson-exchange-current contributions in ppb are minimal, and ppb probes primarily off-shell properties of the nucleon-nucleon amplitude. The contribution from exchange currents in npb enhances the cross section by a factor of two. Thus, npb is a direct probe of meson-exchange contributions to the nucleon-nucleon amplitude. Bremsstrahlung reactions can explore a continuum of photon energies for a given initial condition, and they are therefore complementary to np radiative capture and deuteron photodisintegration reactions. Recent measurements of ppb with polarized beam were made at TRIUMF, and ppb measurements are planned at COSY, CELSIUS, and KVI. In contrast, npb data are very sparse, and no differential npb cross section data exist. The neutron white source at WNR provides a unique tool with which to make such npb cross section measurements as a function of incident neutron energy from 50 MeV to the threshold for pion production.

As a first step towards measuring differential npb cross sections at WNR, inclusive *np* gamma-ray production has been measured. Data have been obtained over a neutron energy range of 50–300 MeV. These measurements will contribute to the understanding of the source of high-energy gamma-rays that have been observed in heavy-ion reactions. Heavy-ion induced gamma-ray yields were calculated assuming binary neutron-proton collisions with a semi-classical "calibrated" formula for the npb cross section. Although the comparison to theory is not yet complete, it appears that the inclusive data support this assumption and collective effects are not necessary to explain the gamma yields in heavy-ion reactions.

Techniques are being developed for measuring the differential npb cross section by observing neutron-proton coincidences. The differential cross section provides a more sensitive measure of meson exchange currents than the inclusive photon cross section. Elastic *np* scattering has been used to verify the techniques necessary to observe bremsstrahlung events. The first npb coincidence measurements are planned to begin next year. These new measurements will test model predictions that 40% of the exchange-current enhancement comes from the little understood heavy-meson component.

NN elastic scattering

The primary goal of the nucleon-nucleon (NN) program at LAMPF has been to determine the NN elastic scattering amplitudes to an accuracy of 5% at energies up to 800 MeV. There are five complex amplitudes, so in principle ten well-chosen experiments are sufficient to determine both real and imaginary parts. The isospin-1 amplitudes have been over-determined by measuring sixteen spin-dependent pp-elastic observables. The isospin-0 amplitudes are determined from np scattering. In 1993, the final year for polarized beam at LAMPF, measurements of polarization observables for np elastic scattering at several energies completed the set of data required to determine the NN elastic scattering amplitudes at 500, 580, 650, and 800 MeV in a model independent way.

The new spin transfer data have a statistical weight about an order of magnitude larger than the best previous data. The unprecedented accuracy of these measurements was made possible by the high intensity beam (up to 1 micro-amp average) from the Optically Pumped Polarized Ion Source (OPPIS) and an extensive system of spin precession equipment and polarization monitoring instrumentation. A detailed study has shown that systematic errors associated with beam from OPPIS are at least an order of magnitude smaller than those from the previous Lamb-shift source.

Although the *np* differential cross section is known at the 5% level throughout much of the energy range from 50-600 MeV, recent measurements very near 180°, where previous data are scarce, indicate a disagreement with theory and other measurements. This region is sensitive to the π-nucleon coupling constant. Preliminary data obtained at WNR for this reaction near 180° are under analysis.

N-Nucleus elastic scattering

It is desirable to determine a realistic medium-energy nucleon-nucleus global optical model potential for both fundamental and applied research reasons. "Global" means that the potential describes the scattering observables as a function of projectile isospin (proton or neutron), projectile energy, and target species (Z, A), and "realistic" means accurate predictive power in addition to accurate reproduction of the experimental data used to produce the potential. No such potential exists. Limited range medium-energy proton-nucleus global optical potentials do exist for both Dirac and Schroedinger approaches. However, no complete global study has been performed that includes projectile isospin in either Dirac or Schroedinger formalisms.

One reason for this lack is the absence of measured intermediate energy (50–800 MeV) neutron elastic scattering observables. The data that do exist consist mostly of neutron-nucleus total cross sections. These total cross sections have been measured very accurately (few percent) at WNR. The neutron total cross section data for ^{208}Pb have been combined with a large amount of corresponding proton scattering observables for ^{208}Pb to produce a global nucleon-nucleus Dirac potential. This potential predicts well the few angular-dependent neutron scattering observables that do exist. The isospin dependence of this potential has been used to predict and compare spin observables for both protons and neutrons. The differences are dramatic and are compelling from the point of view of demand for experimental verification. If the same spin observables are calculated using a Schroedinger approach (JLM folding model) similar dramatic differences are obtained and again are compelling from the point of view of experimental verification. Moreover, the differences between the two calculational approaches are sufficiently large that a good measurement would determine which, if either, is correct. In particular, measurement of the analyzing power A_y for ^{208}Pb using both polarized neutrons and protons, at several energies between 100 and 300 MeV, could shed considerable light on these questions.

(n,p) reactions

Charge exchange reactions have been studied extensively at IUCF, TRIUMF, LAMPF and WNR using both proton beams and neutron beams. Such studies have concentrated on the effective isovector NN interaction and on the excitation of giant spin-isospin resonances. Because the energy dependence of the spin-flip and non-spin-flip components of the NN interaction is different, this relative energy dependence, once it has been quantified, can be used to investigate the spin-dependent character of inelastic excitations.

The energy dependence of the central isovector interaction strengths $V_{\sigma\tau}$ and V_τ has been mapped out at discrete energy intervals using (p,n) reactions at IUCF, TRIUMF, and LAMPF. Measurements using the (n,p) reaction at the WNR have confirmed this dependence in a single experiment. The energy dependence of the effective isovector-tensor interaction has been similarly measured using the $^{10}B(n,p)^{10}C$(g.s.) $3^+ \rightarrow 0^+$ reaction

The energy dependence of the effective interaction has been exploited with dramatic effect in studies of inelastic giant resonances excited with the (n,p) reaction. Spectra obtained at WNR for neutron energies spanning the region from 60-220 MeV reveal the different spin components of the giant dipole resonance as well as a rich variety of other resonance structures at higher excitation energy that have yet to be characterized. Additional measurements of this sort will be pursued on a variety of target nuclides, and the possibility of utilizing the polarization of the neutron beam would further enhance study of the high-lying resonance structures.

This material in this report has been compiled from several sources. For further information, please contact:

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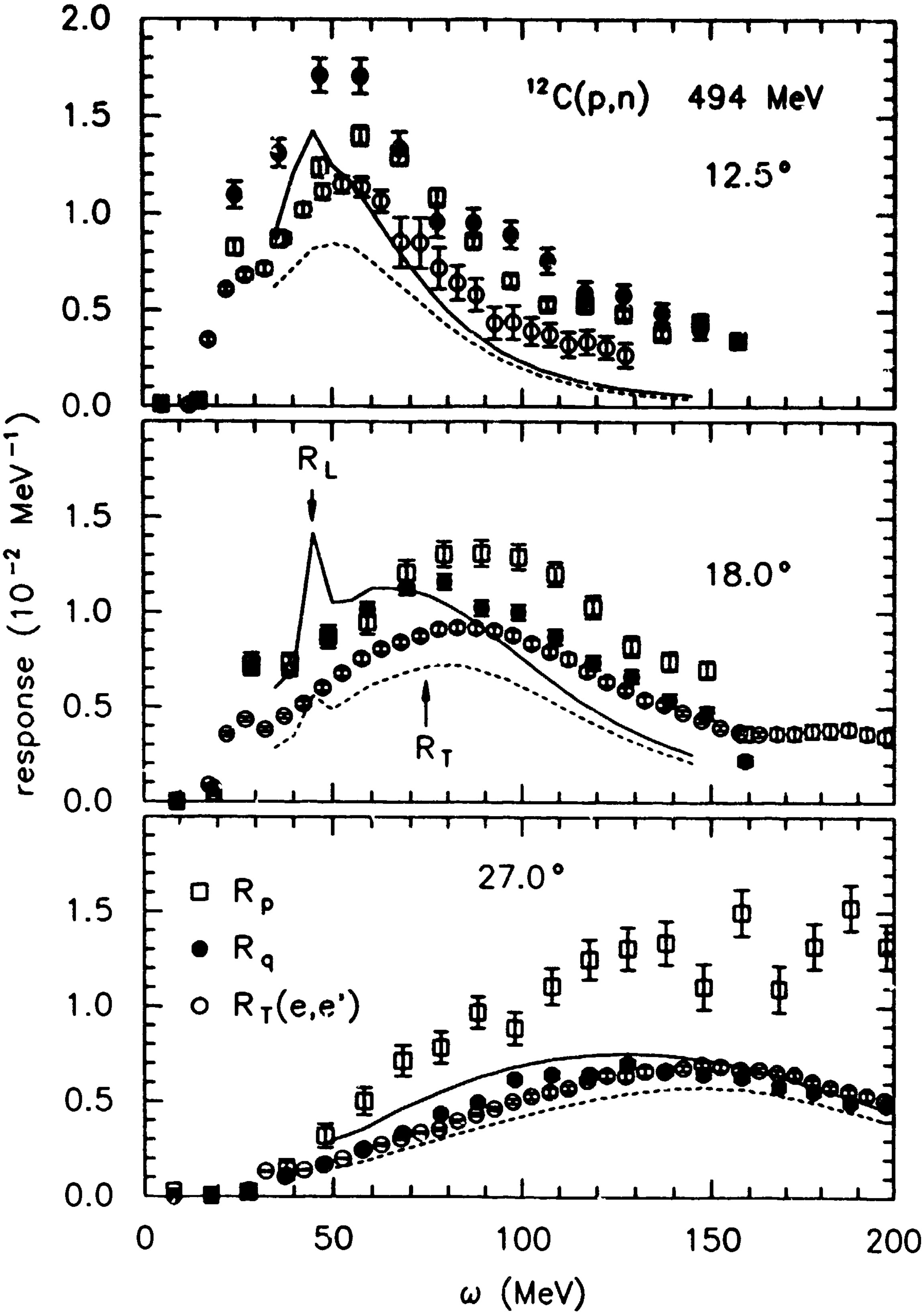
Figures

Figure 1: Longitudinal (R_q, solid circles) and transverse (R_p, open squares) responses for $^{12}C(p,n)$ at 494 MeV compared to longitudinal (R_L, solid lines) and transverse (R_T, dashed lines) RPA responses. The open circles represent the transverse spin response R_T obtained from $^{12}C(e,e')$ at q =250, 350, and 500 MeV/c.

Figure 2: Partial spin-flip cross sections for excitation of the Delta resonance in the $^{12}C(p,n)$ reaction at 795 MeV and 0° scattering angle. The top panel shows the spin-longitudinal cross section σ_L compared to DWIA calculations with RPA correlations (solid line) and without correlations (dashed line). The bottom panel shows the spin-transverse cross section σ_T compared to similar calculations for the transverse channel.

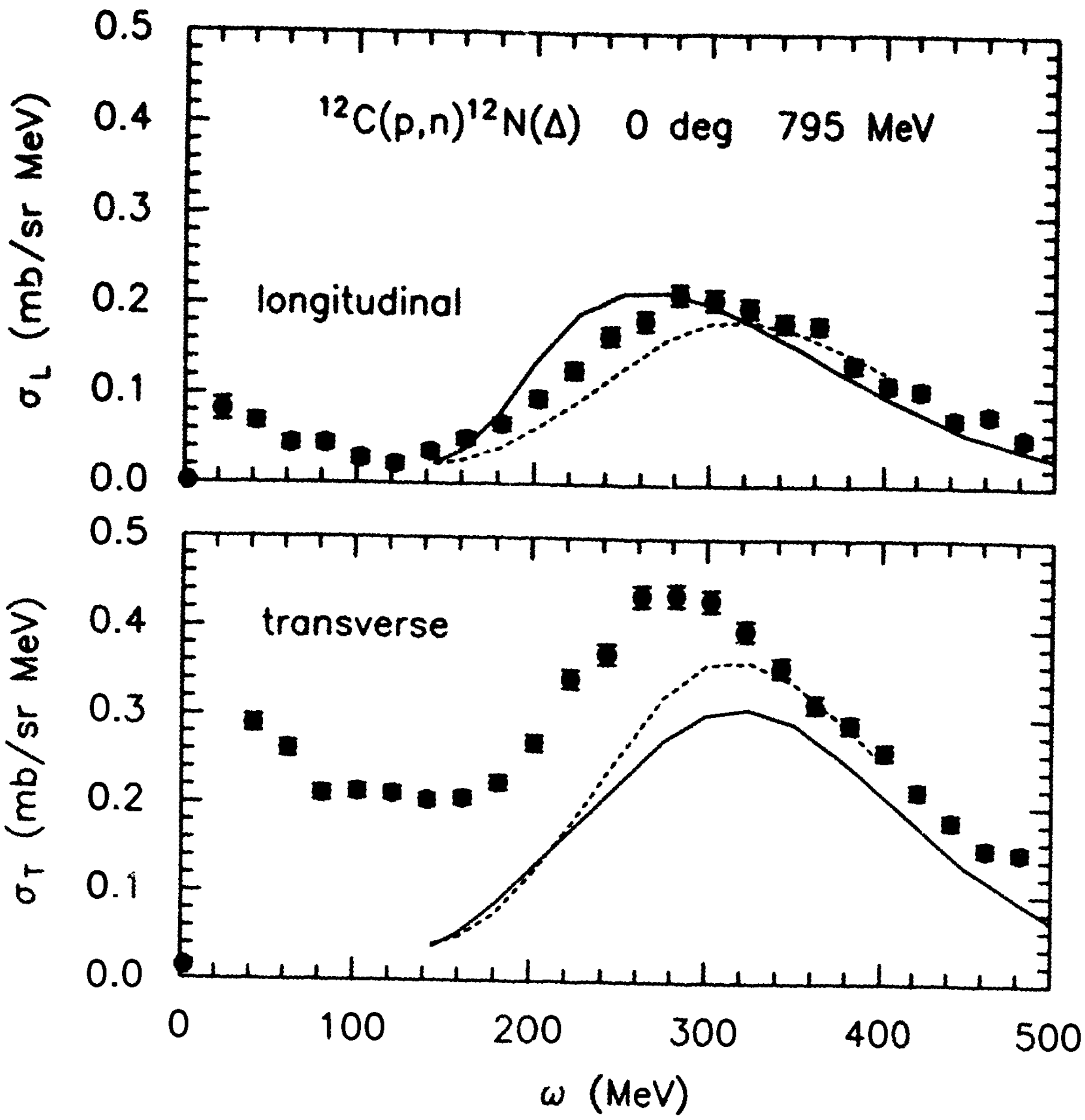
Figure 3: Inclusive proton spectrum obtained with the WNR white neutron source for the $^{32}S(n,p)$ reaction at $\theta_{lab} = 7°$. The energy dependence of the NN interaction causes non-spin resonances to be prominent for the lowest incident neutron energies and spin-flip resonances to be prominent at the highest energies.

Figure 4: Elastic (n,p) scattering observed with three conjugate-angle detector pairs at the WNR white source. In a single measurement, elastic events can be obtained for incident neutron energies in the range from about 50 MeV to 650 MeV. The data shown represent about one day of beam time. These data are being used to refine techniques necessary to observe np bremsstrahlung events.



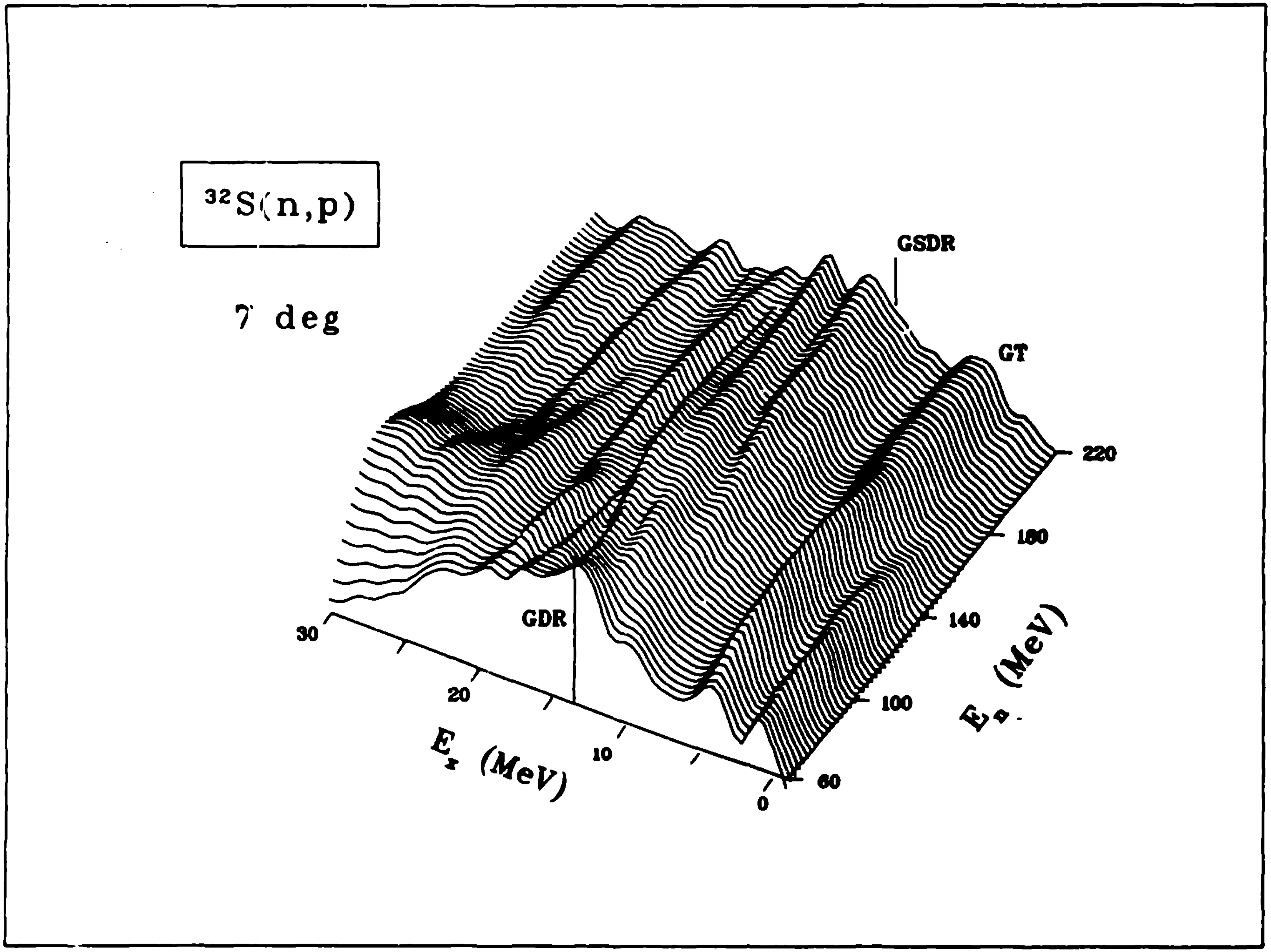
^{12}C(p,n) 494 MeV
12.5°
18.0°
27.0°
R_L
R_T
R_p
R_q
R_T(e,e')
response (10^{-2} MeV^{-1})
ω (MeV)

Figure 1

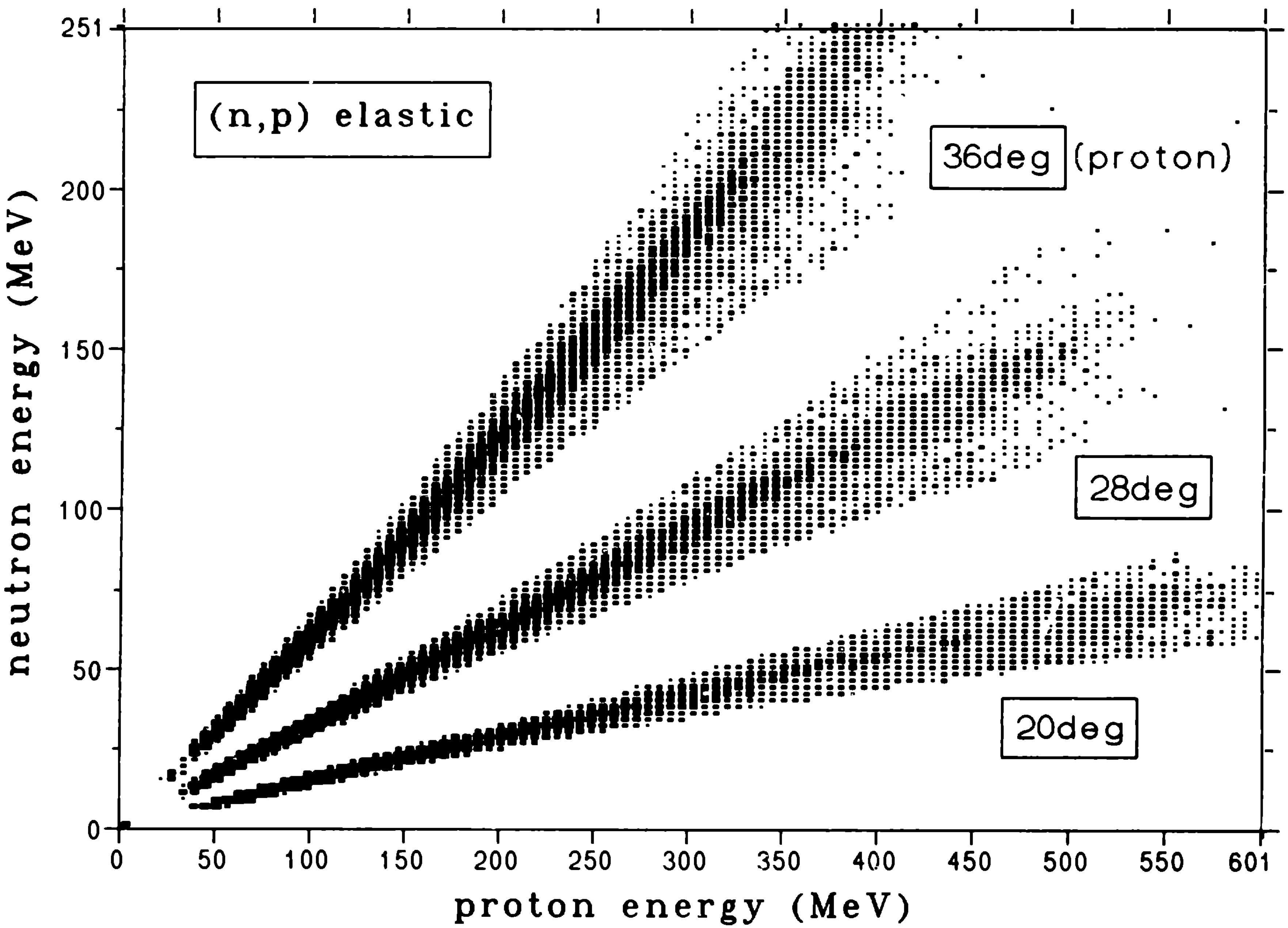


$^{12}C(p,n)^{12}N(\Delta)$ 0 deg 795 MeV
longitudinal
transverse
σ_L (mb/sr MeV)
σ_T (mb/sr MeV)
ω (MeV)
0.0
0.1
0.2
0.3
0.4
0.5
0
100
200
300
400
500

Figure 2



$^{32}S(n,p)$
7 deg
GSDR
GT
GDR
220
180
140
100
60
E_n (MeV)
30
20
10
0
E_x (MeV)



(n,p) elastic
36deg (proton)
28deg
20deg
neutron energy (MeV)
proton energy (MeV)
251
200
150
100
50
0
0
50
100
150
200
250
300
350
400
450
500
550
601