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EXCITATION OF GIANT RESONANCES IN PION INELASTIC SCATTERING

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Abstract - We present some recently obtained data for resonance energy inelastic pion scattering to the giant resonance region of nuclei. New results include the observation of candidates for spin-dipole resonances in $^{12}$C and $^{28}$Si, and the observation of large $K^+,\pi^-$ cross section asymmetries for the continuum region in $^{208}$Pb.

I - INTRODUCTION

Both hadronic and electromagnetic probes have been used to excite giant resonances in inelastic scattering. Although these studies have contributed much to our understanding of the nuclear response, the results have not always been consistent among the different probes. Pion inelastic scattering provides a new hadronic probe which, because of its unique spin-isospin couplings, may both excite new modes and provide new information about previously observed resonances to help resolve existing discrepancies.

Published studies of pion inelastic scattering to the giant-resonance regions of $^{40}$Ca [1], $^{89}$Y [2], $^{12}$C [3], and $^{118}$Sn [4] have shown some interesting results. In the three heavier nuclei the giant quadrupole resonance (GQR) was strongly excited. Although in all three nuclei the deduced sum-rule fraction was generally consistent with that extracted with other probes, in $^{118}$Sn the energy-weighted sum-rule fraction observed in $\pi^-$ scattering was twice that observed in $\pi^+$ scattering. In $^{12}$C little or no quadrupole strength was seen. However, a strong signature of the giant dipole resonance was observed. In addition evidence for the spin-flip dipole modes expected from the generalized [5] Goldhaber-Teller model was observed.

One common feature of these studies was the limited forward angular range of the data. Recently, the EPICS channel and spectrometer [6] at LAMPF have been modified to allow data to be taken at far forward angles. In the present talk we describe these modifications and present some new data obtained with this system.

II - SMALL ANGLE MODIFICATIONS

Small-angle measurements of pion inelastic scattering are difficult because of high counting rates and large muon backgrounds arising from in-flight decays of both beam and elastically scattered pions. Several modifications to the standard EPICS system were made to allow forward-angle data to be obtained. These modifications are shown in the schematic drawings of the pion channel and spectrometer (Fig. 1) and are discussed below.
The proton flux through the EPICS channel is approximately 10 times larger than the pion flux. At angles larger than 20° these protons cause no problems in normal data taking. Forward of this angle the large energy-loss signals produced by elastically scattered protons in the front spectrometer chambers cause reduction in efficiency due to space-charge effects. In order to remove these protons from the incident beam, a 250mg/cm² absorber was placed in the channel at the focus between the last two channel dipole magnets, BM03 and BM04 (see Fig. 1). The magnetic field in BM04 was adjusted to compensate for energy loss of the pions in passing through the absorber. Protons suffered a much larger energy loss in the absorber and were bent out of the beam by BM04. Measurements made with and without the absorber in the beam showed that the only detectable effect of the absorber on the pion beam was degradation of the energy resolution from 150 keV (FWHM) to 200 keV (FWHM).

Remaining problems were due to muon backgrounds. Counting rates with the full channel acceptance (~2x10⁸ π⁻/sec) were too large to handle. The channel acceptance was reduced in momentum from ±1.0% to between ±0.15% and ±0.07%, with the smaller acceptance used at the most forward spectrometer angles, using the collimator FJ04. This resulted in a reduced vertical beam spot size of between 6 and 3 cm. To first order, the beam spot is imaged on the front chambers (C1-4) with a magnification of minus one. A lead collimator with an opening of 5.1 cm was placed in front of C1-4 in order to reduce the acceptance for muons (which result in a larger image than scattered pions) relative to that for pions. The location of this collimator is shown in Figure 1.

A scintillator (S1) 3.8 cm high by 3 mm thick was placed in the center of the collimator opening to eliminate events corresponding to slit-edge scattering from the hardware trigger and to provide a start signal for measuring time of flight (TOF) through the spectrometer dipole magnets. As these TOF signals were not corrected for path-length variations, only about 80% of muon events could be rejected from the hardware trigger using S1 without biasing the acceptance for pions. Path-length corrections were made to the TOF on an event-by-event basis in the software. The resulting time resolution of 700 ps (FWHM) enabled clean separation of pions and muons, as shown in the TOF spectra presented in Fig. 2.

At the most forward angles the muon rejection provided by TOF was insufficient to define a trigger clean enough to obtain inelastic data. Another level of muon rejection was provided by placing a carbon wedge backed by a scintillator in the spectrometer focal plane, as shown in Fig. 1. The thickness of the wedge was set to be close to the pion range as a function of focal plane position (crudely corresponding to momentum). Pions were both ranged out and absorbed by nuclear interactions, whereas muons passed through the absorber and were detected by S4.
The effectiveness of this technique is demonstrated in Fig. 2, where TOF spectra are separately presented for events accepted and rejected by S4. Efficiency scans of the muon rejecter made by observing an elastic line with the spectrometer magnets fixed and channel magnets varied showed approximately 96% of all muons were rejected while only 2% of pions were rejected by this method.

![Fig. 2 - Time of flight spectrum for a) pions, b) muons as determined by the focal-plane muon rejecter.](image)

In addition to the methods listed above each event was required to have a trajectory which projected back to the target, and to have angles entering the spectrometer which were consistent with those exiting the spectrometer within ±10 mrad using the known optics. This requirement was especially useful for rejecting events in which pions decayed between the front and rear chambers.

At forward angles the hardware trigger required the TOF through the spectrometer to be in the range expected for pions, and required the absence of a signal from the focal plane muon rejecter. In addition, a first order hardware calculation of momentum loss, using coarse position information from the drift chambers, was used to reject 99 out of every 100 elastic scattering events from the hardware trigger. At larger angles the trigger requirements were relaxed, and the corresponding cuts were made in the software. The typical fraction of events which were pions varied from several percent at 8° to nearly 1.0 at 20°. More than 96% of the muon events were eliminated from the hardware trigger by the requirements listed above. The remaining muons were eliminated by software cuts.

A missing-mass spectrum obtained at 8° for 162 MeV pion inelastic scattering from $^{12}$C is shown in Figure 3. This spectrum has been corrected for focal-plane efficiency, and has been corrected for the rejected elastic events.
Fig. 3 - Missing mass spectrum for 162 MeV π+ scattering from $^{12}\text{C}$ at 8° laboratory angle.

III - LOW LYING COLLECTIVE STATES

At incident pion energies between 100 and 300 MeV the $\Delta_{3-3}$ resonance dominates the pion-nucleon interaction. In the static-DWIA model, where intermediate $\Delta$ propagation is ignored, the relative strengths of the central, spin-dependent, and isospin-dependent parts of the force are fixed with respect to each other by the quantum numbers of the $\Delta$. The strongest part of the force is the spin-isospin independent part. Consequently collective states are strongly excited in pion inelastic scattering.

A comparison of DWIA calculations using empirically determined form factors from inelastic electron scattering in general gives excellent agreement with pion inelastic scattering to such collective states [7-10]. Cross sections and calculations of resonance energy (incident pion energy of 180 MeV) pion scattering [11] from the ground state and $2^+_1$ member of the rotational band in $^{152}\text{Sm}$ are presented as an example in Figure 4. The DWIA (dashed line) and coupled-channel-impulse approximation (CCIA solid line) calculations shown in the figure have used collective-model form factors determined from elastic and inelastic electron scattering. A departure from the static model is an energy shift of -28 MeV used in evaluating the T-matrix elements from pion-nucleon phase shifts. This phenomenology has been shown to improve fits to elastic scattering [12]. The quality of agreement between the calculations and the data in this case is typical of that obtained in other nuclei for strongly excited collective states.

Some exceptions to this generally good agreement have been observed. In a comparison of DWIA calculations with data for low lying states in $^{12}\text{C}$ and $^{40}\text{Ca}$ [7] small-angle cross sections for the $2^+_1$ (4.44 MeV) state were observed to be underestimated by nearly a factor of two while those for the $0^+_2$ state were overestimated by a similar factor. The results of a more detailed study of pion inelastic scattering from $^{12}\text{C}$ at forward angles at 162 MeV incident pion energy along with some calculations are presented in Figure 5. The explanation of the discrepancies between static-DWIA calculations (solid line) and the data rests in two different higher-order processes. The enhancement of the $2^+_1$ cross sections at forward angles arises from spin-flux tensor coupling terms that appear in the isobar-hole model. These have been evaluated in a dynamic-DWIA calculation by Lenz,
Thies and Horikawa [13] (dashed line). These extra tensor pieces of the interaction do not affect transitions with $\Delta j < 1$, and so do not explain the forward-angle cross sections for the $0^+_2$ state, as can be seen by comparing the dynamic-DWIA and static-DWIA calculations for this state.

This discrepancy has been removed by Sparrow and Gerace [14] by calculating two-step contributions through the $2^+_1$ state. These have been evaluated in the coupled channel impulse approximation (CCIA), shown as the dot-dash line in the figure. The form factors used in these calculations have been fit to available electromagnetic observables and, as can be seen, give a good description of the data.

IV - SPIN-FLIP DIPOLE STATES

Resonance-energy pion inelastic scattering can also excite states which involve $\Delta S \neq 0$ and/or $\Delta T \neq 0$. One example of such an excitation which involves $\Delta S = 0$, $\Delta T = 1$ is the giant dipole resonance (GDR). If the Goldhaber-Teller model of this resonance is extended to include spin degrees of freedom, and if spin-dependent nuclear forces are ignored, then there ought to be states with $\Delta S = 1$ (with $j^s = 0^-$, $1^-$ and $2^-$) degenerate in energy with the GDR. The $T = 0$ members of this multiplet correspond to dipole excitations with spin-up particles oscillating against spin-down particles rather than neutrons oscillating against protons as is the case for the GDR. Strong evidence for considerable $2^-$ strength with $T = 0$ and 1 in the region of the GDR in $^{12}$C has already been observed in pion inelastic scattering [3]. The evidence for $1^-$ spin-flip strength was much weaker because the data did not go to small enough angles.

Both DWIA and eikonal model calculations predict angular distributions for a $J^m = 1^-$; $\Delta S = 1$ excitation to follow $[J_0(qR)]^2$ at forward angles. This is unlike the angular distribution expected for the GDR, which is expected to follow $[J_1(qR)]^2$ and to go to zero at $0^0$, but is the same as that expected for a $0^+$ excitation. The previously described small-angle modifications have been used to measure inelastic scattering from $^{12}$C, $^{28}$Si and $^{40}$Ca to search for states with this predicted forward angle behavior [15].
Fig. 5 - Angular distributions measured for 162 MeV $^{12}\text{C}(\pi^+,\pi^+)^{12}\text{C}$ along with static DWIA (solid), dynamic DWIA (dashed), and CCIA (dot-dashed) calculations.

Spectra for both $^{12}\text{C}$ and $^{28}\text{Si}$ are presented in Figure 6. In both nuclei strongly forward-peaked angular distributions were observed for states or groups of states located at excitation energies of 20.0 and 17.6 MeV respectively. The angular distributions for both states are consistent with that expected for the excitation of a $0^+$ or spin-flip dipole state.

The fractions of the monopole, energy-weighted sum rule required to reproduce the observed cross sections, using a breathing-mode form factor in the DWIA, is 15% in $^{12}\text{C}$ and 25% in $^{28}\text{Si}$. These are much larger than observed in this excitation energy region in (${\text{He}}^3$,${\text{He}}^3$') [16]. Although no monopole strength was observed in any nucleus lighter than $^{64}\text{Zn}$ in earlier $^0\text{(a,a')} [17]$ a more recent experiment [18] reports significant monopole strength in $^{28}\text{Si}$ at a similar excitation energy. Alternatively, microscopic calculations of the cross sections to a doorway state which contains all of the spin-flip dipole strength expected in a $1\hbar_\omega$ shell-model space also reproduce the observed angular distributions. The observed cross sections indicate 62% of this (non-energy weighted) sum rule is exhausted in $^{12}\text{C}$ and 84% in $^{28}\text{Si}$ if these states are assumed to be isoscalar. Neither the spin-flip dipole nor the monopole calculation gives a good account of the energy dependence of these cross sections.

In order for these states to be identified as $T = 0$ spin-flip components of the GDR, the possibility of a monopole assignment needs to be ruled out using measurements made with other probes. Spin-flip probability measurements in $(p,p')$ might be very useful to help sort out this puzzle. Systematics also need to be established in other nuclei.
"ISOSCALAR" GIANT RESONANCES IN 208Pb

We have also used the small-angle modifications to study pion inelastic scattering at an incident energy of 162 MeV for the giant resonance region in 208Pb. Previous work in medium-mass nuclei (discussed earlier) has shown that isoscalar resonances are strongly excited with good signal-to-noise ratios. The spectra obtained (Fig. 7) show that this is also the case for 208Pb. The data have been analyzed as a sum of Gaussian peaks superimposed on a background which varies slowly both in angle and in excitation energy. Peaks were observed at excitation energies of 10.5, 13.5, 17.7, and 22.0 MeV. These correspond to the previously observed giant quadrupole

Fig. 6 - Left) 12C(π⁺,π⁺')12C at 80°(lab) and Tπ=164 MeV. Right) Same for 28Si.

Fig. 7 - Normalized spectra for 162 MeV pion inelastic scattering to the giant resonance region in 208Pb.
(GQR), giant monopole (GMR), high energy octupole (HEOR), and a sum of the isoscalar giant dipole (ISGDR) and the isovector giant quadrupole (IVGQR) resonances. The cross section angular distributions obtained for both $\pi^+$ and $\pi^-$ scattering to the GQR are presented in Figure 8.

One striking feature of the data is the difference in cross sections measured for $\pi^+$ and $\pi^-$ for both the giant resonances and the continuum. This can be readily observed in the figure. This difference suggests that the roles played by neutrons and protons in the surface region (the region probed by pion inelastic scattering) are very different.

A semi-quantitative understanding of these cross section ratios, $R = \sigma(\pi^-)/\sigma(\pi^+)$, can be obtained from the plane-wave Born approximation. Since the isoscalar pion-nucleon interaction is twice as strong as the isovector interaction at energies near the $\Delta_{3-3}$ resonance (near 180 MeV incident pion energies) $\sigma(\pi^+ + p)$ and $\sigma(\pi^- + n)$ are 9 times larger than $\sigma(\pi^+ + n)$ and $\sigma(\pi^- + p)$. Applying this to pion-nucleus scattering gives:

$$R = \frac{3F_n(\bar{r}) + F_p(\bar{r})}{3F_p(\bar{r}) + F_n(\bar{r})}$$

where $F_p(\bar{r})$ and $F_n(\bar{r})$ are respectively the proton and neutron transition densities at the strong absorption radius $\bar{r}$. For an isoscalar excitation $R$ is expected to be unity. For a hydrodynamical model excitation (equal amplitude oscillations of both the neutrons and the protons) $R$ is expected to be approximately $N/Z$. The observed value of $R = 3.0$ for the GQR is not expected from either of the above models.

In order to obtain a more quantitative understanding of the implications of the data we have performed DWIA calculations using collective-model form factors. In these calculations the neutron deformation parameter, $\beta_{1n}$, and the proton deformation parameter, $\beta_{1p}$, were separately scaled to obtain fits to the measured $\pi^\pm$ angular
distributions. These were then used to obtain the fractions of the isoscalar and
the isovector energy-weighted sum rule exhausted by the GQR. The result of such a
calculation using the same radial shape for both the neutron and proton form factors
is shown in Figure 8. The fraction of the E2 isoscalar sum rule, $S_{IS}$, necessary
to explain the data with this model is 71%, in good agreement with other
hadronic [19-21] measurements. However 23% of the E2 isovector sum rule, $S_{IV}$, is
required to explain both the $\pi^+$ and $\pi^-$ cross sections. From the hydrodynamical
model $S_{IV} = [(N-Z)/(N+Z)]^2 S_{IS}$ or 3% is expected.

There are two solutions to Eq. 1) for $S_{IS}$ and $S_{IV}$. The second solution leads to a
predominantly isovector state with $S_{IV} = 330\%$ and $S_{IS} = 5\%$. This solution is
inconsistent with all other measurements.

Another method of determining both the isoscalar and isovector strength for a
transition is the comparison of probes with different sensitivities to the isoscalar
and isovector pieces of the form factor. Such a comparison is provided by $(\alpha,\alpha')$
and $(e,e')$. Unfortunately there is significant disagreement about the amount of
strength observed in $(e,e')$ [22-25]. Although Pitthan et al. [23] have reported
observing a large fraction of the isoscalar E2 sum rule near 10.5 MeV, more recent
high-resolution studies [25] indicate very little E2 strength in this region. The
above analysis can be presented in terms of a neutron and a proton (electromagnetic)
sum rule. We find that although 72% of the neutron sum rule is exhausted by this
state only 8.4% of the proton sum rule is exhausted. Thus the results of this
analysis are consistent with both other hadronic measurements and with the recent
high resolution $(e,e')$ measurements but not with the earlier $(e,e')$ measurements.

We have examined the sensitivity of these results to differences between the
ground-state neutron and proton radii and to differences between the neutron and
proton radii used in obtaining the form factors (leaving the ground-state densities
unchanged). This analysis should indicate whether the differences in $S_{IS}$ and $S_{IV}$. The cross-section ratios could also be explained
by enhancing the isovector $\pi-N$ interaction, $V_1$ with respect to the isoscalar part of
the interaction, $V_0$. The hydrodynamical model would explain the data if $V_1/V_0$ was
1.26 rather than 0.5 as expected from the pion-nucleon interaction. Although
Hirata, Lenz and Theis [26] predict enhancements of 25% in $V_1$ with respect to $V_0
(V_1/V_0 = 0.63)$ this is much smaller than needed to explain the present data.

The analysis presented above indicates that either the GQR in $^{208}\text{Pb}$ is a giant
neutron resonance or we do not understand the pion-nucleus interaction. An analysis
of the HEOR indicates that it is also predominantly a neutron state. If these are
neutron states, where is the missing proton strength? Since the background in the
entire continuum region appears to be $\pi$ enhanced, this missing proton strength must
lie either higher in energy, or must be quenched. If indeed it is a giant neutron
resonance this idea can be further substantiated by measuring the decay from the
analog of this neutron giant resonance in $^{208}\text{Bi}$ using the $(p,p')$ reaction. This
experiment[27] was done for lower-lying states and provides examples for the neutron
parentage of these states in $^{209}\text{Pb}$.

VI - SUMMARY

Some new data for pion inelastic scattering from the giant-resonance region of
nuclei has been presented. New experimental techniques have enabled measurements to
be made at small angles. The data indicate that pions provide a probe which is
useful for locating spin-flip modes as well as for measuring new properties of
previously observed giant resonances.

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VII - REFERENCES