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QUASIELASTIC NUCLEON SCATTERING USING POLARIZED BEAMS AND TARGETS

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Abstract - Inelastic scattering of polarized intermediate energy nucleons to continuum nuclear states is discussed with emphasis on recent results. Spin momentum correlations of protons in polarized targets of $^3$He were observed for the first time. Complete spin observables in $(g,p)$ show effects of the nuclear spin-isospin response and of an NN interaction modified by the nuclear medium. A comparison of Gamow-Teller and isovector M1 giant resonance strengths in the sd shell provides evidence for large meson exchange current effects in the M1.

1 - INTRODUCTION

The subject of this talk is the hard scattering of an intermediate energy nucleon with the nucleus which results in an unbound, or nearly unbound, particle-hole state of the residual nucleus. If directions and momenta of both the scattered and knock-on nucleon are determined four-momentum conservation can be used to calculate the missing energy $E_m$ and the momentum $p$ of the struck nucleon. The differential cross section is proportional to the spectral function $S(E_m,p)$, the joint probability of finding nucleons with missing energy, $E_m$, and momentum, $p$, in the nucleus. Direct evidence for nuclear shell structure has been obtained in the past from proton spectral functions in $(p,2p)$ experiments beginning with early work at Uppsala /1/. An advantage of nucleon induced knockout reactions versus $(e,e'p)$ is that both proton and neutron spectral functions can be obtained and compared /2/. The average momentum transfer of inclusive experiments can be chosen to emphasize the quasielastic scattering from an average over the nucleons in the target. This gives rise to a broad peak in the spectra centered near an energy transfer $\omega = E - E' = q^2/2m$, where $m$ is the nucleon mass. At smaller momentum transfers the collective charge and spin modes of the nucleus are excited. The rich spin and isospin structure of NN scattering allows one to examine the S=0,1 and T=0,1 components of the nuclear response function and their multipole ($L=0,1 \ldots$) composition. Another motivation for these experiments is the question whether the NN interaction in the nuclear medium differs from the free NN interaction.

To obtain solutions for these problems polarization phenomena play a crucial rôle. This will be shown in this talk using a few examples from recent work. The examples focus on the first observation of spin-momentum correlations in a polarized target nucleus, on nuclear response and medium effects in spin transfer measurements in $(p,p')$ reactions, and on advances in the extraction of S=0 and S=1 giant resonance strengths. The equipment required for the experiments (laser optical pumping, focal plane polarimeters, charge exchange facilities) are within the capabilities of several intermediate energy laboratories.

2 - SPIN MOMENTUM CORRELATIONS OF PROTONS IN POLARIZED $^3$He

Targets of polarized $^3$He are of great current interest because of their usefulness for experiments concerned with fundamental properties of the neutron, e.g. the electric form factor, $G_E^p(q)$, and the spin structure function $g_1^p(x)$. The concept of polarized $^3$He as a polarized neutron is qualitatively supported by the $^3$He magnetic moment which is 11% more negative than that of the neutron. The three-body nucleonic wavefunction of $^3$He from Faddeev
calculations /3/ is however complicated, with some 16 components. Of these the mixed-symmetry $S'$ states (about 1.5%) and D-states (about 8%) have non-zero proton spin components parallel to the $^3$He spin. The effect of these small components on electron scattering observables have been calculated by Blankleider and Woloshyn for quasielastic scattering /4/, and by Woloshyn for deep inelastic scattering /5/.

A $^3$He(p,2p) knockout experiment at 290 MeV has recently been completed at TRIUMF (Rahav, Häusser, Miller et al., to be published) which determines the spin-momentum correlations of protons in $^3$He and is sensitive to the small components. Such experiments have become possible because of remarkable developments in producing dense, polarized $^3$He gas targets (see contribution by M. Leduc, this conference). The technique of optical pumping of Rb and spin exchange in Rb-$^3$He collisions which was developed at Princeton and Harvard /6/ has seen a 100-fold increase in the figure of merit, $FOM = N(^3He) \times P^2(^3He)$, over the past four years. The increase in the FOM can be in part attributed to the availability of more powerful infrared lasers (e.g. Ti:Sapphire lasers). An increase in the $^3$He density, from 3.2 to about 12 standard atmospheres, has been achieved at TRIUMF using a novel cryogenic technique (Larson, Delheij, Thiessen and Häusser, to be published). It appears at present that the maximum $^3$He polarization obtainable is somewhat smaller at the higher densities. Typical parameters for polarized $^3$He targets produced at TRIUMF during the past year are: volume 17-30 cm$^3$, $^3$He density 2400-9000 Torr at 273K, N$_2$ density 100-150 Torr, Rb density 0.01 Torr, $^3$He polarization 30-65%, laser power at 795 nm 3-8 W, pump-up time 5-10 h, wall relaxation time 20-100 h. A schematic view of the setup used to produce $^3$He polarization normal to the horizontal scattering plane is shown in Fig. 1. The polarization is reversed and analyzed using adiabatic fast passage NMR. Absolute normalization factors are obtained either by comparison with proton NMR signals from water-filled cells of the same dimension, or from the $^3$He(p,$\alpha$)$^4$He reaction for which the spin correlation parameter, $A_{30}$, is unity at all energies and angles. Both methods agree to within experimental uncertainties (5-10%).

![Fig. 1 - Schematic layout of the polarized $^3$He target system used at TRIUMF.](image)

Results for differential cross sections and spin observables $A_{no}$, $A_{on}$ and $A_{nn}$ in elastic proton scattering from $^3$He (Häusser, Larson et al., to be published) are shown in Fig. 2. The subscripts (pt) refer to the direction of the projectile and target polarization; polarizations of scattered proton and recoil were not measured and corresponding subscripts have been suppressed. Wire chamber tracking has been effective in eliminating background from the glass walls. The cross sections thus obtained are in good agreement with previous data by Hasell et al. /7/ who used a liquid target. Small discrepancies occur for the smallest energies and largest scattering angles and are likely caused by differences in the multiple scattering corrections. The curves in Fig. 2 are from a momentum-space optical potential by Landau et al. /8/. Unlike in elastic NN scattering where strong interaction symmetries imply the equality $A_{no} = A_{on}$ these quantities are seen to be very different for p-$^3$He scattering. Their difference implies
that the $^3\text{He}$ T matrix has a sixth nonvanishing ($f$) amplitude. Although the theory includes such an amplitude there are quantitative disagreements which indicate that explicit four-body calculations may be required.

The results from the $^3\text{He}(p,2p)$ knockout experiment are shown in Fig. 3 together with a plane-wave impulse approximation (PWIA) calculation [5]. The differential cross section and the beam-related analyzing power plotted versus momentum transfer on the left of Fig. 3 are a test of the PWIA. The good agreement between data and experiment indicates that, for proton momenta probed by the experiment ($< 200 \text{ MeV}/c$), rescattering corrections are relatively unimportant. The spin correlation parameter $A_{nn}$, shown versus the momentum $q$ of the struck nucleon, differs strongly from that for PP scattering ($A_{nn}(PP) \approx 0.815$) and reflects the spin-momentum correlation of the protons in $^3\text{He}$. At $q = 0$ about 14% of the protons have their spin antiparallel to the $^3\text{He}$ spin, whereas protons with $q \sim 90 \text{ MeV}/c$ are spin saturated. This is in good agreement with the calculations which, furthermore, show that the spin-momentum correlation effects are predominantly caused by the weak mixed-symmetry $S'$ states. Data for the $^3\text{He}(p,pn)$ reaction taken simultaneously with the $(p,2p)$ data are of poor statistical quality and disagree for $A_{nn}$ by 2-3 standard deviations with the PWIA predictions. The reason for the discrepancy are not established at present and a new $(p,pn)$ experiment with much improved sensitivity is planned at TRIUMF to determine the spin momentum correlations of neutrons in $^3\text{He}$.

The effects of the spin momentum correlations of the protons and neutrons on the asymmetry for deep inelastic electron scattering from polarized $^3\text{He}$ have been calculated in a quark model by Woloshyn [5] and are shown on the lower right of Fig. 3.
3 - NUCLEAR RESPONSE AND MEDIUM EFFECTS IN \((p,\vec{p})\)

Measurements of complete spin transfer coefficients in \((p,\vec{p})\) have been pursued at LAMPF /9/ and TRIUMF /10,11/ using polarized proton beams and focal plane polarimeters to analyze the spin projections of the scattered protons. From the diagonal spin transfer coefficients, \(D_{LL}, D_{LT} \), and \(D_{TT} \), both the longitudinal and transverse spin flip probabilities have been derived. The transverse \((\vec{\sigma} \times \vec{q})\) continuum response, \(R_T(q,\omega) \), can also be measured by inclusive scattering of medium energy electrons, whereas the spin longitudinal \((\vec{\sigma} \cdot \vec{q})\) response, \(R_L(q,\omega) \), is in the domain of nucleon probes. The motivation for these experiments came originally from the work of Alberico et al /12/ who pointed out an interesting contrast between the isovector spin longitudinal and transverse modes. Based on an RPA calculation in nuclear matter with one-pion exchange (OPE) plus one-rho-meson exchange plus a contact interaction with the Landau-Migdal parameter \(g'\), a pronounced enhancement and softening (i.e. a shift towards low \(\omega\)) of \(R_L(q,\omega) \), and a slight quenching and hardening of \(R_T(q,\omega) \) were predicted near \(q = 1.75\) \(\text{fm}^{-1}\), where the OPE interaction is attractive. The collective pion enhancement of \(R_L \) may be related to the softening (towards low quark momentum fractions \(x\)) of the quark structure function \(F_2 \) observed in nuclei relative to those for deuterium (EMC effect) since a slight pion excess in nuclei is one of the competing explanations /13/ for the EMC effect.

The \((p,\vec{p})\) data for the ratio \(R_L/R_T\) for Ca and Pb at 500 MeV and \(q = 1.75\) \(\text{fm}^{-1}\) /9/, and for \(^{12}\text{C}\) at 290 and 420 MeV and \(q = 1.9\) \(\text{fm}^{-1}\) /11/, are shown in Fig. 4. They show, independent of nucleon mass and at energies between 290-500 MeV, a quenching in the \(R_L/R_T\) ratio in strong contrast to the predicted enhancement. Theoretical analyses have shown that the enhancement of \(R_L\) is much reduced when the finiteness of the nucleus is taken into account. The predictions of the semi-infinite slab model (SISM) of Esbensen et al /14,9/ for the LAMPF data is shown in Fig. 4 for different values of \(g'\). More recently a continuum RPA calculation with distorted-wave impulse approximation by Ichimura et al /15/ has shown that distortions further reduce the ratio. Nevertheless, \(R_L/R_T\)
is still predicted to be larger than unity. The ratio is apparently very sensitive and requires an equally realistic treatment of both the isovector and isoscalar contributions, the latter contributing roughly 20% to $R_L$, and about equally to $R_T$.

![Graph showing the ratio of longitudinal to transverse response functions for inelastic proton scattering from Ca and Pb at 500 MeV.](image)

**Fig. 4** - The ratio of longitudinal to transverse response functions for inelastic proton scattering from Ca and Pb at 500 MeV (left, from /9/). The curves represent SISM calculations with different values of $g'$. Results for $^{12}$C(p,$p'$) at 290 and 420 MeV are shown on the right (from /11/).

![Graph showing complete spin observables for inclusive proton scattering from $^{54}$Fe at 290 MeV and $q = 1.36$ fm$^{-1}$.](image)

**Fig. 5** - Complete spin observables for inclusive proton scattering from $^{54}$Fe at 290 MeV and $q = 1.36$ fm$^{-1}$. The theoretical curves on the left are for Breit frame kinematics with the free response (dashed lines) and a SISM RPA response including 2p2h damping and two-step contributions (solid lines). The curves on the right correspond to the free Fermi gas response (dashed lines) and to an enhancement of the lower Dirac components for both target nucleons and incident proton.

In view of these difficulties it is appropriate to examine the individual $D_{ij}$'s. The $D_{ij}$ results from an $^{54}$Fe(p,$p'$) experiment at 290 MeV, and for a lower $q = 1.36$ fm$^{-1}$ to emphasize different aspects of the nuclear response, are
compared in Fig. 5 to two models. The SISM calculation by Smith and Wambach [16,17] is shown on the left (solid lines) together with the free response (dashed lines). The calculation uses a sophisticated nuclear response with \( \text{lparticle-lhole} \) \( \text{lplh} \) and \( \text{2p2h} \) correlations, two-step processes are included in a Glauber approximation. The use of the Breit frame to simulate Fermi momentum averaging is questionable since it introduces slopes versus \( W \) in \( D_{ll'}, D_{ll''} \), \( D_{pp'} \), \( D_{pp''} \) which are opposite in sign compared to Fermi-averaged values and the experimental data. The slopes observed for \( P, A_y \) and \( D_{nn} \) agree with the calculations and are a result of the softening of the \( T=0, S=0 \) part of the nuclear response. The \( P \) and \( A_y \) data are however quenched relative to the calculations. This reduction of \( P \) and \( A_y \) is a general feature of \( \text{(p,p')} \) reactions and persists to small momentum transfers [10].

On the right of Fig. 5 we show the results of a relativistic Fermi gas model [18] which assumes enhanced lower Dirac components for the nucleons associated with strongly attractive scalar fields in the nucleus. Because of the simple Fermi gas response the model should only be compared to data near the quasielastic point, \( W \approx 40 \text{MeV} \). The enhancement of the lower Dirac component goes in the right direction for every observable with the exception of \( D_{nn} \) for which there is essentially no relativistic effect. The model successfully predicts the quenching of \( P \) and \( A_y \) which at present cannot be explained by any other mechanism and appears to be a purely relativistic signature. From the above discussion it is apparent that a complete self-consistent theoretical framework for calculating the \( D_{nn} \)'s in \( \text{(p,p')} \) is not yet available. On the theoretical wish list one may include the optimal choice of a reference frame [19], the realistic treatment of both isovector and isoscalar components in the NN interaction, an RPA finite-nucleus response with \( \text{2p2h} \) damping, the quantum mechanical calculation of distortions and double scattering effects, and the necessity for density dependent (relativistic) medium effects. One is still rather far from fulfilling all these requirements, e.g. a relativistic RPA theory has not yet been developed.

4 - \( S=0 \) AND \( S=1 \) NUCLEAR RESPONSE IN \( \text{(p,p')} \) AND GIANT RESONANCES

Of the spin observables in \( \text{(p,p')} D_{nn} \), and thus the spin flip probability \( S_{nn} = (1 - D_{nn})/2 \), turn out to be most robust, i.e. the changes in \( S_{nn} \) associated with Fermi momentum averaging, distortions and relativistic effects are small. Since \( S_{nn} \approx 0 \) for \( S=0 \) transitions \( S_{nn}(W) \) reflects the relative importance of the \( S=1 \) and \( S=0 \) nuclear response (see the contribution by F.T. Baker, this conference).

![Graph](image)

**Fig. 6** - Spin flip probability \( S_{nn} \) for \(^{40}\text{Ca}(p,p')\) at 800 MeV (top left). The free NN value is shown as the dashed line. The relative nuclear spin response for \( q \approx 0.5 \text{ fm}^{-1} \) and at 800 and 319 MeV is shown at the bottom left. The \( S_{nn} \) values at the right are for 319 MeV and \( q \approx 0.5 \text{ fm}^{-1} \). The theoretical curves represent free NN scattering (dashed), a sum rule calculation (solid lines A and C), and a continuum RPA calculation (solid line C).

The relative spin response \( R_s = f_1/(f_0 + f_1) \) has been defined by Glashausser et al. [20] to measure the ratio of the nuclear response in the \( S=1 \) channel to the total response. With \( f_i = \sigma^A(S = i)/\sigma^{NN}(S = i) \), and using the
approximation \((\sigma^A S_{nn})_{\exp} \sim \sigma^A(S = 1) S_{nn}(S = 1)\), the relative spin response can be calculated from \(S_{nn}^{\exp}\) via

\[
\frac{f_1}{f_0} = \frac{S_{nn}^{\exp}}{S_{nn}^{S=1}} = \frac{\sigma_{NN}(S = 0)}{\sigma_{NN}(S = 1)}
\]

The quantity \(S_{nn}(S = 1)\) is not an observable and has to be calculated, either with the SISM or the continuum RPA. It is not very sensitive because the residual interaction is repulsive in both the isovector and isoscalar \(S=1\) channels. The relative spin response at \(q \sim 0.5\) fm\(^{-1}\) has been shown by Baker et al. /21/ to be the same near 300 MeV and 800 MeV (see Fig. 6). The \(R_s\) values above \(\omega \sim 25\) MeV are surprisingly large and exceed those calculated with the SISM in all nuclei studied so far at LAMPF \((^{12}\text{C}, \ ^{40}\text{Ca}, \ ^{48}\text{Ca}, \ ^{90}\text{Zr})\) and TRIUMF \((^{24}\text{Mg}, \ ^{44}\text{Ca}\) and \(^{54}\text{Fe})\). The enhancement of \(S_{nn}\) persists to \(\omega\) values as high as 75 MeV /21/ and cannot therefore be attributed to an individual \(S=1\) resonance but rather to a depletion of \(S=0\) strength. Boucher et al. have been successful in reproducing the qualitative features of \(S_{nn}\) with either a sum rule method /22/ (solid curves A for \(^{12}\text{C}\) and C for \(^{90}\text{Zr}\) on the right of Fig. 6) or a plane-wave continuum RPA calculation /23/ (solid curve B for \(^{40}\text{Ca}\) on the right of Fig. 6). It is hoped that a full continuum RPA calculation with distortions will be successful in explaining the existing \(S_{nn}(\omega)\) data.

The spin flip probability is very useful in obtaining the strength of individual giant resonances using multipole decomposition techniques. The Gamow Teller analog of the isovector M1 resonance and the isovector spin dipole resonance are seen without significant \(S=0\) background in the spin flip cross section \(\sigma S_{nn}\) (see e.g. /10,24/). Another useful recent development is a novel analysis of \(S=0\) giant resonances /25,10/ which does not use the traditional, but ad hoc, separation of the cross section into resonance and background contributions (see e.g. /26/). From the spin flip cross section \((\sigma S_{nn})_{\exp}\) the pure \(S=0\) cross section \(\sigma_{S=0}\) can be obtained from

\[
\sigma_{S=0} = \sigma_{\exp} - \frac{(\sigma S_{nn})_{\exp}}{S_{nn}^{S=1}}
\]

where \(S_{nn}^{S=1}\) is again calculated from theoretical models, e.g. the SISM. Results of multipole decompositions of \(\sigma_{S=0}\) for the (isovector) giant dipole (IVGDR) and the (isoscalar) giant quadrupole (ISGQR) resonances in \(^{40}\text{Ca}\) /25/ and \(^{54}\text{Fe}\) /10/, expressed in terms of the energy weighted sum rule, are shown in Fig. 7. It turns out that the sum rule strengths are in good agreement with photonuclear results on the IVGDR and with previous analyses of \((p,p')\) data (see e.g. /26/). The agreement implies that the ‘background’ underlying the resonances in the \((p,p')\) cross section data is mainly \(S=1\).

Fig. 7 - Energy weighted sum rule fractions of \(S=0\) giant resonances in \(^{40}\text{Ca}\) (left, from /25/) and \(^{54}\text{Fe}\) (right, from /10/).
Of all the giant resonances excited in NN scattering the $L=0\ S=1$ Gamow Teller (GT) resonance has been studied most thoroughly. This isovector spin flip mode dominates charge exchange reactions at small $q$. The strength of the corresponding effective interaction is now well known at 100-800 MeV from the $^{14}$C($p,n$) reaction populating the 3.95 MeV state in $^{14}$N. The energy dependence of the $0^\circ$ cross section is shown in Fig. 8(b) together with that for the Fermi (F) transition to the 2.31 MeV state in $^{14}$N (Fig. 8(c)) and the ratio of unit cross sections, $\delta_{GT} = \sigma_{GT}(0^\circ, q = 0)/B(GT)$ and $\delta_{F} = \sigma_{F}(0^\circ, q = 0)/B(F)$ (Fig. 8(a)). Recent results from the NTOF facility at LAMPF are included /27/. Neither a t-matrix interaction obtained with free NN amplitudes (dashed lines) nor a G-matrix interaction based on the Bonn potential (solid lines) /28/ are in satisfactory agreement with the data. It is thus dangerous to extract GT strengths from distorted wave impulse approximation (DWIA) calculations using interactions from theory. Substantial inaccuracies in the DWIA may result from the interaction and from extrapolations of optical potentials to different nuclei and energies. Most discrepancies in GT strengths from different nucleonic reactions in the literature arise from normalization to the DWIA rather than to $\delta_{GT}$ systematics based on $B(GT)$ values from $\beta$ decay.

A total of 17 known $\delta_{GT}$ values for nuclei with $A$ between 6 and 54, and for energies $E$ between 135 and 492 MeV, have recently been fitted with a 5-parameter expression to describe the $A$ and $E$ dependence (Häusser et al, to be published). The data set includes recent accurate TRIUMF results on the isospin triads in $A=6,12$ nuclei /29/ which have shown that $(n,p)$, $(p,p')$ and $(p,n)$ cross sections are consistent with each other to a few % provided they are measured relative to Arndt's SP88 phase shift solution /30/ for the elementary PP and NP reactions. Using the fit to the $\delta_{GT}$ data set cross sections for $1^+$ transitions excited in $(p,n)$, $(p,p')$ and $(n,p)$ reactions on targets of $^{24}$Mg have been converted to GT strengths and the running sums are shown in Fig. 9. The $(p,n)$ data are from a recent...
IUCF experiment at 135 MeV (Anderson et al, to be published), the (n,p) data are from a TRIUMF experiment at 198 MeV (Häusser et al, to be published), the (p,p') cross sections at 201 MeV are from Crawley et al /31/, and the spin flip cross sections at 250 MeV are from Sawafuta et al /24/. The dotted lines correspond to GT predictions of the USD shell model of Wildenthal /32/ with free nucleon values for the spin g-factors. All four experiments are in reasonable agreement although the 201 MeV (p,p) data which do not suffer from uncertainties due to the inclusion of (weakly excited) $1^+$, $T=0$ states in the data set. For $E_{\text{max}}$ corresponding to 11.4 MeV and 15 MeV in $^{24}\text{Mg}$ the $\Sigma B(\text{GT})$ values are (0.74±0.09) and (1.20±0.17), respectively. This implies quenching of the GT strength relative to the USD predictions by factors of (0.72±0.09) and (0.71±0.10), respectively. The errors include uncertainties of the individual measurements, their observed spread, and, added in quadrature, an estimated systematic error of ±10% in the unit cross section $\sigma_{\text{GT}}$.

This result takes on added significance when compared to a recent high-resolution $^{24}\text{Mg} (e,e')$ experiment at the Darmstadt DALINAC /33/ which identified 21 $1^+$ states between 8.86 and 14.3 MeV. The running sum of the $B(M1)$ is shown in Fig. 9 (right) together with the USD prediction. We quote $\Sigma B(M1)$ for two values of $E_{\text{max}}$, the upper limit in the running sum, (4.85 ± 0.36 $\mu_B^2$) for $E_{\text{max}} = 11.4$ MeV, and (5.84 ± 0.40 $\mu_B^2$) for $E_{\text{max}} = 15$ MeV, respectively. This corresponds to $B(M1)$ enhancement factors relative to the USD predictions of (1.13±0.08) and (1.11±0.08), respectively. The difference between the GT and isovector M1 quenching factors can be mainly attributed to a meson exchange current (MEC) enhancement of the M1. For a selfconjugate $T_3=0$ target nucleus such as $^{24}\text{Mg}$, and for M1/GT transitions to $1^+$, $T=1$ final states, one may write approximately /34/

$$B(M1) = \frac{3(\mu_p - \mu_n)^2}{8\pi} [M(\sigma) + M(\ell) + M_\Delta + M_\Delta^{\text{MEC}}]$$

$$B(\text{GT}) = [M(\sigma) + M_\Delta + M_\Delta^{\text{MEC}}]^2$$

where the numerical factor in the $B(M1)$ expression is 2.643 $\mu_B^2$, and the ratio of coupling constants, $(g_A/g_V)^2$, is not included in the definition of $B(\text{GT})$. The nucleonic spin matrix elements $M(\sigma)$ and the isobar contributions $M_\Delta$ are the same in both expressions. The MEC contributions are dominated by pion exchange and are predicted /34/ to be large for isovector M1 currents since the virtual photon in $(e,e')$ can couple to the pion. They are strongly suppressed for axial vector (GT) currents because of conservation of G-parity. Unfortunately, the M1/GT comparison tends to be complicated by the (nucleonic) orbital contribution $M(\ell)$ to the M1 matrix element. The combined effects of orbital and MEC contributions are measured by the ratio $R(M1/GT) = (\Sigma B(M1))/2.643\mu_B^2/\Sigma B(\text{GT})$. In their absence $R(M1/GT)$ is unity, irrespective of the complexity of the nucleonic wavefunctions, and of the exact magnitude of delta isobar contributions. Thus the sensitivity to uncertainties in the dominant nucleonic spin contribution is greatly reduced in $R(M1/GT)$.
In Table 1 the summed $B(M1)$ and $B(GT)$ values and the ratio $R(M1/GT)$ are shown. First we point out that configuration mixing within the sd shell results in about a factor of four reduction relative to the extreme (j-j coupling) single-particle model. However, $R(M1/GT)$ is changed by a much smaller amount and is thus much less sensitive to the sd-shell interaction.

$B(M1)$ and $B(GT)$ are given in Table 1 for the free-nucleon operator as well as for the effective operators which include the effects due to higher-order configuration mixing, delta isobar admixtures and MEC's. These are taken from two sources. One is the empirical effective operator obtained by Brown and Wildenthal (BW) from a global fit to individual magnetic moments, M1 and GT transitions in the sd shell /35/. The other is the effective operator from direct theoretical calculations of these effects by Towner and Khanna (TK) /36/. The close similarity between the theoretical and the empirical effective operators is indirect evidence for the success of the theoretical calculations. The isovector M1 and GT results with these two effective operators are almost the same, except that the TK operator gives somewhat less quenching for $B(GT)$ compared to the BW operator.

<table>
<thead>
<tr>
<th>$E_{\text{max}}$</th>
<th>$\Sigma B(M1)$</th>
<th>$\Sigma B(GT)$</th>
<th>$R(M1/GT)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MeV</td>
<td>$\mu_{h}^{2}$</td>
<td>$P_{\mu}^{2}$</td>
<td>$P_{\mu}^{2}$</td>
</tr>
<tr>
<td>11.4 MeV</td>
<td>19.24</td>
<td>7.49</td>
<td>.98</td>
</tr>
<tr>
<td>15.0 MeV</td>
<td>4.85(36)</td>
<td>5.84(40)</td>
<td>2.49(35)</td>
</tr>
</tbody>
</table>

From Table 1, we see that the $R(M1/GT)$ ratio is enhanced about 40% predominantly by the $\delta_{s}$ contribution. In the Towner-Khanna calculations this enhancement in the spin operator is essentially all due to the difference between MEC contributions to $M_{\text{eff}}^{M1}$ and $M_{\text{eff}}^{GT}$. There is an additional 10% enhancement in $R(M1/GT)$ due to the $\delta_{s}$ contribution to the orbital part of the $B(M1)$. In the Towner-Khanna calculations this term originates from a strong cancellation between effects due to MEC's and those due to higher-order nuclear configuration mixing. However, the $\delta_{s}$ contribution is a factor of four less important than the $\delta_{s}$ contribution in this case. The $\delta_{p}$ contribution is negligible.

Thus, the $R(M1/GT)$ ratio clearly is a sensitive and direct measure of the MEC correction to the spin operator. The experimental value of $R(M1/GT)$ is in excellent agreement with expectations based on both the TK and BW effective operators, and hence directly confirms the importance of MEC's in nuclei, as has been shown with the example of $^{24}\text{Mg}$. This has become possible through higher precision of electromagnetic and hadronic cross sections and their combined analysis, an improved knowledge of the effective nucleon-nucleon interaction in nuclei, and the existence of reliable many body wave functions and effective operators for sd shell nuclei. By contrast, the identification of MEC's is straightforward in very light nuclei where there is very little uncertainty in the nucleonic wavefunction (see e.g. /37/). It will be interesting in the future to extend this type of comparison to other regions of the sd shell.

**TABLE II**

Isovector M1 and GT Comparison in $^{24}\text{Mg}$

<table>
<thead>
<tr>
<th>$E_{\text{max}}$</th>
<th>$\Sigma B(M1)$</th>
<th>$\Sigma B(GT)$</th>
<th>$R(M1/GT)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MeV</td>
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<td>4.85(36)</td>
<td>5.84(40)</td>
<td>2.49(35)</td>
</tr>
</tbody>
</table>

**SUMMARY AND OUTLOOK**

The study of nucleon scattering to continuum nuclear states has made significant progress during the past few years. In the quasielastic regime some general features are now established which are largely independent of nuclear mass and bombarding energy. The longitudinal-to-transverse spin response ratio in $(p,p')$ is smaller than unity and does not favor a significant pion enhancement in nuclei. Several spin observables in $(p,p')$, in particular $P_{\mu}$ and $A_{\mu}$, show a systematic deviation from the Fermi averaged free NN values. The NN interaction is apparently modified at nuclear densities, an effect which is well described by a relativistic model. The spin flip probabilities $S_{\text{fit}}(\omega)$, at $q \sim 0.5$ fm$^{-1}$ and $\omega > 25$ MeV, indicate a surprisingly strong dominance of $S=1$, a feature which might be explained by continuum RPA calculations. The combined analysis of cross sections and spin flip cross sections has led to more reliable and accurate estimates for the strength of $S=1$ and $S=0$ giant resonances. The use of polarized targets
(e.g. $^3$He) in knockout reactions allows one for the first time to study spin-momentum correlations of nucleons in individual orbitals of the nucleus.

Much novel work is still left to be done, both theoretically and experimentally. Data on spin observables in $(p,p')$ are difficult to describe theoretically and there exists so far not a single calculation which includes all the effects that are known to be important. A theory which combines a sophisticated nuclear response with medium effects of the NN interaction is badly lacking. Experiments with polarized nuclear targets and beams ($d$, $^3$He, $^6$, $^7$Li, $^{13}$C, $^{15}$N ... ) are still in their infancy and many new results can be expected in the future. The $(d,d')$ reaction at SATURNE shows promise for selectively exciting the $T=0$ $S=1$ part of the nuclear response which is largely unexplored.

The interpretation of spin observables for the $(p',Z)$ reaction expected from future experiments at NTOF is more straightforward than that for $(p,p')$ because of the pure isovector character of the reaction. The commissioning of a second arm spectrometer (SASP) at TRIUMF should make possible novel studies of knockout reactions where conceivably polarizations of beam, target and scattered nucleons can be determined by the experiment. And finally, qualitatively new results are likely to appear from the new cooler rings at IUCF and Julich.

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