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Spin excitations in the ^{40}Ca$(\vec{p},\vec{p}\,')$ reaction revisited

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Double differential cross sections $d^2\sigma/d\omega d\Omega$ and spin-flip probabilities S_{nn} have been measured for the ^{40}Ca$(\vec{p},\vec{p}\,')$ reaction at $E_p=319$ MeV. The angular range of the experiment was $10.5° \leqslant \theta_{\rm lab} \leqslant 23°$ and the range of excitation energies was $6 \leqslant \omega \leqslant 47$ MeV. These data and earlier data at smaller angles are compared to calculations employing random phase approximation nuclear structure and a distorted wave impulse approximation reaction model.

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Several earlier articles [1–4] have reported data and analyses of the ^{40}Ca$(\vec{p},\vec{p}\,')$ reaction at 319 MeV and low momentum transfer ($\theta_{\rm lab} \leqslant 12°$). These data included the spin-flip probability S_{nn} and the cross section $\sigma \equiv d^2\sigma/d\Omega d\omega$ over the range of excitation energies ($6 \leqslant \omega \leqslant 39$ MeV) in bins of width $\Delta\omega = 1.8$ MeV. Two of these articles [2,3] described multipole decompositions of the giant resonance and continuum regions of the spectrum which appeared successful in extracting strength distributions for low multipolarity ($L \leqslant 2$) transitions for both spin transfer $S=0$ and $S=1$ parts of the spectra. In Ref. [4] these low momentum transfer (q) data were compared to distorted wave impulse approximation (DWIA) calculations employing a random phase approximation (RPA) description of the nuclear structure. These RPA/DWIA calculations described many features of the data well but they failed to predict the large cross sections in the continuum. The ground-state wave functions were based on a static mean field; there were indications, however, that the use of Hartree-Fock wave functions would improve the agreement with experiment.

The new data which will be presented here add the angles $\theta_{\rm lab}=10.5°$, 14°, 16°, 18°, 20°, and 23° to the data set; the momentum transfer range thus extends to about 1.65 fm^{-1}. For all these angles the excitation energy range was extended up to 47 MeV; earlier data at 7° and 12° were also extended up to 47 MeV. The entire set thus provides a map of spin excitations in the (q,ω) region leading up to an isolated quasielastic peak, where RPA calculations have been central to the discussion of pionic enhancements [5]. In principle, these data provide an opportunity for an improved multipole decomposition. The new data also include a precise check of instrumental asymmetries and of a central assumption about the reaction mechanism. The theoretical analysis of the data is based on RPA/DWIA calculations with Hartree-Fock ground-state wave functions. As discussed in Ref. [4], the continuum RPA includes *all* particle-hole configurations, so these calculations explicitly include quasielastic scattering.

The measurements were done with a 319 MeV transversely polarized beam at the Clinton P. Anderson Meson Physics Facility (LAMPF) using the high-resolution spectrometer with a focal plane polarimeter which has been previously described [1,6]. Other experimental details are described in earlier publications [1–4]. Absolute cross sections were determined by normalizing yields for elastic scattering and excitation of the unresolved 3^- (3.736 MeV) and 2^+ (3.904 MeV) states to 318 MeV measurements of Kelly *et al.* [7]. Absolute cross sections are estimated to be accurate to better than $\pm 10\%$. Instrumental uncertainties in the measurement of S_{nn} were checked by performing precise measurements at 14° for elastic scattering where conservation laws require that S_{nn} be zero. The measured value of S_{nn} was 0.0006 ± 0.0103.

For inelastic scattering to strongly collective natural parity states, there are no limits from conservation laws on the values of S_{nn}, but transitions to such states are expected to be overwhelmingly dominated by $S=0$ transitions. Since S_{nn} is our measure of spin excitations [4], a small value for such transitions is an important test of our assumptions. No high precision measurements have previously been reported. We carried out such a measurement at 14° for the excitation of the unresolved 3^- and 2^+ pair. The result for S_{nn}, 0.0121 ± 0.0099, is in good agreement with expectations.

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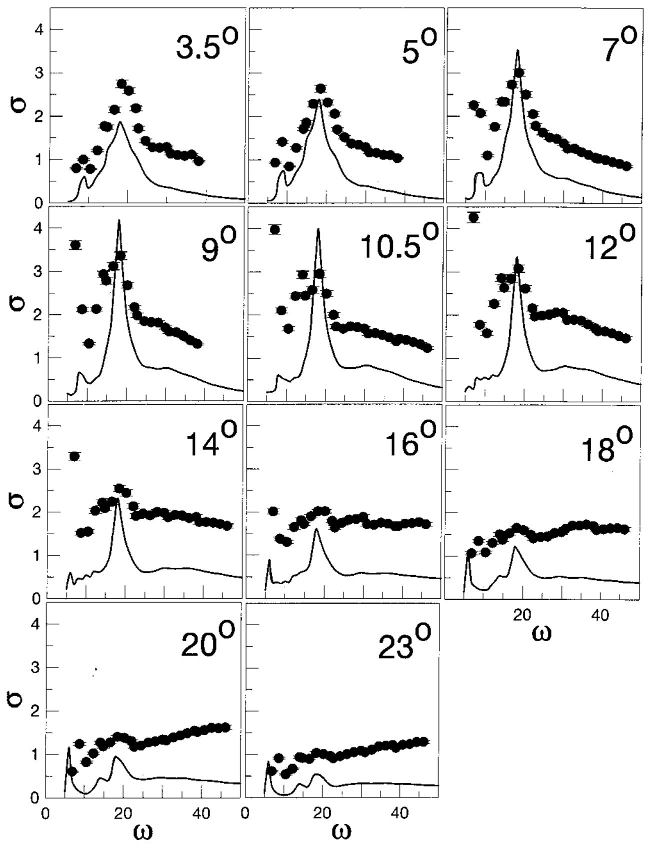

FIG. 1. Cross section [mb/(sr MeV)] data and calculations plotted as functions of excitation energy ω (MeV).

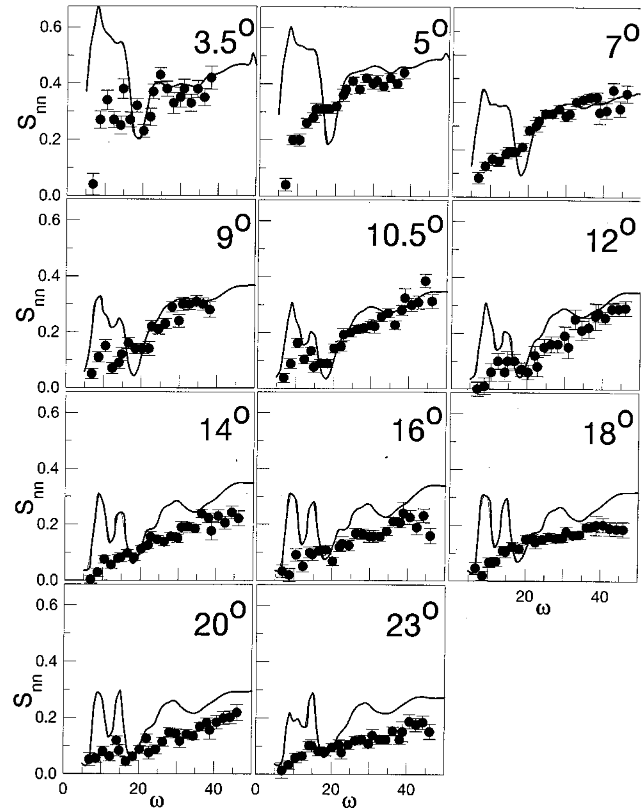

FIG. 2. Spin flip probability data and calculations plotted as functions of excitation energy ω (MeV).

The data and theoretical calculations described below for the observables σ and S_{nn} are presented in Figs. 1 and 2. At smaller angles the giant quadrupole resonance (GQR) is the dominant feature of the spectra, and its influence continues to be noticeable even at the largest angles. The continuum cross sections which were decreasing with increasing ω at smaller angles flatten out around 15° and increase with ω at the largest angles. This is likely due to the quasielastic peak. Spin-flip probabilities in the high continuum decrease significantly at the highest angles.

The details of both the RPA calculations of the transition densities and the DWIA calculations are fully described in Ref. [4]. The calculations presented here used the Hartree-Fock (HF) ground-state wave functions and the finite-range residual interaction described there. The HF wave functions, as noted in Ref. [4], lead to strength distributions which contain about 140% of the usual ''kinetic energy'' sum rules, and the preliminary calculations shown in Figs. 46–49 of Ref. [4] were calculated with full strength. In the present work, all calculations have been renormalized to correspond to 100% of the sum rules (i.e., approximately divided by a factor of 1.4). In addition, a normalization error (which increased the predicted cross sections) in the preliminary HF predictions in Ref. [4] was found after publication and is corrected here.

The cross section data are reasonably described by the theory at small angles in the region of the GQR, as shown in Fig. 1. However, the most obvious feature of the calculations is their failure to predict the size of the continuum spectra at all angles by factors of two or more. The corrected HF/RPA/DWIA calculations thus do little to alleviate this problem noted earlier; in fact, it is even worse for the new data at high q. This is a major issue; it suggests the conventional sum rule strengths are much smaller than the strength actually present.

At small ω the predicted values of S_{nn} shown in Fig. 2 are much larger than the data. As noted in Ref. [4], this is not a surprising feature of the calculations, since the continuum RPA and the $2p$-$2h$ approximation are designed to best represent the spectra above the single-particle binding energies. For $\omega \gtrsim 15$ MeV the calculations are generally in good accord with the data, although they tend to be somewhat too large at larger q. Thus, the S_{nn} spectra in the continuum are much better represented by the theory than are the σ spectra, indicating that although the predicted σ are much too small, the *relative* cross sections for $S=0$ (σ_0) and $S=1$ (σ_1) transitions are well described.

The excess experimental cross section compared with the RPA/DWIA predictions remains puzzling. There is no evidence for a significant instrumental background. Empty target frame runs yielded few counts. Instrumental background would decrease the measured values of S_{nn}, and, at some angles, the ''real'' S_{nn} would seem impossibly large. Finally, LAMPF data for the 800 MeV ^{40}Ca$(\vec{p},\vec{p}\,')$ reaction [4] and data for the ^{44}Ca$(\vec{p},\vec{p}\,')$ reaction [8] at 290 MeV taken at TRIUMF have very similar problems.

Calculations [9] examining the possibility of multistep processes contributing to the background indicate that these should be a very small fraction of the total cross section. Another possibility is that, at large q and ω, the isoscalar spin part of the cross sections could be inaccurate due to a failure of the approximation used to compute the tensor exchange. However, increased isoscalar spin cross section cannot be the whole solution since the predicted S_{nn} would then be far too large. The $S=0$, $T=1$ part of the NN force is probably the poorest known, but a large contribution to the continuum from scalar isovector transitions would certainly be surprising. We conclude that it is difficult to understand the excess experimental cross section.

The new data seem to provide a solid data base both for confirming previous multipole decompositions, and extending them to higher multipolarities. As we shall explain, however, these hopes have proved somewhat deceptive.

The $S=0$ cross sections, extracted according to the methods of Ref. [4], were considered first. In Ref. [2] collective model calculations were used to generate ''prototype'' angular distributions for multipolarities $L=1$, 2, and 4 and multipole strength distributions were extracted for $L=1$ and 2. Reanalysis [10] of the present data followed a similar approach but, because of the extended angular range of the data, multipolarities $L=1$, 2, 3, 4 and 5 were included; the $L=4$ and 5 angular distributions were added to simulate contributions from multipolarities with $L>3$. Except for the GDR, $S=0$, $T=1$ transitions were ignored since they are expected to contribute little. Similarly, since a well-defined giant monopole resonance (GMR) in ^{40}Ca had not been found at the time of this analysis, no $L=0$ contributions were included. Recently the GMR strength has been observed [11] in ^{40}Ca with approximately 100% of the strength in the energy range of 8–28 MeV. Our RPA calculations predict a broad GMR to occur at about $\omega=20$ MeV and predict a relatively small but not entirely negligible cross section for it at angles measured here. The angular distribution of the GMR is quite similar to that of the GQR for angles $>5°$ which would mean that the extracted $L=2$ strengths given below are likely too large. Predicted cross sections for the GMR are less than 5% those for the GQR for $\omega<20$ MeV where the bulk of the GQR strength is but of comparable magnitude for $\omega>25$ MeV; therefore we would estimate that neglecting $L=0$ in a multipole decomposition would, at most, overestimate the $L=2$ EWSR strength by 10%.

For $S=0, L=1$, a total strength of $158\pm16\%$ of the EWSR was observed in the energy region $6\leqslant\omega\leqslant25.4$ MeV. Strength at higher ω is unreliable because q even at the smallest angles of the experiment becomes too large at large ω. The distribution of this strength is quite similar to that shown in Ref. [2], peaking at 20 MeV where the GDR peak is. For $L=2$, a total strength of $126\pm14\%$ of the EWSR was observed in the energy region $9.6\leqslant\omega\leqslant31.8$ MeV. Most of this strength was observed in the region of the GQR, $13.2\leqslant\omega\leqslant21.1$ MeV, where $79\pm8\%$ of the EWSR was seen. For $L=3$ a large amount of strength was found, $161\pm13\%$ of the EWSR, fairly uniformly distributed across the whole spectrum and having a broad maximum near $\omega=30$ MeV. These large $L=2{,}3$, $S=0$ summed strengths are consistent with the excess strength in the measured cross sections relative to the RPA/DWIA predictions presented above.

For the $S=1$ excitations, prototype angular distributions were generated in Ref. [3] using a ''schematic'' model which is, essentially, a plane-wave collective model for spin excitations. Distortion effects were included phenomenologically. In the new analysis of Ref. [10], distortions are included exactly. In Ref. [3] the multipolarities $L=1{,}2$ were used in the decomposition; these were generated by summing all J and T angular distributions for each L. A similar procedure was followed here except that multipolarities through $L=5$ were included; the $L=4{,}5$ angular distributions were added to simulate contributions from multipolarities with $L>3$. The new decomposition yielded a summed strength for the $L=1$, $S=1$ multipole, the spin-dipole resonance (SDR), of $296\pm22\%$ of the EWSR, approximately twice as large as that found in Ref. [3]. About 60% of this strength is contained in the 10 MeV region around 18 MeV. Although very large, this result is again consistent with the large excess of experimental cross section compared to RPA/DWIA calculations discussed above. For the $L=2$, $S=1$ multipole, the summed strength is $139\pm43\%$ of the EWSR; this is only about half the amount of strength found in Ref. [3]. In the earlier work, however, the $L=2$ was the highest multipole included and thus had to simulate strength from all multipoles with $L>1$. Almost no $L=2, S=1$ strength is seen below $\omega=25$ MeV and the strength appears to have a broad maximum near 35 MeV. Interestingly, very little $L=3$, $S=1$ strength is found, about $60\pm28\%$ of the EWSR. A significant amount of $L>3$ strength is observed at higher ω.

The new $S=1$ multipole decompositions [10] described above make several assumptions which are questionable. First, by adding angular distributions with $T=0$, 1 for $S=1$ it is assumed that the strength distributions for isoscalar and isovector transitions are identical. Because of the different residual interactions for these two channels, this will surely not be the case, and spin isoscalar transitions are not negligible for many regions of q and ω. Similarly, by adding $J=L-1$, L, and $L+1$ angular distributions, the assumption is made that channels with different J for a given L have the same strength distributions; the RPA calculations indicate that this is not the case either. Most questionable, though, is the assumption that all angular distributions for a given J, L, T have identically shaped angular distributions (as a function of q), i.e., that the notion of a prototype angular distribution is meaningful. This is tantamount to assuming that the transition densities are identical for any transition to a state of a given J, L, T, S, which is quite unlikely given the different p-h structures of states as a function of ω. What was done for $^{12}C(\vec{p},\vec{p}\,')$ to remedy these problems was to use the RPA/DWIA angular distributions to generate a multipole decomposition for the data at each ω [12]. However, when this was done here for $S=1$ spectra, it was found that for $\omega\gtrsim25$ MeV the extracted multipole strengths had ex-

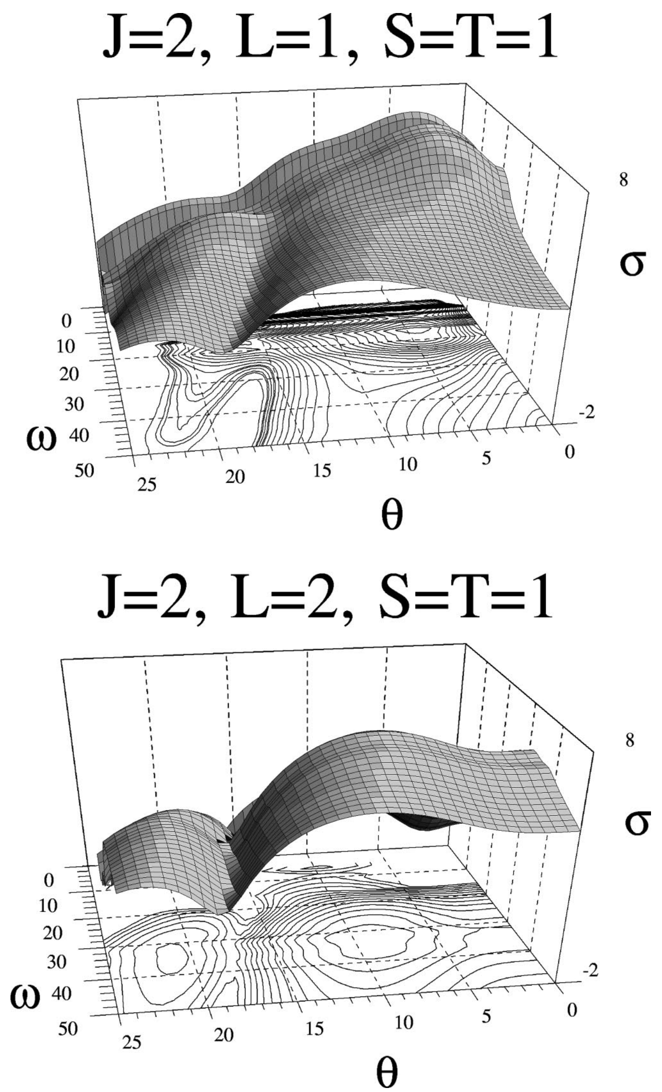

FIG. 3. $S=1$ 2^- and 2^+ cross section [mb/(sr MeV)] angular distributions plotted as functions of excitation energy ω (MeV).

tremely large errors, i.e., the search code was unable to find a well defined minimum in χ^2. The reason for this is illustrated in Fig. 3 where spectra of RPA/DWIA angular distributions for isovector spin states 2^- and 2^+ are shown. For $\omega \approx 20$ MeV, in the vicinity of the SDR, the $L=1$ spectrum peaks near 5° and the $L=2$ spectrum peaks near 10° and the two could be easily separated by a multipole decomposition. As ω increases, however, the shape of the of the 2^+ angular distribution remains relatively constant while the peak of the 2^- angular distribution moves rapidly to larger angles. At $\omega=50$ MeV the two angular distributions are nearly indistinguishable and a multipole decomposition is impossible. Similar problems occur for predicted $S=0$ angular distributions at high ω.

In summary, data for $d^2\sigma/d\omega d\Omega$ and S_{nn} for the $^{40}\mathrm{Ca}(\vec{p},\vec{p}\,')$ reaction at 319 MeV have been measured for the angular range $10.5° \leqslant \theta_{\mathrm{lab}} \leqslant 23°$ and the excitation energy range $6 \leqslant \omega \leqslant 47$ MeV. Precision measurements of elastic and inelastic scattering to collective states at 14° are consistent with zero, as expected. The new data and earlier data for $3.5° \leqslant \theta_{\mathrm{lab}} \leqslant 12°$ have been compared to RPA/DWIA calculations using Hartree-Fock ground-state wave functions and finite-range residual interactions. The calculations of the cross sections in the continuum typically underpredict the data by factors of two or more for all angles. This is a serious problem for which we can find no reasonable explanation. The S_{nn} data, on the other hand, are reasonably well explained by the calculations. Results of the multipole decomposition of the entire data set are consistent with earlier results in the region below 25 MeV of excitation. At higher excitation energies, reliable multipole strengths could not be obtained because the necessary approximations are no longer satisfied.

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