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Direct evidence for an orbital magnetic quadrupole twist mode in nuclei ☆

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Abstract

The reactions ^{58}Ni(e, e') and ^{58}Ni(p, p') have been studied at kinematics favorable for the excitation of $J^\pi = 2^-$ states by isovector spin-flip transitions with $\Delta L = 1$. There are states at an excitation energy $E_x \approx 10$ MeV which are strongly excited in electron scattering but not in proton scattering, suggesting a predominantly orbital character. This is taken as direct evidence for the so-called twist mode in nuclei in which different layers of nuclear fluid in the upper and lower hemisphere counterrotate against each other. Microscopic quasiparticle-phonon model calculations which predict sizable orbital M2 strength at this excitation energy yield indeed a current flow pattern of the strongest transitions consistent with a twist-like motion. © 2002 Published by Elsevier Science B.V.

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The possible existence of an orbital magnetic quadrupole (M2) resonance in finite Fermi systems is of fundamental quantum statistical significance. This mode was originally suggested in nuclei within a fluid-dynamic approach for finite Fermi systems [1] but it should also exist in metal clusters [2] and ultracold atomic Fermi gases [3]. For systems with small particle number its bulk properties are well described [4–7] within the random phase approximation (RPA) which

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is the microscopic analog of the fluid-dynamical picture. Macroscopically, the orbital M2 mode in nuclei can be viewed as a vibrational counterrotation of different layers of fluid in the upper and lower hemisphere where the rotational angle is proportional to the distance along the axis of rotation, hence the name 'twist mode' [1]. Its experimental observation invalidates the hydrodynamical picture of collective modes in finite Fermi systems because in an ideal liquid there is no restoring force for a twist mode [8]. Rather, a zero sound character is suggested where the restoring force is provided by the quantum-kinetic energy and the bulk behavior is that of an elastic medium [9].

Backward electron scattering presents the most promising tool to search for the twist mode in nuclei. However, the experimental observation is complicated by a significant fragmentation of the strength and, in particular, by the mixing with spin-flip M2 excitations which are centered at about the same excitation energies. Recently, a detailed study of M2 resonances in ^{48}Ca and ^{90}Zr with electron scattering at 180° has been reported where the complete M2 response could be extracted up to rather high excitation energies [10]. A very good description of the experimental results was achieved by RPA calculations after inclusion of two particle-two hole ($2p2h$) excitations [11], i.e., within the second-RPA (SRPA). The coupling to $2p2h$ states turned out to be essential for a realistic description of the fragmentation of the mode. The SRPA results showed significant orbital parts which interfere with the spin parts in the excitation. These orbital contributions were essential to achieve agreement with experiment. This finding was interpreted as indirect evidence for the existence of the twist mode [10].

Here, we present a more direct proof by a comparison of 180° electron scattering with proton scattering under forward angles. This method has been shown to be a useful tool for the decomposition of spin and orbital parts of the M1 strength in light [12,13] and heavy [14–16] nuclei and to extract the role of meson-exchange current contributions [17–19] in sd-shell nuclei. Proton scattering or charge-exchange reactions on a target with zero ground-state spin in the appropriate kinematics (bombarding energies $E_0 \simeq 150$–300 MeV/nucleon, forward angles) selectively excite isovector spin-dipole resonances (IVSDR) with quantum numbers $\Delta L = 1$, $\Delta S = 1$, $\Delta T = 1$, $J^\pi = 0^-, 1^-, 2^-$ [20]. The $J^\pi = 2^-$ component is excited by the same operator $O \propto r[\sigma \otimes Y_1]^{2^-}$ as the spin-flip part of the M2 strength observed in electron scattering. While a spin decomposition of the IVSDR has not yet been achieved experimentally, calculations predict the excitation of the 2^- states to dominate the reaction cross sections [21]. Here, we present a comparison of the (e, e') and (p, p') reactions for ^{58}Ni which provides compelling evidence for the existence of the twist mode.

The electron scattering experiments were performed at the superconducting Darmstadt electron linear accelerator S-DALINAC. The special device for the measurement at 180° is described in Ref. [22]. A self-supporting enriched ($> 99\%$) ^{58}Ni foil with an areal density of 7.6 mg/cm^2 was bombarded with electrons at incident energies $E_0 = 56.5$ and 65.4 MeV, corresponding to effective momentum transfers $q_{\text{eff}} = 0.64$ and 0.73 fm^{-1}, respectively. The latter value is close to the maximum of M2 form factors for medium-mass nuclei, see, e.g., [23]. The data analysis methods including the background determination and radiative corrections are described in Refs. [10,24]. Further details of the ^{58}Ni(e, e') experiment are given in Ref. [25]. Instrumental background is almost completely suppressed by using a 10 MHz pulsed electron beam which permits to distinguish target-related events from other beam-induced radiation sources by time-of-flight techniques [24]. Excitation spectra in ^{58}Ni were measured up to $E_x \simeq 25$ MeV. An energy resolution $\Delta E = 90$ keV (full width at half maximum, FWHM) has been achieved with about equal contributions from the energy spread of the beam and the energy loss in the target. The spectrum for excitation energies $E_x = 7$–16 MeV at $E_0 = 65.4$ MeV is displayed in Fig. 1(a). In this region the energy of individual transitions could be determined with a precision of about 15 keV.

The proton scattering data were measured at KVI, Groningen. Unpolarized and polarized protons with an energy of 172 MeV were scattered off a 17 mg/cm^2 thick ^{58}Ni target (enrichment $> 99\%$) and detected with the big-bite spectrometer [26] and the focal-plane detection system [27] developed by the Bari/Darmstadt/Gent/KVI Groningen/Milano/Münster EUROSUPERNOVA Collaboration. The average degree of the transverse polarization was 66%. Data were taken at angles $\Theta_p \simeq 6°$, 10°, 16°, and 19° (unpolarized) and 6°, 10°(polarized) for ^{58}Ni excitation energies up to 35 MeV. The data shown here are restricted to unpolarized beams because of the superior statistics. The data analysis procedure is described in Ref. [28]. The most forward angle roughly corresponds to the expected maximum of the IVSDR cross sections. The $E_x = 7$–16 MeV region measured at $\Theta_p = 6°$ is shown in Fig. 1(b). The energy resolution was $\Delta E = 130$ keV (FWHM), corresponding to about 20 keV uncertainty for the absolute energy values.

Low-multipolarity magnetic resonances in ^{58}Ni were studied previously [29] in high-resolution (e, e') scattering at the DALINAC. Although the momentum transfers investigated were optimized for the observation of M1 transitions, some prominent M2 transitions could also be identified [29]. The strongest M1 excitations deduced in [29], which are also seen in reactions populating the analog Gamow–Teller (GT) strength [30], make small contributions to the cross sections at $q_{\mathrm{eff}} = 0.73\ \mathrm{fm}^{-1}$ only. Thus, the resonance-like structure (and the individual peaks this structure is composed of) observed in the 180° data at an excitation energy $E_x \simeq 8$–11 MeV is predominantly of M2 character.

The dashed lines in Fig. 1 exhibit the correspondence (within the quoted uncertainties) between peaks simultaneously observed in the (e, e') and (p, p') spectra. For excitation energies up to 11 MeV the comparison indicates that the 2^- component of the IVSDR is significantly present in the proton scattering cross sections. This is also supported by an enhanced spin-flip probability in this energy region deduced from the polarized proton scattering data [31]. At $E_x > 11$ MeV some resemblance of the peaks observed with both probes is found, but possible contributions of M3 strength in the (e, e') scattering and the excitation of the other spin components 0^-, 1^- of the IVSDR and $\Delta L = 2$ excitations in proton scattering complicate the picture. A detailed comparison will be given elsewhere [31].

A striking difference between the two spectra is observed for the peak at $E_x = 9.87$ MeV, strongly populated in electron scattering. As indicated by the arrow in Fig. 1, no comparable excitation is visible in the proton scattering data. The same is true for the adjacent transition at $E_x = 10.04$ MeV which actually corresponds to a local minimum in the (p, p') cross section. At both energies the excitation of $J^\pi = 2^-$ states was identified in [29] and in the present work with similar transition strengths. The comparison of (e, e') and (p, p') spectra provides a

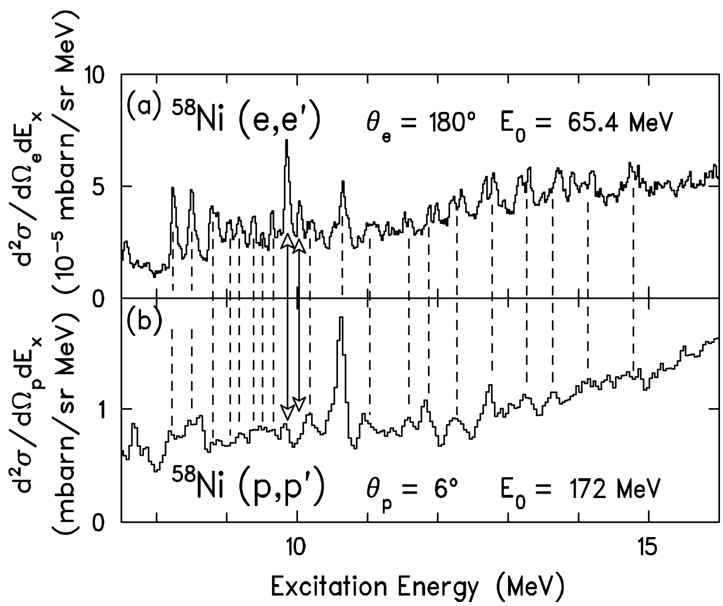


Fig. 1. (a) Spectrum of the ^{58}Ni(e, e') reaction at $E_0 = 65.4$ MeV and $\Theta_e = 180°$. (b) Spectrum of the ^{58}Ni(p, p') reaction at $E_0 = 172$ MeV and $\Theta_p = 6°$. The arrows indicate the energies of transitions strongly excited in electron scattering, but not in proton scattering. The dashed lines connect possible candidates of isovector spin-flip transitions to $J^\pi = 2^-$ states excited in both experiments.

clear signature for a dominantly orbital character of the observed transitions. Orbital contributions to the proton scattering cross sections, which might arise from exchange effects, the spin–orbit potential, or the tensor part of the projectile-target interaction, are expected to be very weak [32].

The interpretation is corroborated by calculations of the ^{58}Ni(e,e') cross sections of the present experiment within the microscopic quasiparticle-phonon model (QPM) which is similar to the SRPA. The basics of the model are described in [33]. The calculations have been performed with wavefunctions for the excited states which include one- and two-phonon configurations:

$$\left|\Psi^{\nu}\right\rangle_{2^-M} = \left\{\sum_i S_i(\nu) Q^+_{2^-Mi} + \sum_{\lambda_1 i_1 \leqslant \lambda_2 i_2} D^{\lambda_2 i_2}_{\lambda_1 i_1}(\nu) \times \left[Q^+_{\lambda_1\mu_1 i_1} \otimes Q^+_{\lambda_2\mu_2 i_2}\right]_{2^-M}\right\}\left|0^+\right\rangle_{\text{g.s.}}, \quad (1)$$

where M is the projection of the total angular momentum, the index i is used to distinguish between QRPA phonons, $Q^+_{\lambda\mu i}$, of the same multipolarity λ but with different excitation energies and internal fermion structure and the index ν labels the set of states (1). The coefficients $S_i(\nu)$ and $D^{\lambda_2 i_2}_{\lambda_1 i_1}(\nu)$ and the energy eigenvalues of the various states are obtained by diagonalizing the QPM Hamiltonian. In the actual calculations, all one-phonon 2^- configurations with excitation energies up to 20 MeV are included in the model space. The two-phonon configurations are built from phonons with spin and parity ranging from $1^\pm$ to $6^\pm$ and have been truncated above 25 MeV.

Neglecting direct excitation of two-phonon configurations from the ground state, the DWBA (e,e') cross section for the excitation of the νth state (1) is given by

$$\left(\frac{d\sigma(E_0,\theta)}{d\Omega}\right)_\nu \propto \sum_{M,m,m'} \left|\sum_i S_i(\nu) A_i\left(2^- M m m'\right)\right|^2, \quad (2)$$

where $A_i(2^- M m m')$ represents the amplitude for exciting the ith one-phonon component with different projections of the incoming and outgoing electron, m, m'. These amplitudes are calculated from the transition current densities of the ith state.

The resulting 2^--strengths functions are presented in Fig. 2 using an energy averaging parameter of 90 keV which corresponds to the experimental resolution. The total (e,e') cross sections as well as a decomposition into spin and orbital parts are shown. Note that a quenching factor $g_s^{\text{eff}} = 0.8 g_s^{\text{free}}$ is included for the spin part of the M2 operator, which was determined by a global fit to M1 and M2 transitions in spherical nuclei. The magnitude of quenching is in reasonable agreement with shell-model [34,35] and SRPA [10,23] predictions in this mass region.

The conclusions on the nature of the observed excitations resulting from the comparison of electron and proton scattering data are supported by the theoretical results shown in Fig. 2. A strong M2 resonance is obtained between about 9 and 12 MeV with comparable contributions from spin and orbital parts and a mostly constructive interference between both. These features qualitatively agree with the SRPA calculations of the

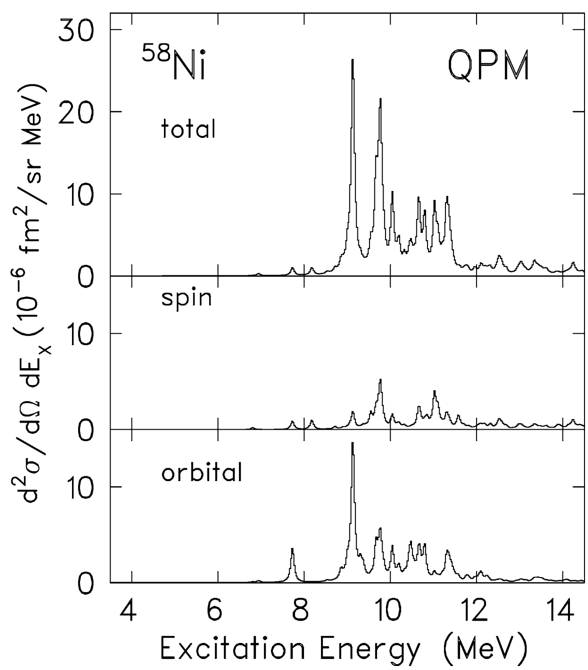


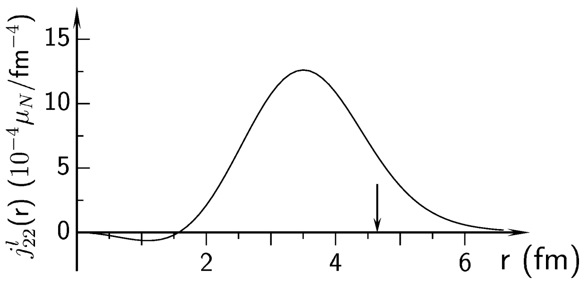
Fig. 2. Quasiparticle-phonon model calculation of the ^{58}Ni(e,e') cross sections due to M2 excitations for the kinematics of the spectrum shown in Fig. 1(a). Upper part: total cross section. Middle part: spin contribution. Lower part: orbital contribution.

M2 strength in ^{48}Ca and ^{90}Zr [10]. From the two most prominent peaks in the QPM calculations, the one at higher energy results from a constructive interference of nearly equal spin and orbital matrix elements, while the one at lower energy is predominantly orbital in character. Thus, the QPM results indicate the possibility of rather pure candidates for the twist mode in line with the experimental findings. As pointed out in Refs. [4,6], the (e, e') form factor of the twist mode has a maximum at larger q value than the one of the spin mode. The conditions of the present (e, e') experiment are in fact close to the maximum of the twist mode form factor. Thus, the contribution of the spin mode in Fig. 2 is somewhat suppressed as compared to its role in the B(M2) strength distribution at the photon point $(q = k = E_{\mathrm{x}}/\hbar c)$.

Two comments are in order. The calculations suggest a strong fragmentation of the twist mode in agreement with previous investigations [10] and therefore the experimental candidates identified here are not expected to exhaust the full twist mode strength. Furthermore, one notes that the orbital transitions are predicted at excitation energies shifted by about 1 MeV with respect to experiment. This can, at least partly, be traced back to the use of a global parameter set to determine the single-particle energies. The discrepancy could most likely be cured by using values optimized for ^{58}Ni, e.g., based on experimental values. However, the prediction of some rather pure orbital M2 transitions would not be affected.

Finally, we investigate to what extent the microscopic results reflect a twist-like motion as predicted by the fluid-dynamical model [1]. In the upper part of Fig. 3 the orbital transition current density $j^l_{22}(r)$ is shown for the 2^- state with the largest orbital M2 cross section in Fig. 2. The lower part presents a three-dimensional plot of the current. Cuts are shown in the xy-plane for fixed values $z = z_0$ and $z = -z_0$. In the xy-plane the current vectors are perpendicular to the radius vector $\vec{r}_{xy}$. This is a direct consequence of the properties of the vector spherical harmonics $\vec{Y}^{\mu}_{221}(\hat{r})$. The angle of rotation is proportional to the z value. The current vanishes at $z = 0$ and the rotation has opposite signs in the upper and lower semispheres. Thus, the properties of the twist mode as predicted in the fluid-dynamical model appear in a natural way.

The current velocity as a function of $\vec{r}_{xy}$—indicated by the length of the arrows in Fig. 3—is proportional to the total $j_{22}(r)$ current density. In the microscopic calculation the current density results from an interference of various $1p1h$ configurations. Thus, the current distribution of any 2^- state complies with the qualitative picture suggested by the fluid-dynamical model, but the magnitude of the velocity varies from state to state. Another difference is observed for the present example in the region of the nuclear interior. At radii below 1.5 fm the transition charge density changes its



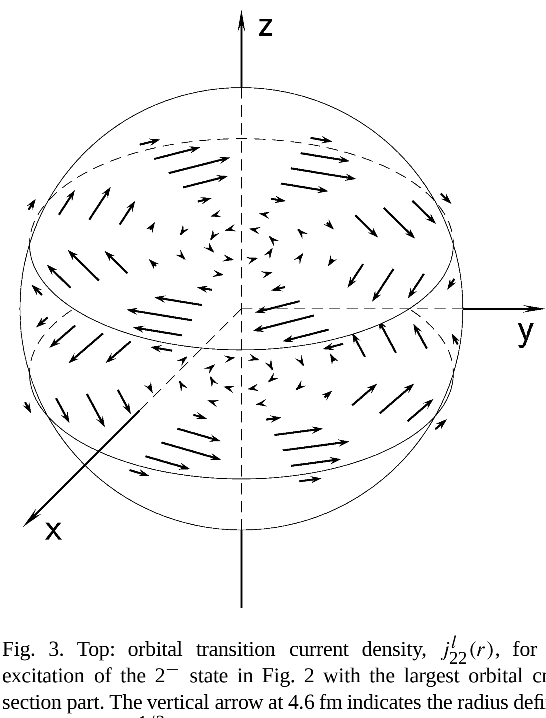


Fig. 3. Top: orbital transition current density, $j^l_{22}(r)$, for the excitation of the 2^- state in Fig. 2 with the largest orbital cross section part. The vertical arrow at 4.6 fm indicates the radius defined as $R_0 = 1.2 \cdot A^{1/3}$. Bottom: three-dimensional plot of the nuclear current with cuts in the xy-plane for fixed values $z = z_0$ and $z = -z_0$. The arrows indicate the current direction and their length is proportional to the current velocity normalized to its maximum value.

sign and correspondingly the direction of flow is reversed.

In summary, we have presented a comparison of electron and proton scattering on ^{58}Ni measured at kinematics where the excitation of isovector spin-flip transitions with $\Delta L = 1$, $\Delta S = 1$ is favored. For excitation energies below 11 MeV a rather good correspondence of the spectra is found indicating the dominance of the excitation of $J^\pi = 2^-$ states. Two transitions near $E_x = 10$ MeV are strongly excited in the (e, e') reaction, but not in proton scattering. This comparison provides a clear signature for the predominantly orbital character of the transitions, thereby providing direct evidence for the excitation of the twist mode in nuclei. This interpretation is corroborated by QPM calculations of the M2 strength function in ^{58}Ni. One may hope to back this result further by a detailed study of the (e, e') form factors of the twist mode candidates because differences between the spin-flip and orbital components are predicted by the QPM and SRPA results which should be measurable for transitions with not too strong mixing of both.

The present work represents yet another example for the power of studies utilizing the complementarity of electromagnetic and hadronic probes to elucidate the structure of elementary modes in nuclei. A complete investigation of the ^{58}Ni(e, e') reaction at $\Theta_e = 180°$ in the relevant momentum transfer range and a full analysis of the $(\vec{p}, \vec{p}\,')$ data promises insight into a number of important structure aspects such as the shear module in finite nuclei, the quenching of spin M2 resonances and the angular momentum composition of the IVSDR. It would be of considerable importance to establish the systematics of the twist mode over a wide mass range and extend the search to the region of well deformed nuclei [7,36]. Work along these lines is in progress.

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