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Search for isovector magnetic quadrupole strength and spin-isospin correlations in ^{20}Ne

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In ^{20}Ne, the isovector $M2$ strength distribution in the excitation region of $E_x=11-24$ MeV was investigated by inelastic electron scattering. Two transitions to levels at $E_x=11.62$ and 12.1 MeV were observed with strengths of $B(M2,k)\uparrow=64\pm13$ and 56 ± 13 $\mu_N^2\text{fm}^2$, respectively. A comparison with the analogous (π^-,γ) reaction shows that orbital contributions are non-negligible in these transitions. The data are compared to model predictions.

I. INTRODUCTION

The isovector magnetic transitions have received much attention due to their sensitivity to nucleonic and possibly mesonic degrees of freedom. In the past, the detailed microscopic calculations and the experimental activities were mainly centered around $M1$ transitions. Recently, the interest in $M2$ transitions has been growing both on experimental and theoretical fronts.[1,2] These odd-parity transitions probe predominantly $1\hbar\omega$ excitations and thus supplement the structural information obtained from even-parity transitions. Like $M1$ transitions, the $M2$ transition strengths can be compared with analogous axial vector processes such as nuclear β decay, (π^-,γ), and (p,n) reactions to assess the relative importance of orbital and spin current contributions.[3]

For light even-even nuclei, model estimates of the isovector $M2$ strengths are now available. A microscopic calculation by Schmid,[4] in the angular momentum projected Hartree-Fock and particle-hole method, predicts the $M2$ strength distribution for ^{20}Ne and ^{28}Si. Also, two of us (Lo Iudice and Palumbo) developed a semiclassical picture for spin-isospin $(\sigma\cdot\tau)$ oscillations in light deformed nuclei with axial symmetry.[5] These oscillations are excited through $M2$ transitions whose strength depends on the interplay among the one-pion exchange (OPE) potential, the short-range interaction, and the nuclear deformation. The $M2$ strengths contain therefore some information about the proximity of a σ-τ phase, which is favored by nuclear deformation.

In oblate nuclei the OPE potential and the short-range interaction are in fact competitive for longitudinal (with respect to the symmetry axis) oscillations while they are cooperative for transverse oscillations, which only result to be collective. This prediction is supported by the experimental results[6] in ^{12}C and ^{28}Si.

In prolate nuclei the semiclassical picture meets with some difficulty because the OPE potential, whose contribution depends on the direction of the axis of spin quantization, favors a transverse spin polarization. With transverse spin polarization, however, the excited states have triaxial symmetry and the model is not fully consistent. The calculations have therefore been performed both with longitudinal and transverse spin polarization. In both cases there are two levels. With transverse polarization the collectivity of each level is lower than with longitudinal polarization and considerably less than *half of it would be with oblate deformation.* Moreover it would presumably be still reduced in a microscopic calculation due to the breaking of axial symmetry.

In particular, for ^{20}Ne with longitudinal polarization the two levels are at $E_x=12.2$ and 22.5 MeV with $B(M2,k)\uparrow=330$ and 280 $\mu_N^2\text{fm}^2$, while with transverse polarization $E_x=13.3$ and 21.5 MeV with $B(M2,k)\uparrow=240$ and 65 $\mu_N^2\text{fm}^2$, respectively. (Here $k=E_x/\hbar c$ defines the photon point.) The present work, as main motivation, had to verify the predictions.

Further incentive to this work comes from the availability of ^{20}Ne(π^-,γ)F data by Martoff *et al.*[8] In this reaction, the 1.30 and 1.84 MeV levels in ^{20}F, analog states of the well established $J^\pi;T=2^-;1$ levels at 11.62 and 12.10 MeV excitation in ^{20}Ne, are populated. Also seen is a transition to the 6.1 MeV level, the analog of which occurs at $E_x=16.4$ MeV in ^{20}Ne. In view of the importance of orbital recoupling effects to the $M1$ transition, it is of interest to investigate if such contributions play a role for $M2$ transitions also.

Section II provides the experimental details and data analysis. The results are discussed in light of the above models in Sec. III A. A comparison with the (π^-,γ) reaction is offered in Sec. III B, with the summary and conclusions following in Sec. IV.

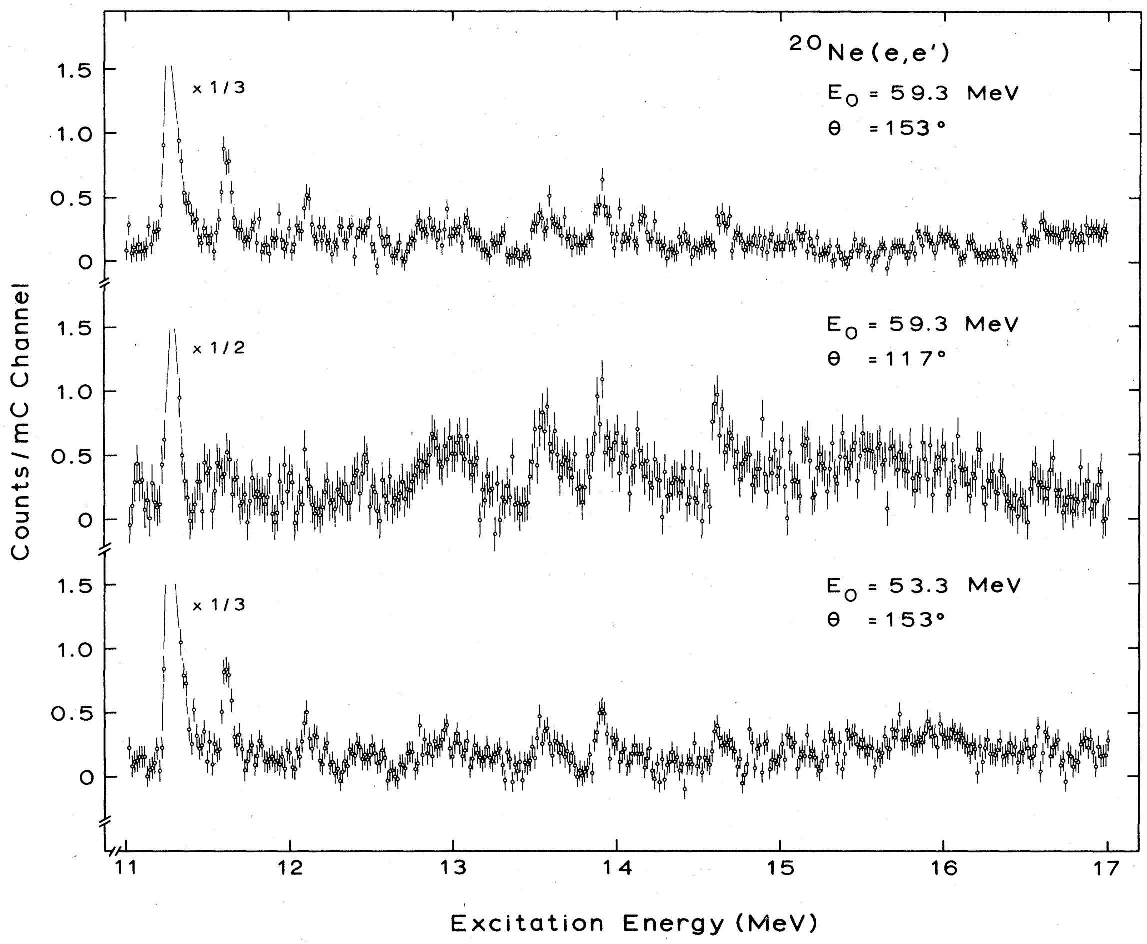

FIG. 1. Three background subtracted spectra of the ^{20}Ne(e,e') reaction covering the excitation energy region $E_x = 11-17$ MeV. One spectrum (top section) has been taken at the incident energy of $E_0 = 59.3$ MeV and the scattering angle $\theta = 153°$ ($q = 0.53$ fm^{-1}).

TABLE I. Kinematic conditions for the measurements of the present work. Series *A* and *B* denote measurements taken in the excitation energy range $E_x = 11-17$ MeV and $E_x = 16-24$ MeV in ^{20}Ne, respectively.

	E_0 (MeV)	θ (deg)	q (fm^{-1})
A	59.3	153.1	0.53
	59.3	117.1	0.47
	53.3	153.1	0.47
	44.9	153.1	0.39
	39.8	153.1	0.34
	36.3	153.1	0.30
B	55.8	129.1	0.47
	53.0	153.1	0.47
	45.0	153.1	0.39
	39.5	153.1	0.34

II. EXPERIMENT AND DATA ANALYSIS

The measurements were carried out at the high resolution electron scattering facility at Darmstadt (DALINAC). The experimental setup has been well documented.[9] The targets consisted of enriched ($>99.95\%$) ^{20}Ne gas filled to a pressure of nine bars in a thin walled (≈ 100 μm) container made of an aluminum alloy. The target handling procedures and the data analyses are previously described.[10]

The data collection was done in two series of measurements under the kinematical conditions shown in Table I. The first series concentrated on the excitation region $E_x = 11-17$ MeV. In total, six spectra were measured. Figure 1 shows three spectra, one taken at an incident energy $E_0 = 59.3$ MeV at the scattering angle $\theta = 153°$ and the other two for the matching momentum transfer $q = 0.47$ fm^{-1}. Besides the strong $M1$ transition to the level at $E_x = 11.260$ MeV excitation, transitions to levels at $E_x = 11.62$ and 12.10 are clearly seen. The Rosenbluth

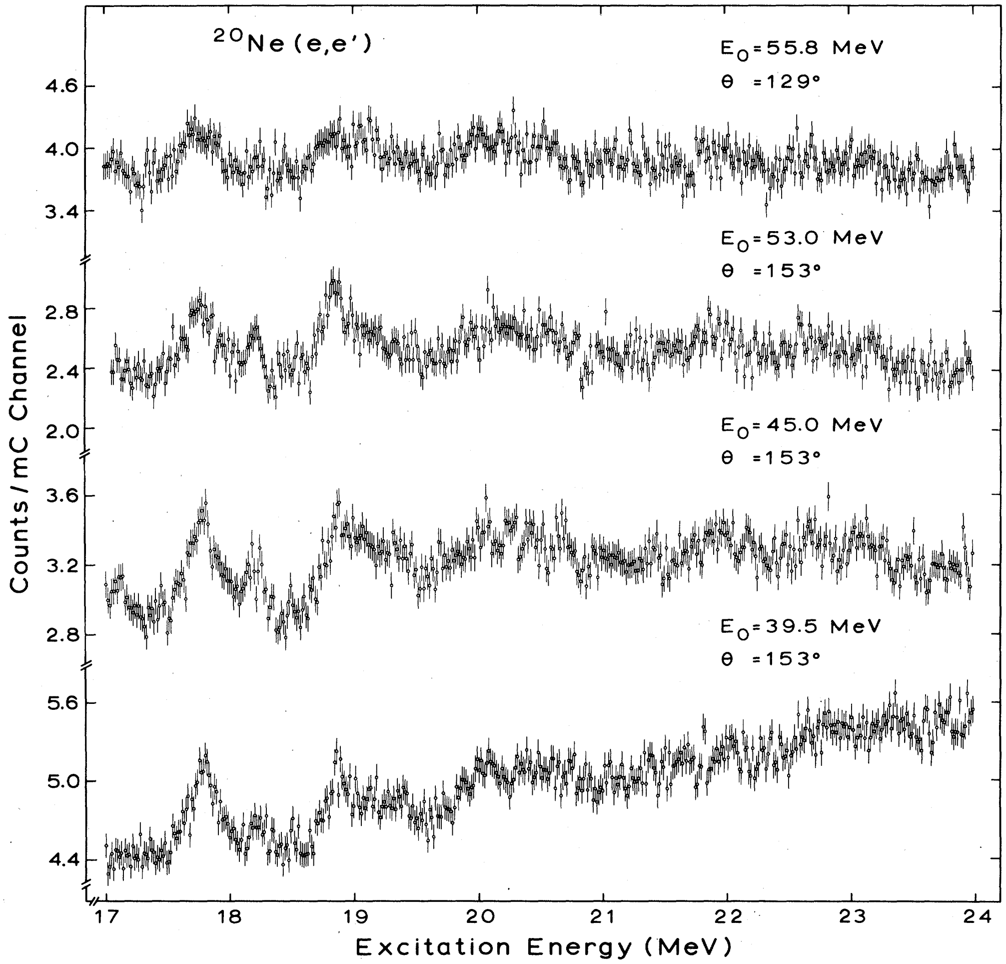

FIG. 2. Four spectra measured in the ^{20}Ne(e,e′) reaction in the excitation energy range of $E_x = 17$—24 MeV. The upper two spectra were taken at a matching $q = 0.47$ fm^{-1}. Note that the background (mainly due to the radiative tail) has not been subtracted for those spectra, contrary to the spectra in Fig. 1.

plots established them to be due to purely transverse excitations. Analyses were also done for the structures seen at higher excitations. No pure transverse component was found in the transitions into this region. Careful searches indicated no measurable $M1$ transition strength to the level at $E_x = 13.48$ MeV with $J^\pi;T = 1^+;1$ and also no $M2$ strength was found near 16.4 MeV excitation. For all the analyses in this work, the cross sections for inelastic excitations were determined with respect to the elastic cross sections,[11,12] which were described by a two parameter Fermi charge distribution with $c = 2.793$ fm and $t = 2.515$ fm.

The second series of measurements were devoted to the excitation region $E_x = 16$—24 MeV. Four spectra were measured which also included two q-matching points (see Table I). As Fig. 2 demonstrates, this region is dominated by broad structures due to electric giant dipole and quadrupole resonances. None of the peaks is found to be due to an entirely transverse excitation. In view of the possibility that the strength is spread over a large region of excitation, the spectra of Fig. 2 were subjected to a further analysis. The first step consisted in a multipole decomposition.[13–16] For this purpose, the spectra were binned into 200 keV wide regions. The q dependence of $E1$ and $E2$ components, i.e., the respective form factors, were calculated in DWBA in the framework of the Tassie model,[17] and the $M2$ components using a $1p_{3/2} \rightarrow 1d_{5/2}$ isovector particle-hole transition. Chi-square analyses were performed to individual bins to determine the partial contributions of each multipole to the total cross sections. This analysis, albeit its model dependence, resulted in $E1$ and $E2$ components that agree with the findings of Szalata *et al.*,[16] within experimental errors. It also showed that, in this region, there is no $M2$ strength beyond the experimental errors. Also, one of the spectra of Szalata *et al.*,[16] taken for incident energy of $E_0 = 59.5$ MeV at the scattering angle of $\theta = 75.3°$, corresponds to a matching q data point taken at $E_0 = 45$ MeV bombarding energy in our experiment. A careful comparison revealed that this region is dominated by longitudinal contributions. Furthermore, our fits to the data with vanishing $M2$ strength for this excitation region yield an $E1$ strength compatible with photodisintegration results.[18] From all these analyses, we could conclude that the $M2$ strength in any individual bin is less than 40 $\mu_N^2\text{fm}^2$ (in most cases, it is consistent with zero).

In passing we note that the ten spectra which have been taken in both series of measurements to search for $M2$ strength at high excitation energies in ^{20}Ne took about five months of consecutive run time at the DALINAC.

III. RESULTS AND DISCUSSION

From inspection of Figs. 1 and 2, it becomes clear that only three transitions to levels at $E_x = 11.26$, 11.62, and 12.10 MeV are clearly seen, besides the fragments of giant electric multipole resonances. The former three transitions were ascertained to be purely transverse. The transition to the $E_x = 11.26$ MeV level is the well-known[19] $M1$, and the other two are isovector $M2$ transitions. The deduced strengths are $B(M2,k)\uparrow = 64\pm13$ and 56 ± 13 $\mu_N^2\text{fm}^2$ with transition radii $R_{tr} = 3.1\pm0.7$ and 4.2 ± 0.7 fm, respectively, for the 11.62 and 12.1 MeV levels. The possible $M1$ strength to the level at 13.48 MeV excitation is found to be less than 0.2 μ_N^2. No measurable $M2$ strength is found at higher excitations up to 24 MeV.

A. Comparison with model predictions

Schmid[4] predicts a large concentration of $M2$ strength around 17 MeV excitation (about 500 $\mu_N^2\text{fm}^2$ for a single transition). For levels at about this excitation energy, the decay by neutron emission is kinematically possible and thus it is likely that the strength is further spread out. However, the experimental upper limit of $B(M2,k)\uparrow < 40$ $\mu_N^2\text{fm}^2$ is much too small to support this model. One interesting feature of the calculation[4] are two isovector $M2$ transitions into levels around 10 MeV excitation with a total strength of about 100 $\mu_N^2\text{fm}^2$, in good agreement with our experiment. However, the individual transition strengths are not well accounted for.

The prediction of the σ-τ model with transverse spin polarization reflects the main feature of the data which is an absence of or at most a very small collectivity. The theoretical strength of 65 $\mu_N^2\text{fm}^2$ at $E_x = 21.5$ MeV is perhaps just compatible with the experimental upper limit of $B(M2,k)\uparrow < 40$ $\mu_N^2\text{fm}^2$, in view of the spreading due to neutron emission, while the strength of 240 $\mu_N^2\text{fm}^2$ at $E_x = 13.3$ MeV is comparable to the strength of 120 $\mu_N^2\text{fm}^2$ distributed between the observed levels (the strength is generally overestimated by a collective model).

We should mention, however, that the observed levels have presumably $K^\pi = 1^-$ and 2^- (they are the analogs of the states at 1.30 and 1.84 MeV in ^{20}F which have these quantum numbers[20]), while the theoretical level at $E_x = 13.3$ MeV has $K^\pi = 1^-$. This fact might be a difficulty in the way of the identification of the observed levels as fragments of the theoretical one, but supports the transverse spin polarization. With longitudinal polarization, in fact, the corresponding level at 12.2 MeV has $K^\pi = 0^-$.

B. Comparison with the analogous (π^-,γ) reaction

As mentioned in the Introduction, one of the interests in isovector magnetic transitions is the possible comparison with the analogous axial vector processes such as the (π^-,γ) reaction. In the $^{20}\text{Ne}(\pi^-,\gamma)^{20}\text{F}$ reaction, the levels with $E_x(J^\pi)$ MeV $= 1.06(1^+)$, $1.30(2^-)$, $1.84(2^-)$, and 6.1 MeV are populated. The comparison of the (π^-,γ) transition to the 1.06 MeV level with the analogous $^{20}\text{Ne}(e,e')$ data to the 11.26 MeV level was done by Martoff *et al.*,[8] and so we concentrate here on other transitions. As discussed above, our measurements do not exhibit any sizable $M2$ strength around $E_x = 16.4$ MeV for any level around this excitation energy to be analogous to the 6.1 MeV level in ^{20}F. This implies that either the 6.1 MeV level in ^{20}F is not of $J^\pi = 2^-$ or that the orbital contribution interferes destructively with the spin part for the analogous $M2$ transition. Considering the transitions to the 1.30 and 1.84 MeV levels in ^{20}F, one finds in $^{20}\text{Ne}(\pi^-,\gamma)$ the ratio of branchings

$$R_{(\pi^-,\gamma)} = \frac{R_\gamma(1.30)}{R_\gamma(1.84)} = 0.64\pm0.24 ,$$

while in $^{20}\text{Ne}(e,e')$ the ratio of form factors [close to the momentum transfer in (π^-,γ)] for transitions to the analogous levels at 11.62 and 12.10 MeV in ^{20}Ne is found to be

$$R_{(e,e')} = \frac{F_T^2(11.62)}{F_T^2(12.10)} = 1.84\pm0.34 .$$

The transition weakly populated in (π^-,γ) has its analog strongly populated in (e,e') and vice versa. The (π^-,γ) reaction is sensitive to spin currents alone, while the (e,e') reaction is influenced by orbital currents also. From the ratios for the pairs of analogs in these two processes, it is thus clear that the interference between spin and orbital parts is constructive for the transition to the 11.62 MeV level and destructive for the one to the 12.10 MeV level. Below, we present a simple phenomenological two-state model for the description of these two pairs of analog levels.

We consider the ^{20}Ne ground state as consisting of a pure $(d_{5/2}^4)$ configuration, and the $M2$ transitions as due to a single particle excited from the p shell into the $d_{5/2}$ shell or a $d_{5/2}$ nucleon promoted into the f-p shell. We set forth three constraints to arrive at the possible configurations, viz., they should reproduce the ratios in (π^-,γ) and (e,e') and also require it to account for the electron scattering form factor at a momentum transfer close to the one in (π^-,γ), i.e., at the so-called pion point defined through the relation $k_\pi = (E_x + E_\pi)/\hbar c$, with E_π being the pion energy. After trying various pairs of configurations we obtain the following unique set for the two levels:

$$|11.62\rangle = 0.3360\,|d_{5/2}^3 f_{7/2}^1\rangle + 0.0122\,|d_{5/2}^5 p_{1/2}^{-1}\rangle + \cdots ,$$

$$|12.10\rangle = 0.0122\,|d_{5/2}^3 f_{7/2}^1\rangle - 0.3360\,|d_{5/2}^5 p_{1/2}^{-1}\rangle + \cdots$$

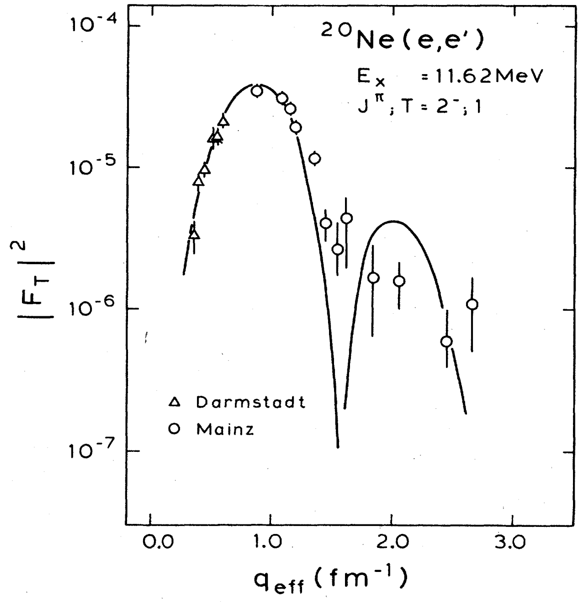

FIG. 3. The transverse form factor for the $M2$ transition to the level at $E_x = 11.62$ MeV excitation in ^{20}Ne. Shown are the data from the present measurements (triangles) and also from Mainz (circles). The solid curve is the result of a phenomenological two-state model calculation described in the text.

that satisfies all these requirements. Furthermore, with the wave function for the 11.62 MeV level, we calculated the $M2$ form factor, shown in Fig. 3. Also displayed in the same figure are the experimental data from our measurements and Mainz data, provided to us by Bergstrom.[21] As seen in Fig. 3, this simple calculation with a harmonic oscillator parameter $b = 1.67$ fm accounts for the experimental data up to the first minimum. At higher momentum transfers where the data are sparse and the error bars are large, the two-state model does not do so well. In this phenomenological description, the orbital contributions amount to about 27% and 13%, respectively, for the transition amplitudes to the 11.62 and 12.10 MeV levels. It is thus seen that the large $|d^3_{5/2} f^1_{7/2}\rangle$ amplitude for the 11.62 MeV level results in the constructive interference between the spin and orbital parts, while the $|d^5_{5/2} p^{-1}_{1/2}\rangle$ amplitude yields a destructive effect for the 12.10 MeV level.

IV. SUMMARY AND CONCLUSIONS

In ^{20}Ne, in the excitation region of $E_x = 11$ to 24 MeV, only two fairly strong isovector $M2$ transitions appear at levels of $E_x = 11.62$ and 12.10 MeV with strengths of $B(M2,k)\uparrow = 64 \pm 13$ and 56 ± 13 $\mu_N^2\text{fm}^2$, respectively. It is found that the calculations of Schmid[4] reproduce the summed strengths of these two transitions but greatly overestimate the $M2$ components at higher excitations.

The σ-τ model with transverse spin polarization is in qualitative agreement with the data. It reproduces the observed reduction in the collectivity which would arise from the short-range interaction by exploiting the attraction which comes from the OPE potential when the axis of spin quantization is properly related to the nuclear shape.

Although the predictions of the σ-τ model are compatible with the data for ^{12}C, ^{20}Ne, and ^{28}Si, we cannot emphasize the agreement, especially in view of the fact that, as already said, the model with transverse spin polarization is not entirely consistent.

In order to have a convincing test of the model it is necessary to verify if the emerging pattern (one single collective level in oblate nuclei, the absence of, or at most, small collectivity in prolate nuclei) could be confirmed in the other light deformed nuclei.

We have also made a comparison of the (e,e′) data with the analogous (π^-,γ) reaction data. It is found that a consistent description of these analog processes requires a non-negligible contribution of the orbital currents for $M2$ transitions, similarly, as in the case of $M1$ transitions.[8,22]

It is to be noted that in ^{20}Ne the decay by neutron emission becomes kinematically possible for levels over 17 MeV excitation energy. The resulting large spreading widths would perhaps render the $M2$ strength further fragmented. With this viewpoint we have also searched for $M2$ strength in ^{22}Ne, another prolate deformed light nucleus, where neutron emission is isospin forbidden for $T_>$ levels. However, this investigation revealed *no* measurable isovector $M2$ strength for $E_x = 15$–20 MeV.

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