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LETTER TO THE EDITOR

On the extraction of the nuclear twist in the (e, e′) reaction

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Abstract. The contributions of the convection and spin components of the 2^- state current transition densities to the (e, e′) cross section at transferred momentum values q_{eff} in the range 0 to 2.5 fm^{-1} are analysed in the DWBA for ^{90}Zr and ^{208}Pb. It is found that the convection component gives the main contribution to the cross section in the region $q_{\text{eff}} = 0.8\ \text{fm}^{-1}$ for ^{90}Zr and $q_{\text{eff}} = 0.6\ \text{fm}^{-1}$ for ^{208}Pb. Thus it is concluded that fragments of the 'nuclear twist' formed by the convection component were detected at Darmstadt in the (e, e′) reaction on ^{208}Pb.

The fluid-dynamical approach predicts the existence of the 'nuclear twist'. This mode is characterised by the quantum numbers $J^\pi = 2^-$ and $T = 0$ and is located at $E_x \sim (45\text{–}50)A^{-1/3}$ MeV (Holzwarth and Eckart 1977, Semenko 1981). It is formed under the orbital part of the M2 operator and can be visualised as a rotation around the z axis of different layers of a Fermi fluid with the angle of rotation proportional to the z coordinate of the layer. Thus for the nuclear twist we use only the convection component

$$\boldsymbol{j}^{c}(\boldsymbol{r}) = -\mathrm{i}\mu_{\mathrm{N}} \sum_k \delta(\boldsymbol{r} - \boldsymbol{r}_k) g_l (\Psi_{\mathrm{f}}^* \nabla_k \Psi_{\mathrm{i}} - \Psi_{\mathrm{i}} \nabla_k \Psi_{\mathrm{f}}^*) \tag{1}$$

of the 2^- state current transition density (CTD). The other component of the CTD is the spin current

$$\boldsymbol{j}^{s}(\boldsymbol{r}) = \mu_{\mathrm{N}} \sum_k \delta(\boldsymbol{r} - \boldsymbol{r}_k) g_s [\nabla_k \times (\Psi_{\mathrm{f}}^* \boldsymbol{s}_k \Psi_{\mathrm{i}})] \tag{2}$$

which forms the 'spin' mode.

The presentation of the 2^- spectrum as twist and spin modes is justified only when the interference between $\boldsymbol{j}^c(\boldsymbol{r})$ and $\boldsymbol{j}^s(\boldsymbol{r})$ is negligibly small. But as the microscopic calculations of Schwesinger (1983) and Wambach (1983) show, both components of the CTD give a comparable contribution to the M2 strength in the region of the twist mode. On the other hand, it is well known that different nuclear reactions are selective to excitation of different nuclear modes. Thus in order to observe the nuclear twist, we ought to find the reaction in which the contribution of $\boldsymbol{j}^s(\boldsymbol{r})$ is suppressed.

The contributions of $\boldsymbol{j}^c(\boldsymbol{r})$ and $\boldsymbol{j}^s(\boldsymbol{r})$ to the (e, e′) cross section have been estimated by Schwesinger *et al* (1980). They considered the excitation of four basis 2^- states $|ST\rangle$ with spin S and isospin T equal to 0 and 1. It was found that the maximum of the $S = 0$ form factor (the twist-mode excitation) was shifted to a higher momentum transfer q in comparison with the maximum of the $S = 1$ form factor (the spin-mode excitation). We thus expect to be able to extract the twist mode experimentally in the (e, e′) reaction in the region of $|F_{2^-}^{S=0}(q)|^2_{\max}$. To prove our hopes we must be sure that the spin component of

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the CTD is suppressed sufficiently under these conditions. For that we need to calculate the (e, e′) cross section with microscopic wavefunctions for the excited states. Such calculations are presented in this Letter.

To start with, let us consider briefly the main features of the M2 strength distribution. The results for ^{90}Zr and ^{208}Pb are shown in figure 1 as strength functions with the average parameter equal to 1 MeV. We describe the excited states in the RPA of the quasiparticle–phonon nuclear model (Soloviev 1976, Vdovin and Soloviev 1983). The wavefunction has the form

$$|\Psi_f\rangle = Q^{+}_{\lambda\mu i}|\Psi_i\rangle = \tfrac{1}{2}\sum_{jj'} [\psi^{\lambda i}_{jj'}[\alpha^{+}_{j}\alpha^{+}_{j'}]_{\lambda\mu} - (-1)^{\lambda-\mu}\varphi^{\lambda i}_{jj'}[\alpha_{j'}\alpha_{j}]_{\lambda-\mu}]|\Psi_i\rangle.$$

To find the amplitudes ψ and φ and the energies of the states we solve the well known RPA equations with separable spin-multipole forces.

The main part of the M2 strength in ^{90}Zr and ^{208}Pb is distributed over the energy range from 3 to 20 MeV. We have the same wide distribution for the spin mode. The nuclear twist is located in a narrow region: in ^{208}Pb we see only a strong bump at 7.3 MeV (which corresponds to $E_x = 43A^{-1/3}$ MeV) while in ^{90}Zr there are two bumps at 9.2 and 11.3 MeV (with the centroid at $\bar{E}_x = 46A^{-1/3}$ MeV). The main bump of the M2 resonance is thus caused by the coherent interference of both CTD components while the high-lying part of the resonance is caused by the spin current only. Holzwarth and Eckart (1977) found that the twist-mode contribution to the M2 sum is about 20% in ^{208}Pb. However, because of the sharp concentration of the twist strength its contribution around $E_x = 45A^{-1/3}$ MeV is larger. If we consider the energy ranges 5.4–11.4 MeV in ^{208}Pb and 7.4–13.4 MeV in ^{90}Zr,

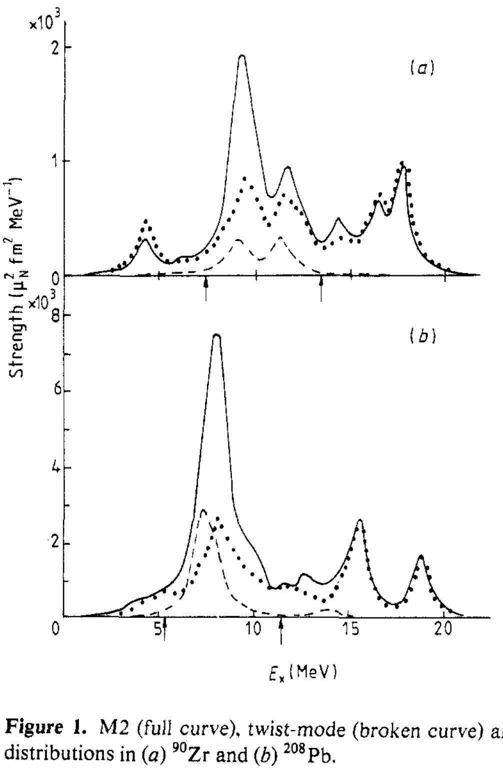

Figure 1. M2 (full curve), twist-mode (broken curve) and spin-mode (dotted curve) strength distributions in (*a*) ^{90}Zr and (*b*) ^{208}Pb.

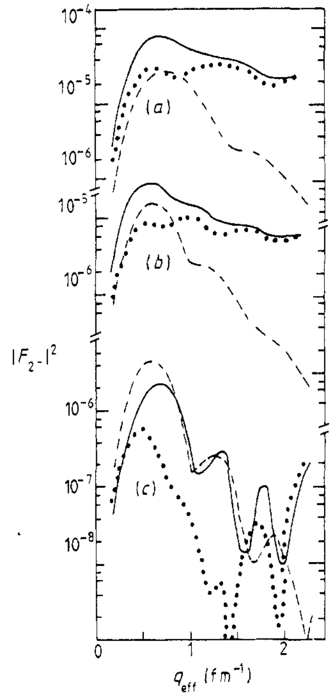

Figure 2. The sum of form factors of all 2^- states from the energy range 7.4–13.4 MeV for ^{90}Zr (*a*) and 5.4–11.4 MeV for ^{208}Pb (*b*); (*c*) the form factor of the 2^- state with $E_x = 7.22$ MeV in ^{208}Pb. The notation is the same as in figure 1.

we find that the twist and spin modes contribute 35.4% and 46.2% of the M2 strength from the interval in ^{208}Pb and 21.3% and 63.1% in ^{90}Zr†. These intervals are marked by arrows in figure 1. The main matrix elements of the twist operator correspond to p–h transitions with high angular momentum l. This is the reason for the increasing contribution of the convection current as A increases ($l_{max} = 3$ in ^{90}Zr and $l_{max} = 5$ in ^{208}Pb for the proton-hole levels).

In this Letter we use an isovector spin-dipole residual interaction which is approximately three times weaker than the one used by Ponomarev *et al* (1979), who investigated the properties of 2^- states in the same theoretical approach. The influence of the residual interaction on the twist-mode features is sufficiently weak. For the spin mode an increase in the residual interaction leads to a shift of part of the spin strength into a high-energy region; for example, in ^{90}Zr a collective one-phonon 2^- state of spin nature which exhausts one third of the M2 sum appears at $E_x \sim 20$ MeV (Ponomarev *et al* 1979). Thus our calculations are performed under the worst twist-mode extraction conditions.

The distributions in figure 1 are very similar to the ones obtained by Schwesinger (1983) and Wambach (1983) using the theory of finite Fermi systems. Schwesinger (1983) and Wambach (1983) investigated the influence of 2p–2h configurations on the twist- and spin-mode distributions. It was found that 1p–1h and 2p–2h coupling caused an additional fragmentation of the spin mode while its influence on the twist mode was insignificant.

Now we examine the excitation of 2^- states in the (e, e′) reaction. We have calculated the cross sections for all one-phonon 2^- states from the energy ranges marked by arrows in figure 1 in the DWBA. In figures 2(*a*) and (*b*) we show the sums of the form factors of these states as functions of momentum transfer, q_{eff}. For the twist and spin form factors only one component of the CTD, either $\boldsymbol{j}^c(\boldsymbol{r})$ or $\boldsymbol{j}^s(\boldsymbol{r})$, is taken into account. We see that the

† In our calculations we use the vacuum values for the g factors in equations (1) and (2).

most suitable conditions for the extraction of the twist mode in the (e, e′) reaction are realised in the interval $0.3 < q_{eff} < 1.0\ fm^{-1}$. At lower q_{eff} the M2 strength distribution is reproduced while for $q_{eff} > 1.0\ fm^{-1}$ the twist form factor decreases swiftly and the cross section is defined by the spin current $\boldsymbol{j}^s(\boldsymbol{r})$ only.

Our calculations confirm the fluid-dynamical predictions of Schwesinger *et al* (1980) concerning the higher value of q for the maximum of $|F_{2^-}^{twist}(q)|^2$ compared with the maximum of $|F_{2^-}^{spin}(q)|^2$. These maxima are shifted by $0.18\ fm^{-1}$ in ^{90}Zr and by $0.12\ fm^{-1}$ in ^{208}Pb. As a consequence, there is a region of q in which the twist mode predominates in the location of the M2 resonance even in ^{90}Zr.

It is obvious that the manifestation of the twist mode should be sought close to the maximum in its form factor. In ^{90}Zr this maximum is reached near $q_{eff} = 0.8\ fm^{-1}$ while in ^{208}Pb it is at $q_{eff} = 0.6\ fm^{-1}$. The value of $q_{eff} = 0.6\ fm^{-1}$ corresponds, for example, to inelastic 40 MeV electron scattering at an angle $\theta = 160°$. We have calculated the electroexcitation cross sections for all one-phonon 2^- states in ^{208}Pb under these conditions and have also calculated the twist- and spin-mode contributions separately; the results are shown in figure 3 as a strength function. A strong bump with $\bar{E}_x = 8$ MeV is seen in the cross section. The twist-mode contribution to the bump is equal to 56%, the spin-mode contribution is only 23% and 21% is the result of interference. The twist-mode contribution to the M2 resonance is much higher here compared with the calculations of the M2 strength.

The above results on the twist-mode contribution are, in fact, a lower limit for the value. First, in our calculations we use the vacuum values of the factor g_s. Different theoretical estimations indicate that $g_s^{eff} = (0.6\text{–}0.8)g_s^{free}$—this will tend to decrease the spin-mode contribution by a factor of 1.5–3 and to decrease the interference term. The same effect will occur if we take the coupling with 2p–2h configurations into account. The major bump in the M2 resonance in ^{208}Pb which we observe in the (e, e′) reaction at $q_{eff} \sim 0.6\ fm^{-1}$ is mainly the manifestation of the twist mode. The 2^- levels in the energy range $E_x = 6\text{–}8.5$ MeV have been investigated at Darmstadt (Frey *et al* 1978, Knüpfer *et al* 1978) by inelastic electron backward scattering at $q_{eff} = 0.43, 0.71$ and $0.85\ fm^{-1}$. The first and last values correspond approximately to the cases where the twist and spin

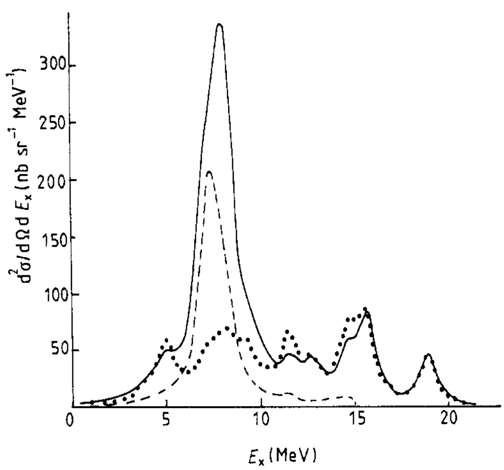

Figure 3. The strength function of the 2^- state excitation in ^{208}Pb in the (e, e′) reaction with $E_0 = 40$ MeV and $\theta = 160°$. The notation is the same as in figure 1.

contributions are equal in figure 2(*b*). At $q_{\text{eff}} = 0.71\ \text{fm}^{-1}$ we are in the region of the predominant twist-mode excitation. Thus our calculations indicate that fragments of the nuclear twist have been observed in this experiment.

In lighter nuclei the convection current is sufficiently weak and we cannot neglect the spin current contribution at any q even by taking a different mechanism for the spin-mode damping into account. However some of the one-phonon 2^- states have predominantly twist nature. These states are formed by particle–hole transitions with high l. One of these states in ^{208}Pb has an energy of 7.22 MeV; its form factor is presented in figure 2(*c*). Over a wide range of q the form factor of the state is defined exclusively by the convection current; the spin-current contribution is lower by an order of magnitude or more. The increasing distance between the maxima of $|F_{2^-}^{\text{twist}}(q)|^2$ and $|F_{2^-}^{\text{spin}}(q)|^2$ with decreasing A gives the possibility of distinguishing the 2^- levels of twist and spin nature in lighter nuclei through the location of the maximum in $|F^{\text{M2}}(q)|^2$.

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