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Isospin mixing in the electroexcitation of the $E_x = 10.84$ MeV, $J^\pi; T = 1^-; 0$ state in ^{12}C at low momentum transfers ⋆

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Abstract

Electroexcitation of the isospin-forbidden transition to the broad $J^\pi; T = 1^-; 0$ state at 10.84 MeV in ^{12}C has been studied for momentum transfers $q < 0.6$ fm^{-1}. The longitudinal form factor exhibits a sensitivity to the interference of small $T = 1$ admixtures. The isospin breaking Coulomb matrix element is determined in a two-state model to $\langle H_C \rangle = 145(80)$ keV. A shell-model calculation using a new effective *psd*-shell interaction qualitatively agrees with the shape of the form factor but underpredicts its magnitude by a factor of about two.

Isoscalar electric dipole transitions are forbidden in self-conjugate nuclei, if isospin is a good quantum number. Notwithstanding, fairly fast E1 transitions have been observed in all 4N nuclei from ^{12}C to ^{40}Ca with transitions strengths, often of the order of average allowed E1 transitions in this mass region or even exceeding it. Because of the forbiddeness in the long-wavelength limit electroexcitation at low momentum transfers q is sensitive to small $T = 1$ admixtures which can be well studied in the form factor. It exhibits a strong dependence on the interference phase between the isospin allowed and forbidden form factor pieces which makes it a real test for any nuclear model accounting for isospin mixing. Experimental studies have been reported for ^{16}O [1,2] and ^{40}Ca [3] and compared to a variety of microscopic calculations [4–8].

The present work deals with an investigation of (e,e′) scattering at low momentum transfers off the broad $J^\pi; T = 1^-; 0$, level in ^{12}C at $E_x = 10.84$ MeV. A special interest in this transition was borne out of a recent study with low-energy inelastic pion scattering [9]. There, approximate charge symmetry was obtained in the ratio of π^+ and π^- cross sections for the excitation of this state. However, because of the Coulomb interaction this does not imply a purely isoscalar nature of the transition as will be shown below.

The paper is organized in the following way. After a brief discussion of the experiment the isospin violating Coulomb matrix element is deduced from a com-

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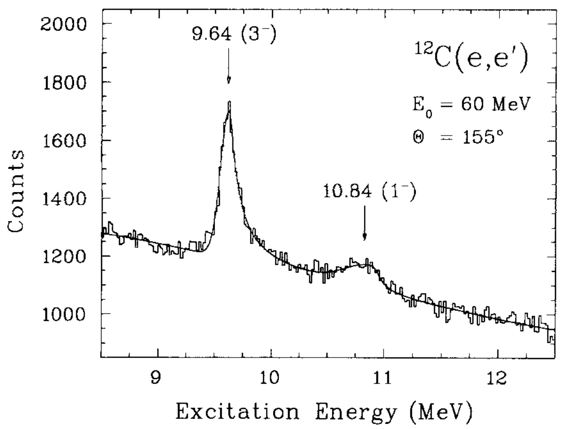

Fig. 1. Excitation energy spectrum of inelastically scattered electrons from a ^{12}C target at $E_0 = 60$ MeV and $\Theta = 155°$.

bined analysis of electron and pion scattering. Then, the results are tested against a shell-model calculation employing a new effective interaction coupling p- and sd-shell configurations [10].

The measurements have been performed at the superconducting continuous wave Darmstadt electron linear accelerator S-DALINAC [11] using the large solid-angle QCLAM magnetic spectrometer [12]. Although with this new experimental equipment data can now be taken much faster than at the old low-duty factor accelerator DALINAC, the main experimental problem lies here in the large intrinsic width [13] of the 10.84 MeV level (Γ = 315 keV) which severely hampers its detectability on top of the radiative tail in the spectra. Data have been taken at an incident energy $E_0 = 60$ MeV and scattering angles $\Theta = 115°$–$155°$. This corresponds to a momentum transfer range $q^2 =$ 0.22–0.28 fm^{-2}. The target consisted of 41 $\mathrm{mg/cm}^2$ natural carbon and typical beam currents were 1–3 μA.

Fig. 1 shows the spectrum taken at 155° where no background or radiative tail is subtracted. In the displayed excitation energy region no other transitions than those indicated are expected. The full line results from a least-squares fit to the data based on the line shape extracted from the corresponding elastic line. The width of the 10.84 MeV level was a variable in the fit, since the intrinsic width is much larger than the typical experimental resolution of $\Delta E \approx 120$ keV (FWHM). The resulting intrinsic width was always in good agreement with the value from the literature [13].

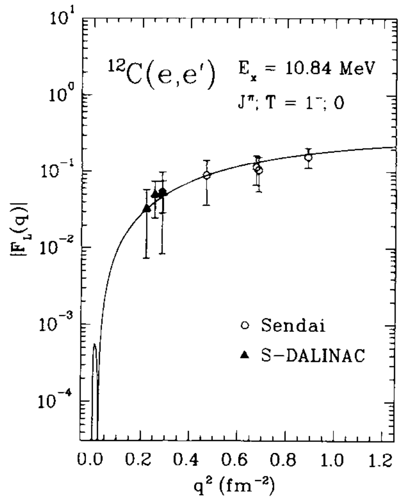

Fig. 2. Longitudinal form factor F_L as a function of q^2. The open circles are data from [17]. The solid line represents the result of Eq. (2) with parameters $A_0 = 0.078$, $A_1 = 0.070$ and a relative phase $\Phi = -1$.

The cross sections have been determined by comparison to the elastic ones (as described, e.g., in [14]). The elastic scattering cross section was calculated in the distorted wave Born approximation (DWBA) with the code PHASHI [15] using the charge density distribution parameters of [16]. In order to derive the longitudinal form factor the transverse part was subtracted assuming validity of Siegert's theorem

$$B(\mathrm{E1},q) = B(\mathrm{C1},q)\ \frac{k^2}{q^2}\ , \tag{1}$$

where $k = E_x/\hbar$ defines the photon point. For the highest q in the present measurement this assumption could also be tested experimentally taking into account the corresponding data point of [17] and unpublished results from experiments at the DALINAC accelerator by one of us. The Rosenbluth plot was consistent with Eq. (1), however with large experimental errors on the individual data points.

The longitudinal form factor is displayed in Fig. 2 together with data taken at higher q from Torizuka et al. [17]. The error bars are due to statistics, background subtraction and line shape fitting. Additionally, an error of 10% of the respective correction has been added linearly for uncertainties in the subtraction of the transverse cross sections. The experimental results (as previously for ^{16}O [1] and ^{40}Ca [3]) are compared to an expression that can be derived within the harmonic oscillator model

$$|F_l(q)| = |A_0(q^3b^3 + \Phi A_1 qb)\exp(-\tfrac{1}{4}b^2q^2)|\,. \quad (2)$$

Here, A_0, A_1 are fit parameters being a measure for the isoscalar and isovector form factor strengths, respectively, Φ denotes the relative phase between the isoscalar and isovector contributions, and $b = 1.747$ fm is the oscillator parameter [18]. The q^3 dependence of the $T = 0$ part of the form factor results from the removal of the spurious state which eliminates the leading term of the transition matrix element expansion linear in q. On the contrary, the higher-order q terms can be neglected for the orthogonal $T = 1$ part. The exponential term in Eq. (2) describes the radial matrix element dependence in an oscillator potential. Eq. (2) allowed a very good analytical description of the results obtained in ^{16}O and ^{40}Ca [1,3].

One might argue that the q-value range experimentally accessible for the 10.84 MeV transition is still not close enough to the photon point to permit an unambiguous determination of the isovector part from a simultaneous fit of the three parameters A_0, A_1 and Φ. However, as discussed below, one of the free parameters is eliminated utilizing the $\pi^\pm$ scattering results of [9] which demand a negative phase Φ. Furthermore, the parameter A_0 can be normalized to (e,e′) results obtained for the corresponding E1 transition to the $J^\pi;T = 1^-;0$ state in ^{16}O [1,19] by comparison of the form factors in a q-value range where Eq. (2) is still expected to hold, but $T = 1$ contributions can be neglected. With these assumptions we obtain $A_0 = 0.078(7)$. A least-squares fit to the data then yields $A_1 = 0.070(36)$.

As pointed out above, the phase between the isoscalar and isovector pieces in Eq. (2) can be inferred from the a study of $\pi^\pm$ scattering off the 10.84 MeV state. In a reanalysis of the data obtained at the lowest energy ($E_\pi = 50$ MeV) in [9], which cover a comparable momentum transfer range, the proton and neutron deformation parameters in the form factor calculation were adjusted in such a way to permit a simultaneous description of π^+ and π^- scattering cross sections. This yields proton and neutron matrix elements $M(p) = 0.394(28)$ fm and $M(n) = 0.344(48)$ fm, respectively. For all reasonable fit conditions consistently $M(n) < M(p)$ is obtained. Therefore, the relative sign of the two isospin matrix elements [20]

$$\frac{M_{T=1}}{M_{T=0}} = \frac{M(n) - M(p)}{M(n) + M(p)} \quad (3)$$

is also negative. In principle, the ratio in Eq. (3) is a direct measure of the isospin mixing. However, the experimental errors are too large for quantitative conclusions, since within the errors given above $M_{T=1}/M_{T=0}$ can vary between 0 and 17%.

The transition to the lowest $J^\pi;T = 1^-;1$ level in ^{12}C at $E_x = 17.23$ MeV is well known [13]. Thus, one can utilize Eqs. (2) and (3) to determine from the electron scattering results the mixing amplitudes α, β in a two-state model [21] where the wave functions are written as

$$|1^-, 10.84\rangle = \alpha|T = 0\rangle + \beta|T = 1\rangle\,, \quad (4)$$

$$|1^-, 17.23\rangle = -\beta|T = 0\rangle + \alpha|T = 1\rangle \quad (5)$$

and the longitudinal form factors as

$$|F_L(10.84)| = |\alpha M_{T=0}q^3 + \beta M_{T=1}q|\,, \quad (6)$$

$$|F_L(17.23)| = |-\beta M_{T=0}q^3 + \alpha M_{T=1}q| \quad (7)$$

with $\alpha^2 + \beta^2 = 1$ and $\beta < 0$.

The amplitudes can be determined by comparison of Eqs. (6) and (7) at the photon point. The extrapolation of Eq. (2) to the photon point yields $B(\mathrm{E1})_{T=0} = 0.39(20) \times 10^{-5}e^2$ fm^2 for the isoscalar transition which corresponds to a hindrance factor 1×10^5, about a factor of five larger than the average value in this mass region [22]. The isovector transition strength $B(\mathrm{E1})_{T=1} = 0.25 \times 10^{-1}e^2$ fm^2 is derived for from the g.s. partial decay width $\Gamma_{\gamma_0} = 44(4)$ eV [13]. Since $\alpha \gg \beta$ and $k \gg k^3$, the first term in Eq. (7) can be neglected and one obtains $\beta = -0.023(12)$. This small number yields a corresponding Coulomb matrix element

$$\langle H_C\rangle = \alpha\,\beta\,|E_x^{T=1} - E_x^{T=0}| = 145(80)\text{ keV}\,. \quad (8)$$

This is in good agreement with the analyses of isospin mixing of the $J^\pi;T = 1^+;0$ and $1^+;1$ transitions in ^{12}C at $E_x = 12.71$ and 15.11 MeV, respectively (see [23] and references therein). The most precise value, $\langle H_C\rangle = 117(8)$ keV comes from a recent (e,e′) experiment at low momentum transfers [24]. Further-

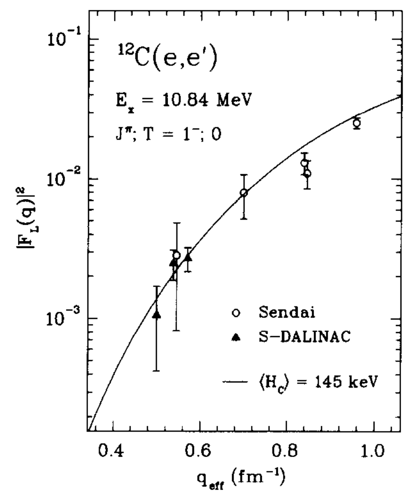

Fig. 3. Longitudinal form factor F_L as a function of q_{eff}. The solid line is a shell-model calculation with the effective *psd*-shell interaction of [10] and an isospin mixing matrix element $\langle H_C \rangle$ = 145 keV. The calculation is normalized to the data with a factor N = 2.0.

more, the derived magnitude fits well into the systematics of isospin breaking matrix elements in this mass range (see Fig. 14 in [25]). If, on the contrary, instead of the lowest T = 1 level at 17.23 MeV the isovector giant dipole resonance with its largest fragment at E_x = 22.6 MeV and with Γ_{γ_0} = 2500(250) eV [13] is made responsible for the mixing, a much smaller value $\langle H_C \rangle$ = 38(20) keV is obtained, i.e. a value too low as compared to the systematics.

As the next step the form factor is compared in Fig. 3 to a shell-model calculation using a harmonic oscillator potential and a new effective interaction coupling the p- and sd-shells and taking into account perturbing effects of the neighboring s- and fp-shells [10]. The experimental results are corrected for effective q-values for comparison with the PWBA calculation which in light nuclei is a good approximation to the full DWBA calculation. The formalism of the longitudinal form factor calculation is displayed in detail in [26]. Isospin mixing is explicitly introduced as, e.g., described in [27].

The solid line in Fig. 3 gives the result for a mixing matrix element $\langle H_C \rangle$ = 145 keV as determined above. The shape of the longitudinal form factor is well accounted for up to $q_{eff} \approx 1$ fm^{-1}, but overshoots the data of [17] at higher momentum transfers (not shown here). While the results at the lower q should be fully explainable in a $1\hbar\omega$ model space, the interference with $3\hbar\omega$ contributions neglected here might well be able to explain the reduction for $q_{eff} > 1$ fm^{-1}. Such a behaviour was qualitatively demonstrated in the calculations of Arima et al. [5] for the $J^\pi;T = 1^-;0$ transition in ^{16}O.

The sensitivity of the calculation to the magnitude of $\langle H_c \rangle$ is not very pronounced at the lowest q values accessed in the present work. However, the description for the momentum transfer range $q \approx 0.7$–1 fm^{-1} is considerably worsened if a larger Coulomb matrix element is assumed.

A normalization constant N = 2.0 is needed to scale the model results to the data in Fig. 3. This underprediction of the experimental form factor can be related to various model approximations, i.e. uncertainties of the single-particle energies [4], the use of harmonic oscillator instead of Woods–Saxon wave functions [5,7] or the neglection of coupling to the continuum [7]. However, comparison with typical variations of form factor and life time calculations due to these effects [4–7] can well explain the observed factor and one can still conclude that the main features of the isoscalar E1 transition are reasonably explained by the present model.

In summary, electroexcitation of the isospin-forbidden transition to the $J^\pi;T = 1^-;0$ state at 10.84 MeV in ^{12}C was measured at momentum transfers $q < 0.6$ fm^{-1}. The longitudinal form factor was analyzed with an empirical approach [1,3] which explicitly considers the influence of isospin mixing. Utilizing the unambiguous phase determination in low-energy inelastic pion scattering experiments on this transition [9], one obtains a reduced transition probability B(E1) = 0.39(20) × $10^{-5}e^2$ fm^2. The strength of the isospin breaking matrix element is determined in a two-state model of mixing with the lowest $J^\pi;T = 1^-;0$ transition in ^{12}C to be $\langle H_C \rangle$ = 145(80) keV. This agrees well with similar analyses of magnetic dipole transitions in ^{12}C [23,24] and also with the systematics of isospin mixing in other light nuclei [25].

A shell-model calculation using a new effective *psd*-shell interaction provides a successful description of the longitudinal form factor shape in the momentum transfer range where $3\hbar\omega$ contributions can be neglected. However, as observed in other attempts to describe this type of transition [4–7], the absolute strength is extremely sensitive to various approximations in the calculations. Even with the present advanced shell-model interpretation of the properties of p- and sd-shell nuclei, isospin-forbidden E1 transitions in self-conjugate light nuclei present a challenge which merits further experimental and theoretical investigations. Using different probes - like electrons and pions in the present work - and a combined analysis of data is clearly beneficial in this task.

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