Electron Scattering, Isospin Mixing, and the Structure of the 12.71- and 15.11-MeV Levels in ^{12}C

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(Received 24 September 1979)

The structure and the degree of isospin mixing for the 1^+ levels in ^{12}C at 12.71 MeV ($T=0$) and 15.11 MeV ($T=1$) are determined from measured 180°-electron-scattering form factors. The resulting charge-dependent isospin-mixing matrix element ranges from 130 to 165 keV depending on the theoretical model of the isoscalar form factor.

Isospin mixing beyond that which can be accounted for by the simple Coulomb interaction implies the existence of a charge-dependent component in the nuclear force.[1] A classic example of isospin mixing involves the pair of 1^+ levels in ^{12}C at 12.71 MeV ($T=0$) and 15.11 MeV ($T=1$). For this doublet, values of the charge-dependent matrix element H_{CD} deduced from studies using hadronic probes[1-4] vary between 120 and 250 keV. The divergence in these values underlines the point emphasized by Adelberger *et al.*[3] that many of the hadronic particle-transfer reactions may not be sufficiently well understood to allow reliable determinations of the expected small degree of isospin mixing. On the other hand, inelastic electron scattering involves the well-known electromagnetic interaction, and can be used to place constraints on the structure of these states, including the isospin mixing, with little uncertainty attributable to the reaction mechanism.[5-7] Moreover, electron scattering can be extremely sensitive to small isovector admixtures in an isoscalar wave function since, if we ignore convection current contributions, the ratio of isovector to isoscalar cross sections is proportional to $[(\mu_p-\mu_n)/(\mu_p+\mu_n)]^2=28.6$. In this Letter we present the first measurement of the momentum-transfer dependence of the 12.71-MeV isoscalar $M1$ form factor as well as new measurements of the 15.11-MeV isovector $M1$ form factor, with emphasis on the first diffraction minimum and second maximum.

Data spanning a momentum transfer range from $q=0.5$ to 2.8 fm^{-1} were obtained at the Bates Linear Accelerator by 180° and 140° electron scattering. At 180° the radiation tail and the longitudinal cross sections are minimized so that transverse cross sections may be measured in the relative absence of other contributions.[8] The data taken for the 15.11-MeV level at 180° proved to be of better quality than those taken at 140° for which the region between the 15.11- and 16.11-MeV peaks was filled in by a broad background possibly resulting from the excitation[9] of a level at 15.4 MeV. Also the extraction of cross sections for the 12.7-MeV. Also the extraction of cross sections for the 12.7-MeV level was easier for the 180° than for the 140° data because of the suppression of neighboring longitudinal excitations. Representative spectra taken near peaks of the form factors are shown in Fig. 1. The data were corrected for Coulomb distortion effects,[10] so that they could be compared with plane-wave Born-approximation calculations. A detailed discussion of the experimental technique and analysis procedure will be present elsewhere.[11]

The resulting 15.11-MeV form factor is shown in Fig. 2 together with all previous measurements that we judge to be reliable.[12] The present data define the diffraction minimum and the high-q behavior of the form factor, and thus complement many earlier measurements primarily clustered at low q.

Our present analysis of the 15.11-MeV form factor follows that of Ref. 5, and supersedes it because of the full inclusion of the data reported here. Our aim is to use only experimental information in describing the transition so as to derive the $1p$-shell density matrix.[5] Higher configurations than $1p$ typically contribute 12–15% to the levels of interest as was found in a full $2\hbar\omega$ calculation.[6] In this $1p$-shell approximation the one-body contribution to the $M1$ form factor is

$$|F_T(q)|^2=[8q^2/(ZM_N)^2][f_{SN}{}^2(q)f_{c.m.}{}^2(q)e^{-2y}(A+By)^2], \quad (1)$$

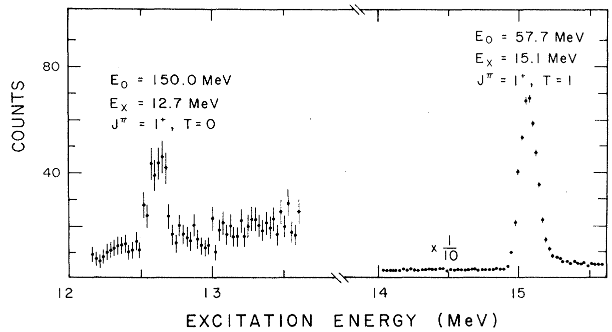

FIG. 1. Excitation spectra for the 12.71- and 15.11-MeV transitions to ^{12}C by 180°-electron scattering.

for harmonic-oscillator single-particle wave functions, where M_N is the nucleon mass, Z the nuclear charge, f_{SN} the single-nucleon form factor, $f_{c.m.}$ a center-of-mass correction, and $y=(qb/2)^2$, with b the oscillator parameter. Thus, as discussed in Ref. 5, the $M1$ form-factor data determine b and two constraints, A and B, on three combinations of the $1p$-shell density matrix elements: $\psi_{1/2,1/2}$, $\psi_{3/2,3/2}$, and $\psi_{1/2,3/2}-\psi_{3/2,1/2}$.

After computing the meson exchange corrections to Eq. (1) we have determined b (1.813 fm), A (0.477), and B (−0.341) by fitting the data shown in Fig. 2. Two additional constraints on the density matrix are provided by the experimental μ-capture and β-decay analog transition rates. Using these, we find $\psi_{1/2,1/2}=-0.121\pm0.020$, $\psi_{1/2,3/2}-\psi_{3/2,1/2}=0.291\pm0.010$, and $\psi_{3/2,3/2}=0.087\pm0.010$. Effectively this analysis separates the orbital and spin-flip contributions to the $M1$ form factor. We also obtain $\psi_{1/2,3/2}+\psi_{3/2,1/2}=-0.15$, with a large associated uncertainty of ±0.50.

In Fig. 3 the measured 12.71-MeV form factor is compared with the results of two calculations using wave functions of good isospin. One calculation is the shell-model Cohen-and-Kurath (CK) result[13] for the (8-16) 2BME potential, which differs only slightly from results with either the (6-16) 2BME or (8-16) POT interactions. In addition, two full $2\hbar\omega$ nonspurious shell-model calculations[6] which use a combination of CK, Kuo-Brown[14] (KB), and either the Millener-Kurath[15] (MK) or Gillet[16] (G) potentials have been performed with one result shown in Fig. 3. These form factors, in contrast to the 15.11-MeV case, are quite sensitive to the interference between the orbital and spin components of the transition operator. This leads to a suppression of these form factors at low q, and relatively large second maxima. We believe that there is considerable agreement among various theoretical predictions for this isoscalar strength and remarkable disagreement between these results and experiment.

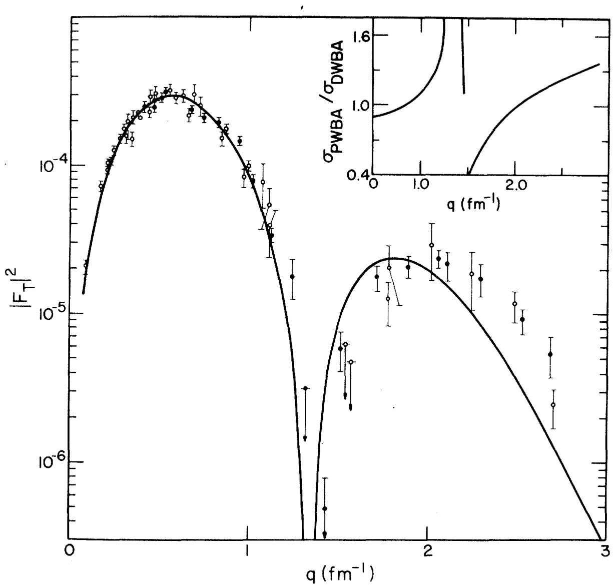

FIG. 2. The 15.11-MeV form factor. Solid circles are the data of this experiment, and open circles those of other experiments (Ref. 5). The solid curve was obtained as described in the text, and includes meson-exchange currents. The inset shows the 180°-Coulomb distortion correction used to obtain the points shown.

On the other hand, extensive arguments[3,17] have been advanced in support of the validity of the CK shell-model wave functions for ^{12}C. We are thus led to consider whether the systematic disagreement between our calculated form factors and experiment can be explained in terms of isospin mixing. We have repeated the above shell-model calculations with full inclusion of the Coulomb interaction in order to test whether a two-level mixing approximation is valid. For all of these calculations approximately 85% of the isovector component of the 12.71-MeV state is generated by mixing with the 15.11-MeV state, which has a large fraction of the isovector $M1$ strength to the ground state. Thus under the assumption that any additional components in the charge-dependent Hamiltonian H_{CD} will mix levels similarly, we can make the two-level mixing approximation:

$$|12.71\rangle=(1-\beta^2)^{1/2}|T=0\rangle-\beta|T=1\rangle,$$

with $\beta=\langle T=1|H_{CD}|T=0\rangle/\Delta E$. Since the mixing is weak, the unperturbed energy separation ΔE is equated to the observed doublet splitting of

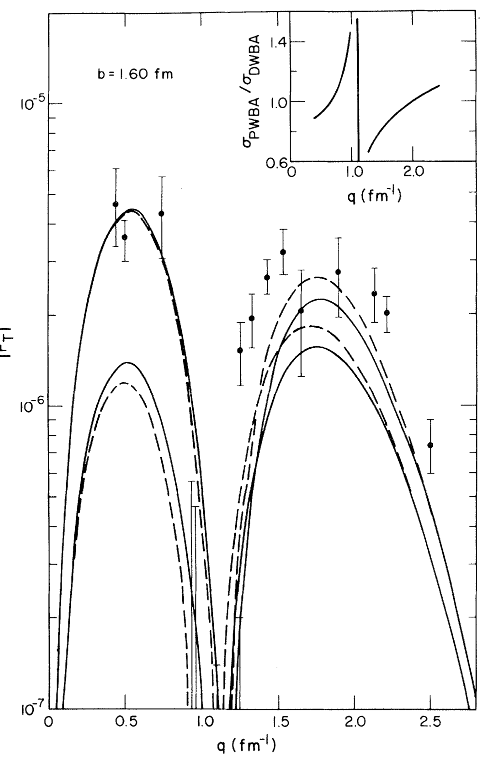

FIG. 3. Shell-model predictions for the 12.71-MeV form factor compared with the present data. The solid lines show the (8-16) 2BME prediction and the dashed lines the CK-KB-G prediction. The upper curves include isospin mixing with amplitude β as given in Table I but the lower curves do not. The inset shows the 180°-Coulomb-distortion corrections used to obtain the points shown.

2.40 MeV. Furthermore, because of the weakness of the isoscalar component, the measured 15.11-MeV form factor can be assumed to represent the isovector transition accurately. Thus, given a model for the isoscalar strength, the data of Fig. 3 provide stringent constraints on the single unknown parameter $\langle 1|H_{CD}|0\rangle$.

Values of β deduced by performing a χ^2 fit to the 12.71-MeV data are shown in the last column of Table I. Good agreement is found with one of the solutions obtained by fitting only to the radiative width with the procedure found in Refs. 3 and 6. The second solution obtained in this manner is clearly ruled out. In addition, the present fit certainly provides a much more stringent test of isospin mixing: A single parameter, $\langle 1|H_{CD}|0\rangle = 140\pm35$ keV, removes the large discrepancy between and experiment over a wide range of momentum transfers, yielding a form factor with the proper magnitude at both maxima as well as correctly defining the position of the diffraction minimum. The error we assign to $\langle 1|H_{CD}|0\rangle$ is statistical; the model dependences of this result may be seen in Table I.

Our result for $\langle 1|H_{CD}|0\rangle$ is smaller than the 250 ± 50 keV originally obtained[1] from $^{12}C(d,d')^{12}C$, but is consistent with the value of 179 ± 75 keV from the more recent measurements of Lind *et al.*[2] As discussed above, our value, 140 ± 35 keV, agrees with that obtained from measurements of the radiative width,[7] 130 ± 26 keV, although neglect of meson-exchange-current calculations in a previous analysis[3] yielded a somewhat smaller matrix element of 110 ± 30 keV.[17] On the other hand, our theoretical evaluations of $\langle 1|H_{Coul}|0\rangle$ employing harmonic-oscillator $1p$ shell-model wave functions give matrix elements of approximately 60 keV, much smaller than the experimental determination. This discrepancy can be removed, at least in part, by employing more suitable shell-model bases, for instance a $1p$-shell basis of Woods-Saxon wave functions.[18]

TABLE I. Mixing parameters β determined from various model calculations of the isoscalar *M*1 strength. The first column gives pairs of solutions determined by fitting only $\Gamma_\gamma(12.71\to0,0)$ while the second column gives the single solutions obtained when we fit, in addition, the data presented in this Letter. An oscillator parameter $b=1.60$ fm (as favored by the fitting procedure) was used in the model prediction of the isoscalar form factor.

Model	$\beta(\gamma$ only)	$\beta(\gamma+(e,e'))$
CK (8-16) POT	-0.202 ± 0.055; 0.057 ± 0.016	0.056 ± 0.016
CK (8-16) 2BME	-0.203 ± 0.055; 0.055 ± 0.015	0.054 ± 0.015
CK (6-16) 2BME	-0.201 ± 0.055; 0.058 ± 0.016	0.057 ± 0.016
FULL $2\hbar\omega$ (MK)	-0.191 ± 0.052; 0.067 ± 0.018	0.069 ± 0.018
FULL $2\hbar\omega$ (G)	-0.201 ± 0.055; 0.058 ± 0.016	0.059 ± 0.016

Alternatively, harmonic-oscillator single-particle wave functions can be retained if the model basis is expanded sufficiently. Employing the MK $2\hbar\omega$ oscillator wave functions, we find $\langle 1|H_{\rm Coul}|0\rangle = 85$ keV, which may indicate that the long-range nature of the Coulomb force requires even further expansion of the shell-model basis. On the other hand, the remaining disagreement between the experimental $\langle 1|H_{\rm CD}|0\rangle$ and the theoretical $\langle 1|H_{\rm Coul}|0\rangle$ could also be attributed to the existence of a charge-dependent component in the strong interaction.

This work was supported in part by the U. S. Department of Energy.

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[17]Adelberger *et al.*, (Ref. 3) compare several experimental results with the CK predictions for the electromagnetic properties and spectroscopic factors of ^{12}C and conclude that these wave functions are reliable to within about 20%. They note that the CK prediction for $\Gamma_\gamma(15.1\to 0.0) = 30.8$ eV is about 20% smaller than the experimental value, 37.0 ± 1.1 eV. Believing that theoretical ratios are more reliable than predictions of absolute rates, they advocate scaling the CK predictions for both $\Gamma_\gamma(15.1\to 0.0)$ and $\Gamma_\gamma(12.7\to 0.0)$ by the amount needed to bring $\Gamma_\gamma(15.1\to 0.0)$ into agreement with experiment. They argue that this is more consistent than the treatment of Ref. 7 where the experimental $\Gamma_\gamma(15.1\to 0.0)$ was used along with the unscaled prediction of CK for $\Gamma_\gamma(12.7\to 0.0)$. We wish to note, however, that when exchange-current effects are included in the CK prediction, we find $\Gamma_\gamma(15.1\to 0.0) = 36.6$ eV, in excellent agreement with experiment. Since exchange currents in lowest order have no effect on isoscalar transitions, we believe that the scaling approach is not justified. Therefore our analysis of the photon point agrees with Ref. 7, and gives a somewhat larger value of $\langle 1|H_{\rm CD}|0\rangle$ than Ref. 3.

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