ELECTRON EXCITATION OF PARTICLE-HOLE STATES IN C^{12}†

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We present theoretical and experimental results for electron excitation of particle-hole states in C^{12}.

Electron excitation is a powerful means for studying the nature of excited states in nuclei, for by working at a fixed energy loss and varying the three-momentum transfer one can in principle map out the Fourier transforms of the transition charge and current densities. By working at high-momentum transfers, one can enhance the contribution of high-spin states and states of a magnetic character. In this way one can study the properties of excited states that are not easily accessible by other means.

The simplest shell model of C^{12} is that of closed $1s_{1/2}$ and $1p_{3/2}$ shells.[1-3] In this picture one should see groupings of single-particle-hole excitations. These are the states that are expected to be most strongly excited in inelastic electron scattering since the transition operator here is just the sum of single-particle operators. In particular at large scattering angles, where transverse excitations are dominant, one expects the $T=1$ particle-hole levels to be the ones most strongly excited. Our discussion will center on the results of experiments in this angular range and will only consider $T=1$ excitations. Intuitively, if the inelastic spectrum is averaged over energy intervals of the order of 1 MeV, one expects to see the single-particle-hole structure of the excitations. This corresponds to looking at excitations in the nucleus that take place over a relatively short time, the states initially excited being single-particle-hole excitations, the so-called "doorway" states.[4] Indeed, strong well-defined peaks are observed in the continuum in inelastic electron scattering when the data are averaged over energy intervals of the order of 1 MeV. If one looks with greater resolution, one would expect to see additional structure corresponding to collision admixtures of more complicated many-particle states. We proceed to discuss only the contributions of the dominant particle-hole states.

Figures 1(a) and 1(b) are typical of the inelastic electron spectra observed at large angles from C^{12} in the range of excitation 12-32 MeV. The spectra are dominated by complexes of levels at excitations of approximately 16 and 19 MeV. These structures are well known, and form factors have been reported for values of the three-momentum transfer q up to 350 MeV/c. In this paper we report form factor measurements for these complexes in the range 190-710

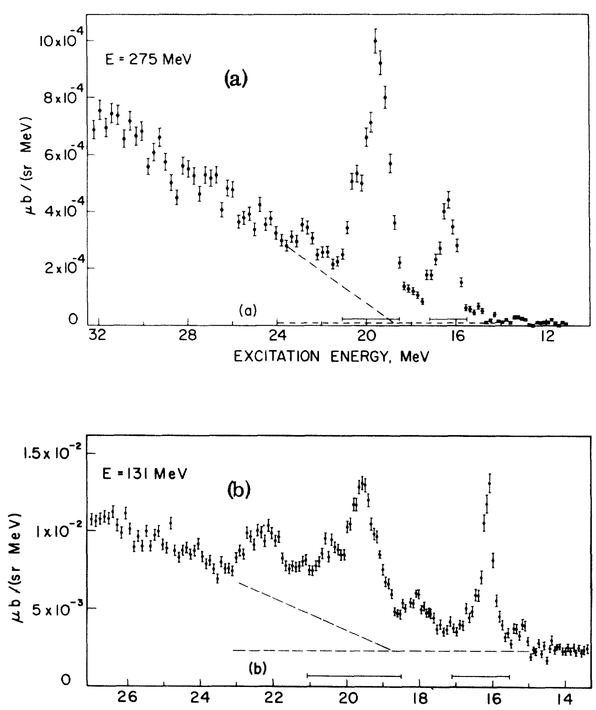
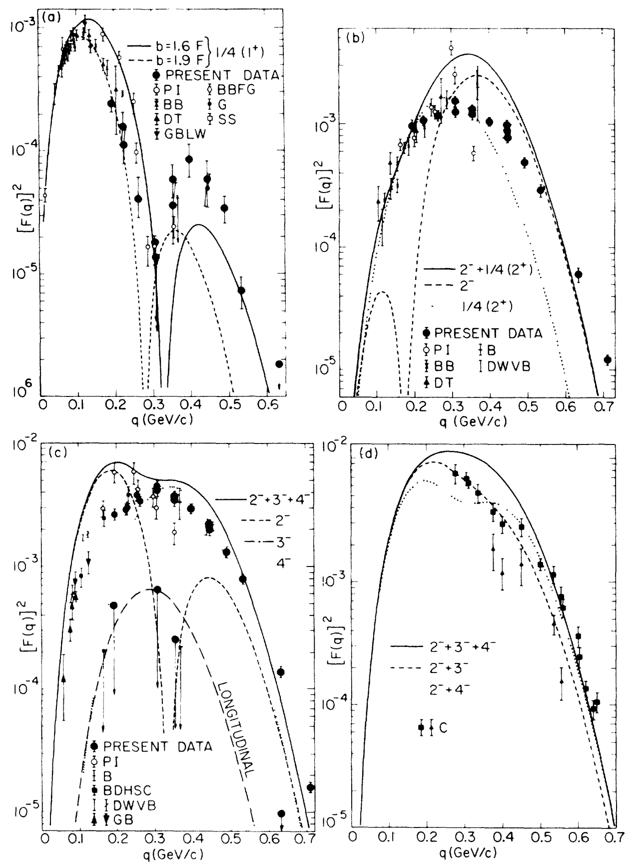


FIG. 1. (a), (b) Typical inelastic electron cross sections at 135° from C^{12}. Cross sections for the 16- and 19-MeV complexes are obtained by integration over the ranges of excitation energy indicated. The backgrounds subtracted for radiative tails of unobserved levels and for quasielastic scattering are indicated by the dashed curves. Note in (b) the clear excitation of the giant resonance at ~23 MeV and of the 18.1-MeV level.

MeV/c. We also report form factor measurements for the $T=1$, 1^+ level at 15.1 MeV and give upper and lower limits on the form factor for the giant resonance in C^{12} in the same q range.

The measurements were made at the Stanford Mark III linear electron accelerator at a scattering angle of 135°. The spectrometer and detection apparatus are fully described elsewhere.[5] Care was taken, through control of the beam-momentum width and target thickness, to obtain a scattered-electron-momentum resolution close to that which can reasonably be achieved at the Mark III accelerator. This was done to determine the excitation energies and widths of the major components of the complexes as closely as possible. Typically, the elastic peak in C^{12}, which was used to calibrate the scale of excitation energy, was observed with a full width at half-maximum of 0.3%. The data, such as displayed in Figs. 1(a) and 1(b), were corrected for radiative effects[6] and normalized against elastic electron-proton cross sections measured in the same experiment. Backgrounds were subtracted, as indicated, (a) for the effects of radiative tails of unobserved levels at smaller excitation energy and (b) for the effects of quasielastic scattering. The latter has a threshold for neutrons at 18.7 MeV. The quasielastic background was not computed, but instead constrained to fit the observed electron spectrum at large excitation energies and to fall to zero at the threshold. (The proton threshold was taken to be effectively equal to the neutron threshold because of the Coulomb barrier.) For the 19-MeV complex, the quasielastic background is significant for the lowest momentum transfers only, but presents a serious problem at all momentum transfers for the giant resonance. Calculations of nucleon transitions from bound states into the continuum are presently being made to obtain quasielastic cross sections in this region. In Fig. 2(e) we simply give upper and lower limits for the cross section in the range of excitation energy 21-27 MeV. The upper limit is obtained by assuming no quasielastic background and the lower limit by subtracting the quasielastic background as estimated above.

The form factors obtained for the 15.1-MeV level, the 16- and 19-MeV complexes, and the giant resonance are shown in Fig. 2.[3,7-19] The cross section for the 15.1-MeV level was obtained by fitting an experimental resolution function to the data points centered at 15.1 MeV. No attempt was made in the present analysis to determine separate form factors for the constituent levels



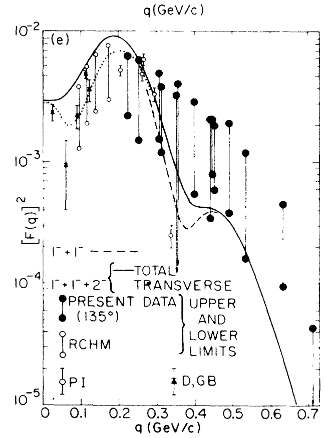


FIG. 2. $[F(q)]^2=(d\sigma/d\Omega)_{\mathrm{inel}}/4\pi\sigma_{\mathrm{Mott}}(\frac{1}{2}+\tan^2\frac{1}{2}\theta)$ is shown as a function of three-momentum transfer q where σ_{Mott} is the Mott cross section (Ref. 21). (a) 15.11-MeV level, $\theta=135°$. (b) 16-MeV complex, $\theta=135°$, $b=1.6$ F. The data of Ref. 7 are for the 2^+ level alone. (c), (d) 19-MeV complex; $b=1.6$ F; $\theta=135°$ and 40°, respectively. Giant resonance, $\theta=135°$, $b=1.6$ F. The data of Ref. 19 are treated in exactly the same way as the present data. The data at 180° should be compared with the transverse form factor only (dotted curve). Previous experimental data referred to are the following: PI, Ref. 7; BB, Ref. 8; DT, Ref. 9; BBFG, Ref. 10; G, Ref. 11; SS, Ref. 12, B, Ref. 13; DWVB, Ref. 14; BDHSC, Ref. 15; GB, Ref. 16; C, Ref. 17; RCHM, Ref. 18; GBLW, Ref. 19; and D, Ref. 3.

of the 16- and 19-MeV complexes. It is apparent, however, that the 16-MeV complex consists of two major components at 16.1 and 16.6 MeV, which we can identify with the well-known $T=1$, 2^+, 16.1-MeV and the $T=1$, 2^-, 16.6-MeV levels, respectively. Both of these components have widths consistent with the experimental resolution. The 19-MeV complex has a major component at 19.6 MeV and another at 20.4 MeV, neither of which we can identify with known levels in C^{12}. The width of the major component, 0.9 MeV, is clearly larger than the experimental resolution function. Measurements of the 16- and 19-MeV complexes were also made at 90° at selected values of q to establish the transverse nature of the excitations. No significant Coulomb contribution was observed for either complex at any value of q.

The first particle-hole configuration in carbon is $(1p_{3/2})^{-1}(1p_{1/2})_{1^+,2^+}$ whose unperturbed configuration energy, determined by looking at neighboring nuclei, is $E_0=13.8$ MeV. A calculation of the position of these levels using a Serber-force fit to free nucleon-nucleon scattering[2] shows that this doublet should lie between 15.5 and 16.5 MeV [using a value of the oscillator parameter $b=(\hbar/M\omega)^{1/2}$ between 1.6 and 1.9 F, see below] and that they are split by less than 0.5 MeV with the 2^+ lying lower. This is in essential agreement with the calculations of Vinh-Mau and Brown who found a 1^+ at 16.1 MeV and a 2^+ at 16.5 MeV, both corresponding to almost pure configurations. One would expect that more detailed intermediate-coupling calculations in this nucleus would give considerably more mixing of configurations. Hopefully, the dominant effect of such calculations would be simply to lower the overall transition strength to these two levels.[19,20] In Figs. 2(a) and 2(b), we have plotted the electron scattering form factors for this 1^+-2^+ doublet, calculated using the formulas of deForest and Walecka[21] including relativistic and center-of-mass corrections to the operators. The overall strength of both the 1^+ and 2^+ levels has been arbitrarily reduced by a factor of 4 in order to fit the experimental data. This indicates that the single-particle-hole picture of this excitation cannot be correct in detail. We have plotted the 1^+ form factors using two values of the oscillator parameter, $b=1.6$ F, the value obtained by fitting the ground-state elastic form factor in C^{12}, and $b=1.9$ F, a value obtained by an initial empirical fit to the $M1$ form factor at lower momentum transfers.[21] These curves are compared with all existing data on electron excitation of these two levels and with the new experimental results presented in this paper. A particularly interesting feature of the theoretical calculations is the prediction of a diffraction minimum in the form factor for the 1^+ level. Since the 1^+ lies below the particle-emission thresholds in carbon, and since it is an isolated level, the comparison of this prediction with the experiments is unambiguous.

The next particle-hole configuration is $(1p_{3/2})^{-1}$-$(1d_{5/2})_{1^-,2^-,3^-,4^-}$ with an unperturbed configuration energy of 17.6 MeV. The 1^- is pushed up by the particle-hole interaction and forms the main component of the giant electric dipole resonance which lies at 22.8 MeV. We will return to this level shortly. The 2^- is believed to form the main component of the giant magnetic quadrupole resonance in C^{12}. A simple calculation using the pure particle-hole configuration and the Serber force referred to previously places the 2^- in the range 18.7-19.3 MeV. The calculations of Brown and Vinh-Mau place this level at 19.2 MeV, and those of Lewis and deForest at 20.7 MeV. These latter two calculations include the mixing of all the 2^- single-particle-hole excitations in C^{12}. A calculation of the position of the 3^- level using the pure configuration gives a value 18.3 to 18.7 MeV. A 3^- $T=1$ level has recently been reported[22] to be located at 18.6 MeV. This level has previously been discussed by Friar[23] on the basis of a harmonic-oscillator shell model and also of a continuum model with configuration mixing. Friar found very little mixing with the $(1p_{3/2})^{-1}$-$(1d_{3/2})$ configuration, indicating that this level may be quite pure. Interestingly enough, the form factor for excitation of this level is almost completely longitudinal. A calculation of the position of the 4^- using the pure configuration (this is actually the only way the 4^- can be made with the single-particle-hole excitations considered here) places the 4^- within 100 keV of the 2^- for all values of the oscillator parameter considered. The form factors for electron excitation of the $2^-, 3^-, 4^-$ complex of states are indicated in Figs. 2(c) and 2(d). They are compared with existing data at large angles in Fig. 2(c) and at 40° in Fig. 2(d). In Fig. 2(c) we also compare with experimental upper limits on the longitudinal form factors.

The next configuration is $(1p_{3/2})^{-1}(2s_{1/2})_{1^-,2^-}$ with an unperturbed configuration energy of 16.9 MeV. Using a pure configuration the 1^- is predicted to lie between 18.2 and 18.8 MeV and the 2^- between 17.8 and 18.3 MeV. These levels should really be mixed with all other 2^- and 1^- levels, and Lewis and deForest find a 1^- at 19.6 MeV and 2^- at 18.9 MeV from these more complete calculations. In calculating the form factors for the 1^- and 2^- levels we have used configuration-mixed wave functions with the parameters of deForest.[3] The 2^- level we associate with the experimentally observed level at 16.6 MeV and its contribution to the 16-MeV complex is indicated in Fig. 2(b). If we include the 1^- in the 19-MeV complex, we find that it gives an unacceptably large contribution to the transverse form factors at small q, where the 2^- quadrupole state explains the data. Consequently, we identify this 1^- with the 18.1-MeV peak seen at small values of q.[17] The computed form factor for this level agrees with previous measurements and with estimates taken from the present experiment out to ~300 MeV/c. At larger momentum transfers we are unable to obtain accurate values for the form factor since this level is dominated by the tail of 19-MeV complex.

The remaining particle-hole configurations are $(1p_{3/2})^{-1}(1d_{3/2})_{0^-,1^-,2^-,3^-}$ and $(1s_{1/2})^{-1}(1p_{1/2})_{0^-,1^-}$ with configuration energies $E_0 = 22.1$ MeV and $E_0 = 30.1$ MeV, respectively. The 0^- levels are not excited by electrons. Friar[23] has shown that the 3^- lies at about 27 MeV. The form factor for this level is again almost entirely longitudinal and we have no evidence for it. The particle-hole calculations[3] with configuration mixing place two 1^- levels [essentially $(1p_{3/2})^{-1}(1d_{5/2})_{1^-}$ and $(1p_{3/2})^{-1}(1d_{3/2})_{1^-}$] as well as the remaining 2^- in the energy interval 23-25 MeV.[24] The form factor for these three levels is compared with the available experimental results for the giant resonance in Fig. 2(e). While it is difficult to draw any quantitative conclusions, the predictions of the particle-hole model are certainly qualitatively correct. Data at $q = 93$ MeV/c[18] yield a longitudinal form factor which is consistent with the calculated value (which has been divided by 2; see Ref. 2).

On the basis of the overall fit to these particle-hole complexes, one finds the best results using the value of the oscillator parameter obtained from elastic scattering. The large-q behavior is particularly sensitive to the exact value of the oscillator parameter and to the configuration admixtures used. For example, in the 16-MeV complex the large-momentum-transfer dependence comes from the 2^- level. Note that we have not succeeded in reproducing the exact experimental fall-off of this form factor for large q in this model. Also, for both of the 2^- levels, it is the $2s$ component in the wave function which gives the large q behavior. These results indicate that in principle, inelastic electron scattering may serve as a powerful tool for disentangling detailed configuration admixtures in the wave functions. In both the particle-hole model with configuration mixing and in the Goldhaber-Teller model of the giant magnetic quadrupole resonance, a diffraction minimum appears at about 350-MeV momentum transfer. The inclusion of the 4^- state, which theory indicates to lie within 100 keV of the 2^- in the 19-MeV complex, fills in this diffraction minimum at large angles. No experimental evidence for this diffraction minimum was found for the 19-MeV complex, although two states lying within 300 keV of each other would not have been resolved. The 3^- form factor, being mainly longitudinal, is significant only at small angles. The relative contribution of longitudinal and transverse components is in agreement with existing experimental evidence on this ratio.

In conclusion we see that the simple particle-hole model successfully accounts for the gross features of the inelastic electron scattering data in the range of excitation 12-32 MeV.

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[1]N. Vinh-Mau and G. E. Brown, Nucl. Phys. 29, 89 (1962).

[2]F. H. Lewis, Jr. and J. D. Walecka, Phys. Rev. 133, B849 (1964).

[3]T. deForest, Jr., Phys. Rev. 139, B1217 (1965).

[4]H. Feshbach, in Proceedings of the International Nuclear Physics Conference, Gatlinburg, Tennessee, 1966, edited by R. L. Becker and A. Zucker (Academic Press, Inc., New York, 1967), p. 181.

[5]L. R. Suelzle and M. R. Yearian, in Proceedings of the International Conference on Nucleon Structure at Stanford University, 1963, edited by R. Hofstadter and L. I. Schiff (Stanford University Press, Stanford, California, 1964), p. 360.

[6]H. Crannell, Phys. Rev. 148, 1107 (1966), and High Energy Physics Laboratory, Stanford University, Stanford, California Report No. 510 (unpublished).

[7]G. A. Proca and D. B. Isabelle, Nucl. Phys. A109, 177 (1968).

[8]G. R. Bishop and A. Bottino, Phys. Letters 10, 308 (1964).
[9]B. Dudelzak and R. E. Taylor, J. Phys. Radium 22, 544 (1961).
[10]W. C. Barber, F. Berthold, G. Fricke, and F. E. Gudden, Phys. Rev. 120, 2081 (1960).
[11]F. Gudden, Phys. Letters 10, 313 (1964).
[12]H. Schmid and W. Scholz, Z. Physik 175, 430 (1963).
[13]G. R. Bishop, Phys. Rev. Letters 19, 659 (1967).
[14]T. deForest, Jr., J. D. Walecka, G. Vanpraet, and W. C. Barber, Phys. Letters 16, 311 (1965), and T. deForest, private communication (see Ref. 3).
[15]G. A. Beer, T. E. Drake, R. M. Hutcheon, V. W. Stobie, and H. S. Caplan, Nuovo Cimento 53B, 319 (1968).
[16]J. Goldemberg and W. C. Barber, Phys. Rev. 134, B963 (1964).
[17]H. Crannell, H. A. Dahl, and F. H. Lewis, Jr., Phys. Rev. 155, 1062 (1967).
[18]G. Ricco, H. S. Caplan, R. M. Hutcheon, and R. Malvano (to be published).
[19]J. Goldemberg, W. C. Barber, F. H. Lewis, Jr., and J. D. Walecka, Phys. Rev. 134, B1022 (1964).
[20]D. Kurath, Phys. Rev. 134, B1025 (1964).
[21]T. deForest and J. D. Walecka, Advan. Phys. 15, 1 (1966).
[22]W. Feldman, M. Suffert, and S. S. Hanna, Bull. Am. Phys. Soc. 13, 822 (1968).
[23]J. Friar, thesis, Stanford University, 1967 (unpublished).
[24]The $(1s_{1/2})^{-1}(1p_{1/2})_{1^-}$ is predicted to be above 30 MeV (Ref. 2).

ANOMALY IN THE PHOTODISINTEGRATION OF Ni^{58} AND Ni^{60} IN THE GIANT-DIPOLE RESONANCE REGION*

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The photoneutron cross sections for Ni^{58}, Ni^{60}, and natural nickel from threshold up to 25 MeV have been measured. The integrated (γ, n) cross section for Ni^{60} is 2.6 times as large as the value for Ni^{58}, and the two cross-section curves exhibit markedly different structure over the giant-dipole resonance region. The results suggest that it is important to include the shell effects explicitly in the theoretical treatment of the giant-dipole states in the medium nuclei such as nickel isotopes.

Several investigators[1,2] have suggested that there is a marked dissimilarity in the photoneutron cross sections of Ni^{58} (67.9% abundance) and Ni^{60} (26.2% abundance) in the giant-dipole resonance region. Their main observations, which were based on the existing photonuclear data on Ni^{58} [3,4] and natural nickel,[1,2] were two: (1) The cross section reaches maximum at 16 MeV in Ni^{60}, but at 19 MeV in Ni^{58}. (2) The integrated (γ, n) cross section for Ni^{60} is about three times as large as the value for Ni^{58}. So far there has been no direct measurement of the photoneutron cross section in separated Ni^{60} to verify the above inferences. We have recently completed the measurement of photoneutron cross sections on separated Ni^{60} (99.79% enriched), Ni^{58} (99.89% enriched), and natural nickel samples. The cylindrical samples of Ni^{60} and Ni^{58} isotopes, loaned to us from Oak Ridge National Laboratory, were 3 cm in diameter and 2.3 cm thick. The natural nickel sample was 4.3 cm in diameter and 5.2 cm thick. The collimated bremsstrahlung beam from the University of Virginia 70-MeV electron synchrotron irradiated the sample which was placed at the center of a 4π neutron detector made of paraffin and eight BF_3 counters. The photoneutron yields from each sample were measured from 10.5- to 25-MeV bremsstrahlung energy in steps of 0.5 MeV. In all neutron yield measurements, the statistical counting error was better than 0.3%. The least structure method[5] for unfolding the photonuclear yields was used to obtain the photoneutron cross sections in 0.5-MeV bins. The cross-section results for Ni^{60} and Ni^{58} are shown in Fig. 1. In each case, the corrected values for $(\gamma, 2n)$ process are shown by circles. These corrections were made using the statistical-model formula given by Blatt and Weisskopf.[6] In this correction the fraction of direct neutrons was taken to be 10%,[7] and the value of the level density parameter $a = 5.49\ \mathrm{MeV}^{-1}$ was obtained from the semiempirical formula of Thomson.[8] The cross-section results for natural nickel are shown in Fig. 2. The solid line in Fig. 2 represents the Ni^{60} and Ni^{58} contributions in the natural nickel cross section. Table I lists the integrated (γ, n) cross sections up to 25 MeV for Ni^{60}, Ni^{58}, and natural nickel.