Electroexcitation of ^{4}He in the near continuum

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Inelastic electron scattering cross sections for ^{4}He have been measured at 180° for incident electron energies of 130 and 200 MeV. Spectra measured up to excitation energies of 54 MeV are relatively featureless and show no evidence for resolvable excitations. The data are compared with continuum shell-model calculations which include all one-body breakup channels.

A thorough knowledge of the spectroscopy of ^{4}He is crucial for our understanding of this fundamental, doubly magic system. About ten excited states have been identified,[1] all of which are in the continuum above particle-emission threshold; these states are broad and many overlap. Such an interpretation emerges from a detailed R-matrix analysis which uses as input results from a variety of reactions. Most of these are hadronic reactions in which ^{4}He is formed as a compound system, with or without another reaction product. Unfortunately, such reactions are often difficult to interpret. For electron scattering, however, the electromagnetic reaction mechanism is well understood, and the structure of the final states can be directly studied. Thus (e,e') measurements of the near continuum of ^{4}He should provide important information for unraveling the structure of the mass-4 system. Such experiments have already been carried out by Frosch *et al.*,[2] Walcher,[3] and Kobschall *et al.*[4] However, these measurements were made primarily at forward angles, and therefore emphasize longitudinal excitation of natural parity levels through the Coulomb multipoles $C0$, $C1$, $C2$, etc. Only the Coulomb monopole transition to the relatively narrow quasibound $J^\pi=0^+$, $T=0$ level at 20.1 MeV, which lies between the $^4\mathrm{He}(e,e'p)^3\mathrm{H}$ disintegration threshold at 19.815 MeV and the $^4\mathrm{He}(e,e'n)^3\mathrm{He}$ threshold at 20.578 MeV, was clearly identified in these experiments. Excitation of the unnatural parity states proceeds only through the exchange of transverse virtual photons, however, and the experiments of Refs. 2–4 would not be particularly sensitive to them.

This paper describes a search for transverse excitations by using 180° electron scattering for which longitudinal cross sections are severely suppressed and the elastic radiation tail is minimized, especially for a spin-zero nucleus such as ^{4}He. Thus the sensitivity to transverse electric and magnetic excitations is greater than in the complementary forward angle measurements.[2–4] In particular, low-multipolarity $\Delta T=1$ transitions are emphasized at low to moderate momentum transfers for scattering at 180°. Since $1\hbar\omega$ transitions to $T=1$ odd-parity states are expected to dominate the (e,e') spectrum, the transitions most likely to be observed are those to the very broad 1^- and 2^- $T=1$ levels considered[5] to lie in the excitation region near 27 MeV.

The data were taken at the MIT-Bates Linear Accelerator Center using incident electron energies $E_0=130$ and 200 MeV. Inelastic cross sections were measured up to an excitation energy ω of 54 MeV; the corresponding three-momentum transfers q (which depend on excitation energy) were from 1.04 to 1.27 fm^{-1} for $E_0=130$ MeV and from 1.66 to 1.93 fm^{-1} for $E_0=200$ MeV. A cylindrical gas target cell[6] 10.5 cm long made of stainless steel and cooled by liquid nitrogen was used. Its entrance and exit windows were made of 25 μm Havar[7] foils designed to accept a dispersed beam spot as large as 30 mm in the vertical direction. The dispersion of the beam reduced localized heating, thereby allowing the use of average beam currents as large as 40 μA. By continuously monitoring the temperature and pressure inside the cell, the gas thickness were determined to be 39 mg cm^{-2} at 130 MeV and 45 mg cm^{-2} at 200 MeV, with 3% uncertainties. Scattered electrons were measured using a high-resolution dispersion-matching magnetic spectrometer[8] in conjunction with a magnetic deflection system[9] which permits the observation of scattering at 180° into constant solid angle, independent of excitation energy. The energy resolution was approximately 200 keV at $E_0=130$ MeV and 300 keV at $E_0=200$ MeV. Thus structures as narrow as a few hundred keV could be identified.

Figure 1(a) shows the spectrum of scattered electrons obtained with $E_0=130$ MeV. The background contribution from the window foils, measured at each spectrometer setting, was smoothed to reduce statistical fluctuations and then subtracted from the data. The radiation tail was calculated using the formalism of Mo and Tsai,[10] and an iterative unfolding procedure[11] was used. Figure 1(b) shows the 130 MeV data after foil background subtraction both before and after radiative unfolding. The cross sections were normalized to known proton elastic cross sections[12] by comparing the ^{4}He data with data taken using an identical target cell filled with hydrogen gas. The inset in Fig. 1(b) shows a typical elastic peak for scattering from the proton; this also serves to display the experimental resolution which was obtained. Finally, Fig. 1(c) shows the 200 MeV data after both foil background subtractions and radiative corrections were made.

The most distinctive feature of the measured cross sections is the sharp rise at threshold. Since this occurs over an energy range several times larger than the experimental resolution, it is not resolution limited. Above 25 MeV excitation, the 130 MeV cross section decreases uniformly, whereas the 200 MeV cross section increases gradually. Otherwise, as may be seen, both spectra are featureless. In particular, little evidence is obtained for the existence of any new resonant transverse excitation. Notably, these results are qualitatively similar to what is seen[13] and calculated[14] for electron scattering to the continuum of ^{3}He.

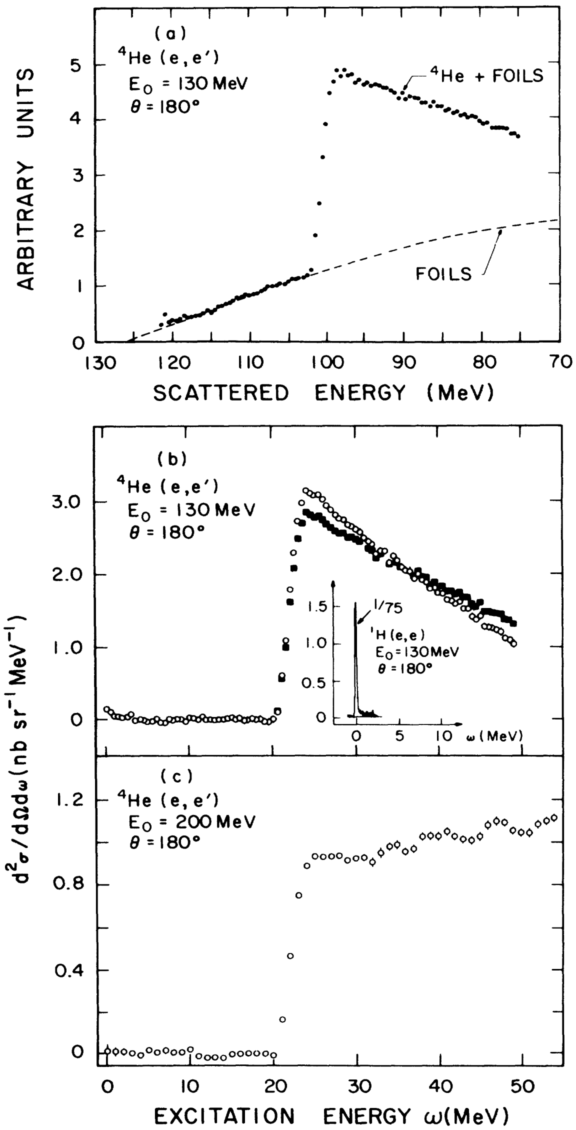

FIG. 1. (a) The spectrum of electrons of initial energy 130 MeV after scattering through 180° from ^{4}He. The dotted line represents the fitted background contribution from the window foils of the target cell. (b) The experimental cross section after the foil background has been subtracted (solid squares) and after radiative corrections have been applied (open circles). The inset shows the cross section obtained for elastic scattering from hydrogen gas in an identical target cell. (c) The experimental cross section, after foil subtraction and radiative corrections, for an incident electron energy of 200 MeV.

The theoretical interpretation of these experimental measurements presents a special challenge to our understanding of nuclear structure. On the one hand, ^{4}He is too light to apply the standard techniques used for heavier nuclei since these are usually based on some sort of "mean field" approximation, and one cannot expect only four nucleons to establish a reasonable mean field. On the other hand, the problem remains too complex for an accurate treatment with Faddeev-like approaches because the number of particles and the number of contributing channels is simply too large (although as theoretical and computational techniques improve, this situation can be expected to change). Thus, the structure of the mass-4 system remains an open and interesting challenge.

In addition to the usual questions of nuclear structure, there is the long-standing puzzle regarding the role of isospin mixing in the ^{4}He system. Measurements[15,16] of the photonucleon cross section ratio $\sigma(\gamma,p)/\sigma(\gamma,n)$ at excitation energies below 30 MeV yield a ratio which varies between 1.5 and 1.9, where a value of 1.0 would be expected if charge symmetry in the nucleon-nucleon force were exact. Such unexpectedly large isospin mixing in the $A=4$ system has been confirmed by studies[17,18] of the inverse reactions ^{3}He(p,γ) and ^{3}He(n,γ). However, recent measurements of the π^+/π^- cross section ratio by Blilie *et al.*[19] contradict these results. In particular, they found this ratio to be 1.05 ± 0.08, which implies that isospin mixing between the $T=0$ and $T=1$ states in ^{4}He is quite weak. Our measurements will not resolve this problem, but they should provide information for sensitive tests of models for the structure of ^{4}He.

One model which has been fairly successful in describing the structure of ^{4}He above breakup threshold is the recoil-corrected continuum shell model (RCCSM) of Philpott[20] which is based on the R-matrix approach of Lane[21,22] as developed by Halderson and Philpott.[23,24] This model has been used to describe both inelastic pion scattering, where agreement[19] between theory and experiment was rather good, and the photonuclear reactions (γ,p) and (γ,n), where the *shapes* of the measured cross sections were predicted reasonably well. In the latter case the magnitudes were not in agreement with experiment. An attempt was made to reduce the calculated (γ,n) cross section by including a charge symmetry breaking force;[25] however, the force required to produce agreement with experiment was three times stronger than that required to reproduce Coulomb energy shifts in mirror nuclei.

Electron scattering cross sections have been calculated within this model, including partial wave cross sections for the emission of a single nucleon into total angular momentum channels of spin-parity 2^-, 1^-, and 2^+. The RCCSM wave functions of Ref. 23 were employed. These wave functions are solutions of a translationally invariant Hamiltonian with the $M3Y$ G-matrix interaction[26] in a 1p-1h basis. Two approximations employed in calculating the (π,π') cross sections[19] were also made in calculating the (e,e') cross sections. First, the ^{4}He ground state was assumed to have a pure $(0s_{1/2})^4$ configuration, neglecting 1p-1h, 2p-2h, and other correlations in the ground state. Second, the excitation was calculated as a single-particle transition in only coordinate r_4 as shown in Fig. 2. This approximation was made because the wave function for the coordinate ϵ_3 is readily available in the RCCSM. This procedure is an approximation because, although particles 1, 2, and 3 remain in a relative $(0s_{1/2})^3$ state, they do move with respect to the center of mass when particle 4 is excited. Therefore, one is ignoring a correction due to the recoil of the core. This effect has always been ignored in RCCSM calculations at low momentum transfer and for heavy systems.

These RCCSM predictions are compared with the present measurements in Fig. 3. Also shown in this figure is a comparison with the earlier 180° measurements of Jones *et al.*[27] for $E_0=60.6$ MeV. As published, these data were not radiatively unfolded; we have therefore applied the radiative corrections as described above. The errors shown for these data include both the original statistical errors and estimates of the errors associated with our reanalysis including background subtractions.

Although the *shapes* of the calculated cross sections are in qualitative agreement with experiment, the theory significantly underestimates the cross section, particularly for the higher incident energies. However, as described above, the calculations do not properly treat the target recoil. For a light nucleus this neglect can be quite serious even at moderate momentum transfer. In order to *estimate* the magnitude of this problem we may apply the usual shell-model "center of mass correction" to the electron scattering cross sections:

$$f^2_{\mathrm{c.m.}}=e^{q^2b^2/2A} ,$$

where b is the length parameter of a harmonic oscillator potential "equivalent" to the shell-model potential. Using the somewhat arbitrary value of $b=1.5$ fm, we find that $f^2_{\mathrm{c.m.}}\approx 1.4$ for $E_0=130$ MeV, and 2.4 for $E_0=200$ MeV. Since these factors are only crude estimates for the proper treatment of the center of mass, we have ignored the slight ω dependence when applying them to the theoretical calculations presented in Fig. 3.

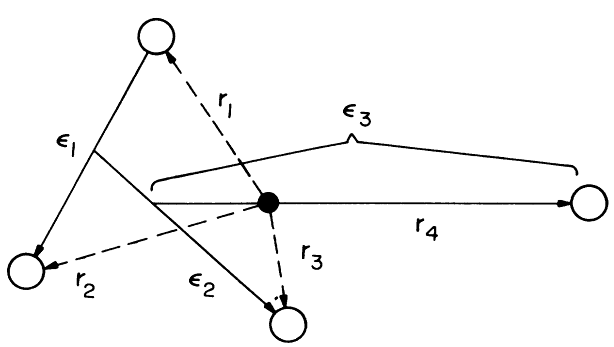

FIG. 2. The internal coordinate system of the recoil-corrected continuum shell model. r_j (dashed line) specifies the location of the jth nucleon relative to the center of mass (the solid circle) of the nucleus, while ϵ_j (solid line) specifies the location of nucleon $j+1$ relative to the center of mass of the first j nucleons.

When such factors are applied, one finds reasonable agreement in magnitude over the range of excitation energies measured. At 60.6 MeV, the center of mass correction is only a few percent and the theory is about 15% below the measured cross sections at the peak ($\omega=24$ MeV). The calculations fall off a bit too slowly with excitation energy for $E_0=130$ MeV, but given the crudeness of the center of mass corrections, such agreement is encouraging. For an incident electron energy of 200 MeV, however, the calculated cross sections do not

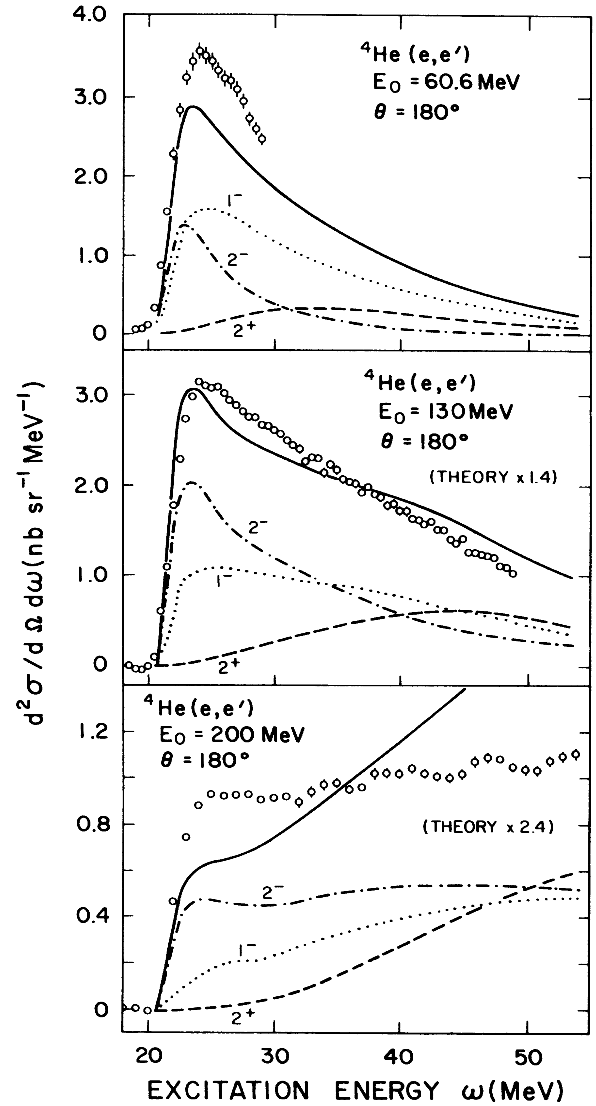

FIG. 3. The measured cross sections (including the data of Ref. 27 for an incident energy of 60.6 MeV) are compared with the theoretical continuum shell-model calculations as described in the text. The solid line represents the full calculation; the dashed, dotted, and dash-dotted lines show the contributions of 2^+, 1^-, and 2^- channels in the final state. The theoretical curves for $E_0=130$ and 200 MeV have been multiplied by factors of 1.4 and 2.4 as a rough estimate of the center of mass correction (see the text). The data presented span the momentum transfer ranges of $0.46\ \mathrm{fm}^{-1}\leq q\leq 0.52\ \mathrm{fm}^{-1}$ for $E_0=60.6$ MeV, $1.04\ \mathrm{fm}^{-1}\leq q\leq 1.19\ \mathrm{fm}^{-1}$ for $E_0=130$ MeV, and $1.66\ \mathrm{fm}^{-1}\leq q\leq 1.85\ \mathrm{fm}^{-1}$ for $E_0=200$ MeV.

have the same energy dependence seen in the experiment. In this case the measured cross sections quickly rise from threshold to a value of about 0.95 nb/sr MeV and then remain roughly constant, whereas the calculated cross sections, including the center of mass factor given above, go to 0.65 nb/sr MeV at $\omega=24$ MeV and then increase roughly linearly with excitation energy to a value of about 1.5 nb/sr MeV at $\omega=50$ MeV.

Although the 1^- channels dominate the photonuclear reactions, for electron scattering other partial waves become more important as the momentum transfer increases. At $E_0=60.6$ MeV, it is the 1^- channel that gives the largest contribution, although excitation of the 2^- channels is important in the first few MeV above threshold. For $E_0=130$ MeV, the 2^- peaks near 23 MeV and makes the largest contribution to the cross section for $\omega<36$ MeV, while the 1^- contribution remains rather flat above $\omega=25$ MeV. In each case, the 2^+ becomes significant only for $\omega\geq 35$ MeV. For $E_0=200$ MeV, the 2^- contribution again dominates near threshold but remains rather flat for increasing ω, behaving in much the same way as the experimental results. It is the 2^+ and, to a lesser extent, the 1^- channels which rise with excitation energy, thereby giving a total theoretical cross section which overshoots the data. The basic agreement between experiment and calculation for incident energies of 60.6 and 130 MeV and the disagreement at $E_0=200$ MeV suggests that the calculations do not have the proper momentum transfer behavior. Indeed, the various channels are predicted to have diffraction minima in the region of $q=2.2-3.3$ fm^{-1}, so the $E_0=200$ MeV calculations, spanning the momentum transfer range of $1.66-1.85$ fm^{-1}, should be particularly sensitive to q. Of course, the higher-q calculations will also be more susceptible to errors in the treatment of the center of mass. Finally, we note that to fit the inelastic pion scattering data, for which the momentum transfer was approximately 0.7 fm^{-1}, the authors of Ref. 19 found it necessary to multiply the 2^- contributions by a factor of 1.35. Such a factor does tend to improve agreement between the measured and calculated electron scattering cross sections as well, but it alone cannot resolve the problems for $E_0=200$ MeV.

The electron scattering data presented here span a considerable range of both excitation energy and momentum transfer and, in so doing, they present a difficult challenge to any structure model which attempts to describe them. The RCCSM calculations discussed above have only mixed success in describing this data. However, there are some ingredients missing from this model which may have important effects, particularly at the higher q's and/or ω's. The model considers only single-nucleon breakup channels, whereas one might expect the ^{2}H-^{2}H, and three- and four-body channels to become significant by $\omega=50$ MeV. In particular, the deuteron channel is likely to compete with the single-nucleon breakup channels at the larger excitation energies, especially in the 2^+ partial wave. In addition, a pure $L=0$ ground state for ^{4}He is inherent in the 1p-1h basis, whereas in reality configuration mixing may play an important role. Indeed, recent work[28] suggests that the D-state component in the ground state wave function may be substantial. Of more immediate concern is the effect of the approximations described above for calculating (e,e') cross sections with the RCCSM. To date, only the (γ,n) and present 180° (e,e') experiments have shown serious disagreement with the RCCSM in the 1p-1h basis. It is important to remove these approximations from the (e,e') calculations in order to determine whether it is the model or the approximations which produce the discrepancy. Only then can one continue the search for the charge symmetry breaking mechanism in (γ,N).

To summarize, this paper reports measurements of transverse inelastic electron scattering at 180° from ^{4}He for excitation energies up to 54 MeV. The absence of relatively sharp discrete levels in the experimental spectra is consistent with the predictions of continuum shell-model calculations. Furthermore, these calculations provide reasonable quantitative predictions at low momentum transfers, but fail at higher momentum transfer. Thus, the electron scattering data presented in this paper present a challenge to theoretical attempts to understand the structure of the four-nucleon system.

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