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LETTER TO THE EDITOR

The $^{12}C(\gamma, p)$ reaction at E_γ = 60, 80 and 100 MeV

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Abstract. The angular distribution of the $^{12}C(\gamma, p)$ reaction has been measured at E_γ = 60, 80 and 100 MeV for excitation energies 0–7 MeV in the residual nucleus. The measured cross sections are considerably larger than IPM predictions and are compared with a calculation which uses a Jastrow correlation factor to simulate the effect of two-nucleon interactions.

We report here an experimental investigation of the nuclear photo-effect, a process dependent on the presence of high-momentum components in the nuclear wavefunction. The deficiency of high-momentum components in conventional shell-model wavefunctions is already evident in several reactions involving pions, eg $(\pi, 2N)$ and (p, π). The present (γ, p) measurements examine a wide range of initial momenta (300–500 MeV/c) in a single, relatively simple reaction. The results confirm the inadequacy of the picture of direct single-stage photo-ejection from shell-model states as suggested by earlier investigations (Gardiner *et al* 1973, Matthews *et al* 1968, Manuzio *et al* 1969, Sanzone *et al* 1970), and are of sufficient extent and precision to provide a stringent test of the theory of the (γ, p) process.

In this experiment the angular distribution of the $^{12}C(\gamma, p)$ reaction was measured at photon energies of 60, 80 and 100 MeV. A single-difference bremsstrahlung unfolding technique (Matthews and Owens 1971) was employed which yields both high intensity and good energy resolution. Use of a magnetic spectrometer allowed unambiguous detection of high-energy protons with virtually no background. The experimental method and apparatus have been described briefly by Gardiner *et al* (1973) and will be fully documented in a future publication. For each photon energy the proton spectrum was measured over a range covering excitation energies 0–7 MeV in the residual nucleus, ^{11}B, at angles between 30° and 150° (over the range 0–20 MeV at 45°). The proton spectra typically display a peak corresponding to the population of the ground and low-lying states of ^{11}B as shown in figure 1. For each spectrum the sum of the cross sections to the ground state and 2·1 MeV state of ^{11}B is tentatively interpreted as the p-shell cross section‡ (ie populating the $(1p)^{-1}$ state in ^{11}B).

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‡ The excitation of higher-lying ^{11}B states becomes increasingly important at backward angles (see figure 2). The possibility that this cross section arises from another process (eg inelastic scattering of the predominantly forward-peaked outgoing protons) must be investigated before these states are included in the p-shell cross section.

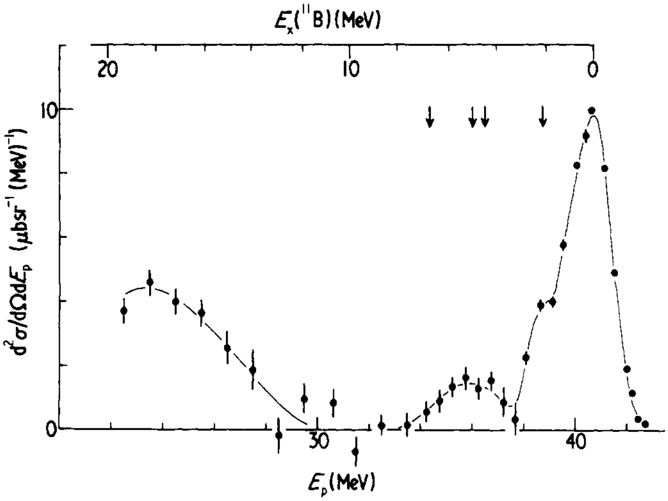

Figure 1. The proton spectrum from the $^{12}C(\gamma, p)$ reaction for $E_\gamma = 60 \pm 1$ MeV, θ_p(lab) = 45°. The excitation energy in the residual nucleus, ^{11}B, is shown, and arrows indicate the low-lying states.

A few measurements (Manuzio *et al* 1969, Penner and Leiss 1959) of the $^{12}C(\gamma, p)$ cross section leading to the ground and low-lying states of ^{11}B have been made previously in this photon energy range at angles near 45° and 90°. The agreement with the present data is reasonable when due account is taken of systematic errors and differences in the residual excitation energy range included in these experiments.

The angular distributions determined in the present measurements for $^{12}C(\gamma, p)$ reactions leading to the $(1p)^{-1}$ hole state are presented in figure 2 together with the theoretical predictions of Weise (1972 private communication, see also Weise and Huber 1971). In all cases the single-stage ejection calculation in which the distortion of the outgoing proton wave is taken into account (curve 2) falls well below the experimental points. It would seem that the effect of strong two-nucleon forces must be included to enhance the high-momentum components if agreement with experiment is to be obtained. However, the form in which the N–N interactions affect the (γ, p) reaction at these photon energies is still unclear. The contributions due to initial-state correlations, final-state interactions, and meson exchange currents must all be considered.

Fink *et al* (1972), using a Jastrow correlation factor obtained from a many-body calculation with a hard-core potential, find the effect of short-range correlations in the initial state to be negligible for photon energies below 100 MeV. Although this contribution to the cross section might increase if a different N–N force were used, it seems unlikely to be the major one in this energy range. In fact, to bring the calculated cross section up to the same order of magnitude as the experimental results by using a phenomenological Jastrow factor, Weise (1972, private communication) is obliged to pick a correlation factor with a healing radius of 2 fm, which he recognizes is unrealistically large.

Another approach to the role of N–N interactions in (γ, p) reactions has been taken by Gari and Hebach (1974), who calculate explicitly the effects of initial- and final-state interactions and then attempt to obtain the combined effect of all other diagrams by using the gauge invariance condition. The latter contributions, which the authors attribute to meson exchange terms, are found to be large compared to those of the

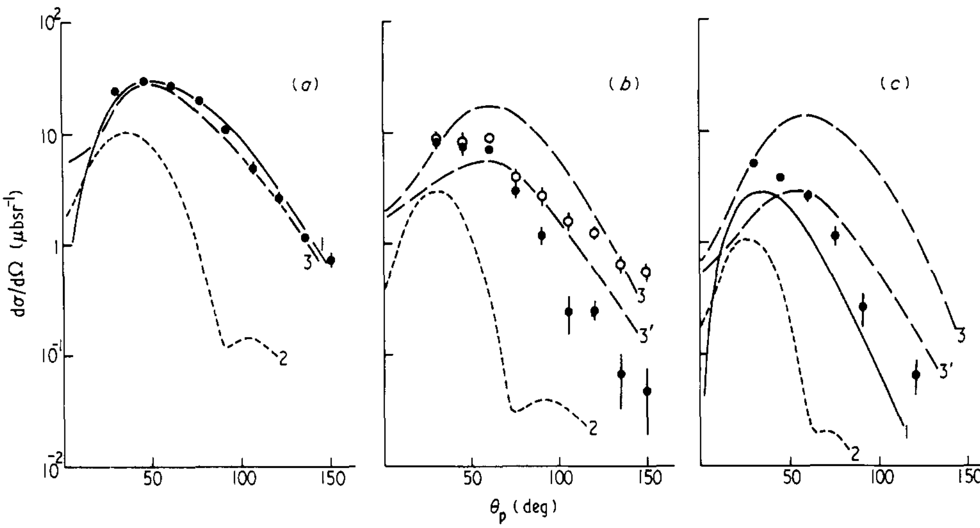

Figure 2. Angular distributions, $(d\sigma/d\Omega)_{cm}$ against $(\theta_p)_{cm}$, at: (*a*) E_γ = 60 MeV, (*b*) 80 MeV and (*c*) 100 MeV for the $^{12}C(\gamma, p)$ reaction leading to ^{11}B states below 7 MeV excitation. Full circles: ground state and 2·1 MeV state only; open circles: all states below 7 MeV. The errors shown are purely statistical; an additional systematic uncertainty of $\pm 10\%$ is estimated. The theoretical results of Weise (1972, private communication) are as follows. Curve 1: plane-wave approximation for outgoing protons. Curve 2: a continuum wavefunction in a complex energy-dependent Woods–Saxon potential for the outgoing protons Curve 3(3′): initial- and final-state correlations simulated by a Jastrow correlation factor corresponding to a Gaussian momentum-exchange distribution of width q_c = 100 MeV/c centred at q_c = 300 (350) MeV/c (otherwise like curve 2). The initial-state wavefunctions are calculated in a Woods–Saxon well chosen to reproduce the experimental separation energies, except in the plane wave calculation for which harmonic oscillator wavefunctions were used.

initial- and final-state interactions. For the $^4He(\gamma, p)$ reaction the cross section is considerably increased compared to the shell-model prediction but still falls below the experimental data. No calculations have been performed for heavier nuclei but it is suggested that the results will be similar.

The theoretical results obtained by ignoring the distortion of the outgoing proton wave in the optical potential (plane-wave curve 1 in figure 2) are seen to be closer to the experimental points than any of the other theoretical curves. The extent to which N–N interactions are required to boost the high-momentum components in the shell-model wavefunction is thus entirely dependent on the extent of the reduction in the calculated cross section produced by this distortion. While there is no reason to suppose that the outgoing proton does not feel an average attractive interaction due to the other nucleons, it is possible that the optical potential chosen by Weise is not ideal. The uncertainty in the calculated cross section arising from the inexact knowledge of the well parameters for the continuum state (and also the bound state) should clearly be examined.

In summary, we note that the present $^{12}C(\gamma, p)$ angular distribution measurements confirm the deficiency of high-momentum components in shell-model wavefunctions over a wide range of initial momenta. Attempts to remedy this deficiency by including the effects of the short-range two-nucleon interaction in various forms have been only partially successful.

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