Measurement of ^{6}Li(γ,π^+)^{6}He$_{g.s.}$ at 200 MeV

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Differential cross sections for ^{6}Li(γ,π^+)^{6}He$_{g.s.}$ have been measured for an incident photon energy of 200 MeV at laboratory angles of 23.5°, 64°, 90°, and 135°. Good agreement is obtained with several calculations based on the distorted-wave impulse approximation.

INTRODUCTION

There is now a sizable number of measurements of pion photoproduction on $1p$-shell nuclei from near threshold through the delta resonance region.[1] To fit these data in the delta region, it is necessary to account for medium modifications on delta production and propagation.[2,3] At lower energies, however, calculations in the distorted-wave impulse approximation (DWIA) framework appear to work reasonably well.[4-6] Nevertheless there are a few cases at these lower energies ($E \leq 200$ MeV) which would be expected to be particularly simple and well understood, and particularly well fit by DWIA calculations, but for which in fact there are significant discrepancies between experiment and theory. These cases are dominated by the spin-dependent nonresonant part of the photopion amplitude.

One such case is ^{10}B(γ,π^+)^{10}Be$_{g.s.}$. This is a pure $M3$ transition where the nuclear structure is well understood and only one matrix element can contribute (corresponding to the orbital, spin, and total angular momentum transfers L, S, and J given by $LSJ=213$). The Kroll-Rudermann spin-flip term in the production operator is expected to dominate the cross section. Yet at 183 MeV, at back angles where the cross section peaks, calculation[6,7] exceeds experiment[8] by nearly a factor of 2, while at 200 MeV, calculation[6,7] is greater than experiment[9] by some 50%. Recently, Bennhold, Tiator, and Wright[10] significantly reduced the discrepancy at 200 MeV by performing a DWIA calculation using a relativistic production operator and Woods-Saxon rather than harmonic oscillator wave functions.

Another case is ^{12}C(γ,π^+)^{12}B$_{g.s.}$, a pure $M1$ transition. At 186 MeV there exists a set of good-quality data from Mainz.[11] This is moderately well fit at forward angles (to about 40%) by DWIA calculations[6] using phenomenological harmonic oscillator-based wave functions, but there are larger discrepancies at back angles. In the local approximation, two transition amplitudes contribute, corresponding to $LSJ=011$ and 211. The first of these is mainly given by the Kroll-Rudermann spin-flip term and should dominate at forward angles. At back angles interference effects between the two amplitudes and small nonlocal amplitudes should become important. Failure to correctly account for these interference effects could account for some of these observed discrepancies.

^{6}Li(γ,π^+)^{6}He$_{g.s.}$ appears to be a favorable transition to check the origin of these discrepancies. Like the ^{12}C transition, this is a pure $M1$ transition and the nuclear structure is well known. Here, however, the ^{6}Li ground state is near the LS coupling limit. The β decay transition connecting ^{6}He and ^{6}Li ground states has the lowest ft value of any Gamow-Teller transition. The 011 spin-flip $L=0$ amplitude should be dominant in (γ,π^+) at all angles, and the 211 amplitude should play a less important role here than in ^{12}C. Hence interference effects in (γ,π^+) should be small. Moreover the strong spin-flip character means that delta effects should not be important at 200 MeV. Final state interaction effects should also be small. Hence this should be an excellent case to study photopion production in a situation where the $L=0$ Kroll-Rudermann spin-flip term is dominant.

Earlier experiments on ^{6}Li include (γ,π^+) total cross section measurements within 7 MeV of threshold by Audit *et al.*[12] which were reproduced at the 10% level by calculations using phenomenological wave functions.[13] Angular distribution measurements were made by Shoda, Sasaki, and Kohmura[14] at energies of 170, 180, and 195 MeV, but with limited statistical accuracy, especially at back angles.

EXPERIMENT

The experiment was performed at the MIT-Bates Linear Accelerator Center. A 200 MeV electron beam from the Bates Linac, with momentum spread of $\pm 0.15\%$, passed through a 150 mg/cm^2 rolled lithium metal target enriched to 96% in ^{6}Li. Positive pions emitted from the target at each of four angles (laboratory angles of 23.5°, 64°, 90°, and 135°) were momentum analyzed and detected using the medium-energy pion spectrometer MEPS. In order to increase rates at 90° and 135°, a 0.014

radiation length tantalum foil radiator was placed about 10 cm upstream of the target.

The experimental arrangement and data analysis procedure have been described previously.[15] Briefly, two crossed vertical drift chambers determined the particle position and angle at the focal plane, while four scintillators were placed behind the focal plane and operated in coincidence to provide the event trigger. An aerogel Cerenkov detector was placed between the third and fourth scintillator in order to greatly reduce the positron background. The particle momentum calculation was corrected for kinematic broadening. Additionally, corrections were made for pion decay (50% of pions lost), loss of pions through scattering and absorption (3% loss), and other system inefficiencies. These corrections are well defined and do not contribute significantly to systematic errors. The solid angle was verified by measuring electron scattering on hydrogen and carbon and by measuring positive pion photoproduction on hydrogen and comparing the results to the world data. The experimental differential cross sections were obtained by fitting the momentum spectra by effective photon spectra which at forward angles included both virtual photons (92%) and real photons from bremsstrahlung in the target (8%). At 90° and 135° the real photons also included bremsstrahlung from the radiator (61% of total flux).

A typical pion spectrum corrected for positron and muon background is shown in Fig. 1 together with the fitted curve. Since the first excited state in ^{6}He is at 1.8 MeV, those pions within 1.8 MeV of the spectrum end point result only from transitions to the ground state of ^{6}He and their spectrum shape reflects that of the effective photon spectrum.

RESULTS AND DISCUSSION

The experimental differential cross section values are plotted against momentum transfer q in Fig. 2. The error bars shown on the data points are statistical only. Systematic uncertainties for each point are dominated by normalization errors, estimated to be 10%. Other systematic errors are estimated at 7%, giving an overall systematic error of 12% when these are combined in quadrature. Also shown in Fig. 2 are earlier data of Shoda *et al.*[14] at an electron energy of 195 MeV. Their two forward-angle points appear to be consistent with the present results but their 90° point is higher than our data point by an amount greater than the combined errors.

The curves in Fig. 2 are the results of two recent DWIA calculations, one by Doyle,[16] the other by Tiator and co-workers.[7] Doyle's calculation uses the unitarized photoproduction operator of Wittman and Mukhopadhyay,[17] and the optical potential of Stricker, McManus, and Carr[18] (SMC) to describe pion final state interactions. His p-shell harmonic oscillator wave functions labeled $L1$ use different oscillator parameters for the $p_{1/2}$ and $p_{3/2}$ radial wave functions. They are constructed to fit the ground state magnetic dipole and electric quadrupole moments, the beta decay ft value, and the elastic electron scattering form factor data and $M1$ inelastic form factor data to the 3.56 MeV 0^+ analog of the ^{6}He ground state, up to momentum transfer cutoffs of

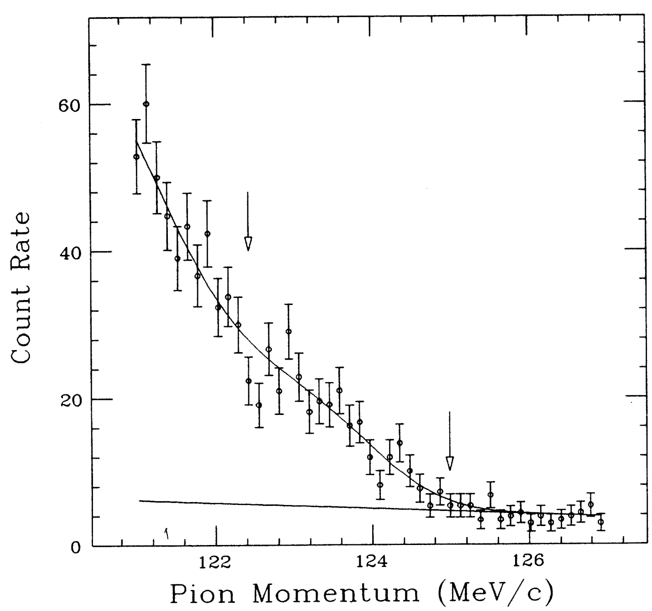

FIG. 1. Typical pion spectrum for ^{6}Li. Pion events with momenta between the two arrows involve only transitions to the ^{6}He ground state, and the pion spectrum shape in this region reflects the photon spectrum shape. The solid curve is a fit to the data using the known photon spectrum shape. Error bars are statistical only.

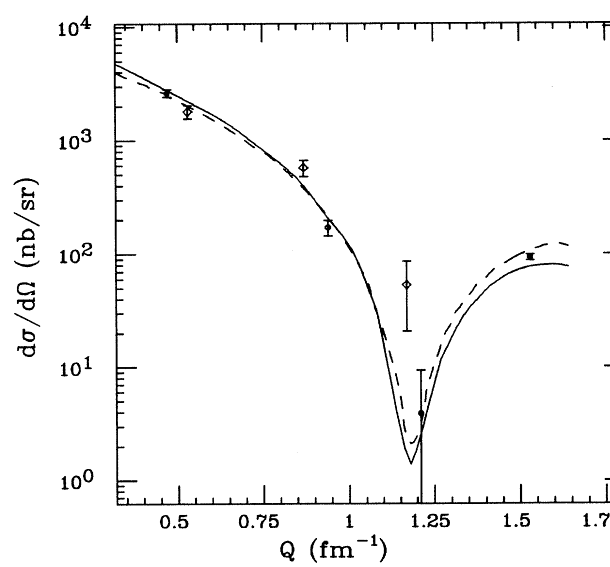

FIG. 2. Angular distribution data for $^6Li(\gamma,\pi^+)^6He_{g.s.}$. Differential cross sections are plotted against momentum transfer q. Solid points are the present results at 200 MeV. Open diamond points are the data of Shoda *et al.* (Ref. 14) at 195 MeV. The solid and dashed curves are the results of DWIA calculations by Tiator *et al.* (Ref. 7) and Doyle (Ref. 16), respectively. Error bars are statistical.

1.71 and 1.03 fm^{-1}, respectively. The nonlocal momentum space calculations of Tiator *et al.*[7] use the Blomqvist-Laget[19] photoproduction amplitude and the SMC pion optical potential.

It can be seen that these two calculations yield very similar results. Moreover, the agreement between these calculations and the present data is excellent at all angles, spanning a range of momentum transfer q from 0.5 fm^{-1} up to 1.5 fm^{-1}. In contrast to this agreement for pion production, Doyle's calculated form factor for the inelastic electron scattering using his $L1$ wave functions fits the experimental data[20,21] well only up to $q \sim 1$ fm^{-1} and deviates significantly at larger q's [see Fig. 3(b)].

One possible source of this discrepancy in electron scattering is meson exchange currents (MEC), which might be expected to contribute to the form factor at large q while being almost absent in pion photoproduction. However, the calculations of Dubach *et al.*[22] for this electron scattering transition suggest that while MEC contribute importantly to the form factor at large q, their contributions over the momentum transfer range of the present experiment are only at the few percent level.

There is a consistent pattern of enhancement of $M1$ electron scattering form factors in $1p$-shell nuclei at $q > 2$ fm^{-1} as compared to $1p$-shell model calculations, even with the inclusion of MEC.[23] The full understanding of these discrepancies is still an open question but it does appear necessary to include higher configurations beyond the $1p$ shell in the wave functions. Except for the case of $^{13}C(\gamma,\pi^-)^{13}N_{g.s.}$,[24–26] there has been no real theoretical effort to assess the importance of such higher configurations in the corresponding pion photoproduction transitions.

Doyle[16] has, however, explored the sensitivity of $^6Li(\gamma,\pi^+)^6He_{g.s.}$ to nuclear structure effects within the $1p$ shell. Figure 3(a) shows the results of DWIA calculations of the pion angular distribution at 200 MeV compared to the present experimental results for three harmonic oscillator wave function choices: Doyle's $L1$ as described above, SASK-B phenomenological wave functions[20] (with harmonic oscillator radial wave functions), and Cohen-Kurath[27] (CK). Figure 3(b) shows the calculated $M1$ electron scattering form factors for these wave functions together with the experimental data.[20,21] The CK wave functions fit the elastic form factor data well but overestimate the first maximum of the inelastic form

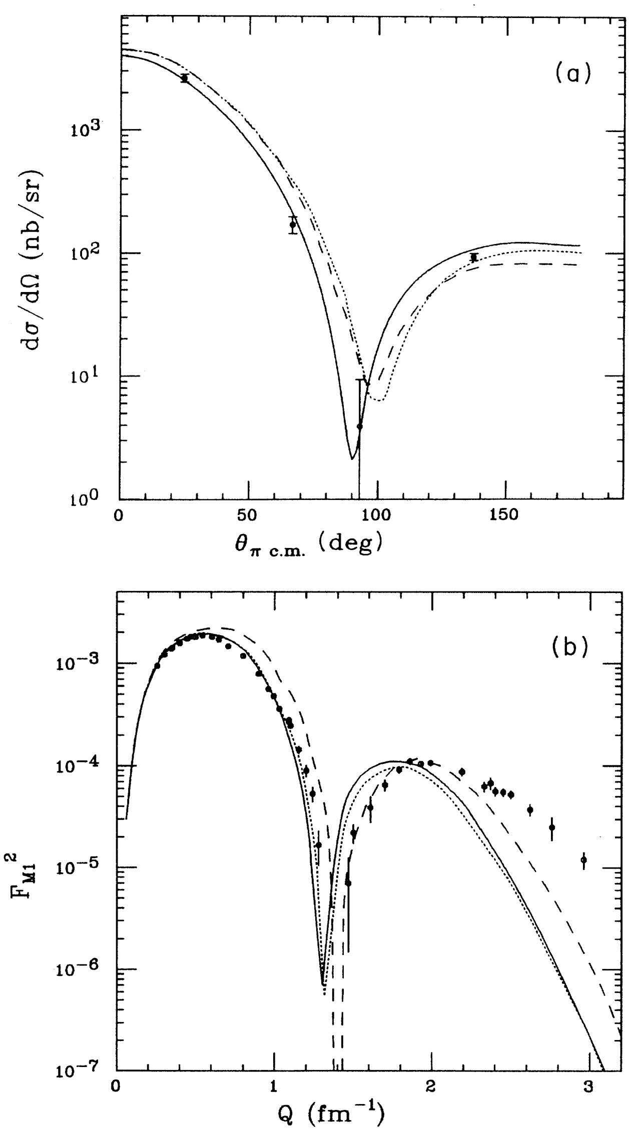

FIG. 3. Calculations by Doyle (Ref. 16) for three choices of nuclear wave functions as discussed in the text. The solid, dashed, and dotted curves are obtained using the Doyle $L1$, Cohen-Kurath, and SASK-B wave functions, respectively. (a) Results for $^6Li(\gamma,\pi^+)^6He_{g.s.}$ at $E=200$ MeV together with present data. (b) Results for $^6Li(e,e')^6Li^*(3.56$ MeV). Experimental data are due to Bergstrom *et al.* (Refs. 20 and 21).

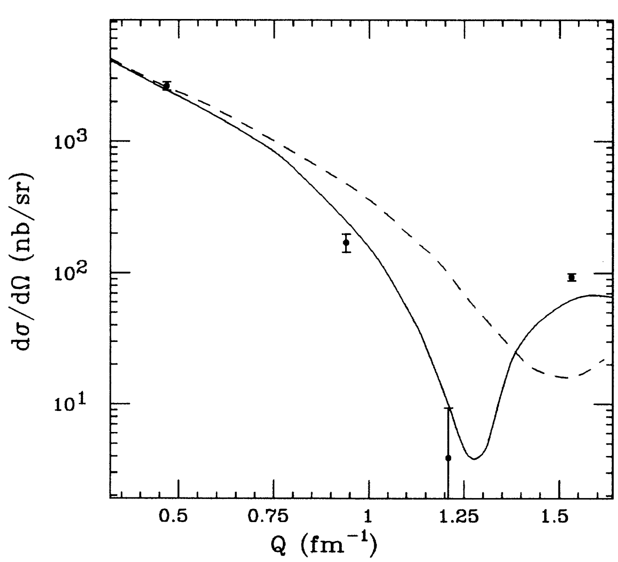

FIG. 4. Solid curve is from the calculation of Bennhold *et al.* (Ref. 10) as discussed in the text. Dashed curve is due to Eramzhyan *et al.* (Ref. 29). Data points are present results.

factor. SASK-B and L1 fits to the inelastic form factor are comparable, though the SASK-B fit to the elastic form factor is much less satisfactory. Both SASK-B and CK fit the photopion data less well than $L1$. They are above experiment at forward angles by some 50%. None of the three provides a consistently satisfactory fit to the elastic and inelastic form factor data and to the present photopion results.

There have been several other efforts to improve on conventional calculations within a $1p$-shell basis. Bennhold *et al.*[10] have made photopion calculations for ^{6}Li in DWIA using a more complete production operator and employing Woods-Saxon wave functions. They also include the Coulomb potential but this plays a negligible role. Their Woods-Saxon wave functions are chosen to fit the elastic magnetic form factor data for ^{6}Li; they obtain a good fit to these data across the first and second maxima. Figure 4 shows their results calculated at 200 MeV and plotted against q along with our 200 MeV experimental results. At forward angles, their calculation agrees well with the data and with the harmonic oscillator calculations, shown in Fig. 2. However, in their calculation the minimum is shifted and filled in compared to the harmonic oscillator calculations, and at back angles their result is below those calculations. Their cross section is below our 135° measurement by about 40%. The authors attribute this disagreement at back angles to a possibly incorrect amplitude for the $LSJ=211$ component in their wave function.

In recent years there has been considerable activity in developing three-body cluster wave functions for ^{6}Li which are largely parameter free.[28] The photopion angular distribution shown as the dotted line in Fig. 4 was calculated by Eramzhyan *et al.*[29] using an early version of these wave functions. Agreement with our data is not good near the minimum or at back angles.

In conclusion, there is remarkably good agreement between the present results and several harmonic oscillator-based DWIA calculations in the $1p$ shell due to Doyle and Tiator *et al.*, even though, as Doyle has shown, there is considerable sensitivity in these calculations to the nuclear structure input.

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