Total Cross Section for (γ, π^-) Reactions in the Δ Region

P. E. Bosted, K. I. Blomqvist, and A. M. Bernstein
Physics Department and Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
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Total cross sections for ^{12}C(γ, π^-)^{12}N and ^{7}Li(γ, π^-)^{7}Be have been measured from threshold to 360 MeV photon energy by detecting the radioactivity of the residual nuclei, thereby singling out the ground state of ^{12}N and the ground and first excited states of ^{7}Be. The cross sections are found to peak at about 40 MeV pion energy and then to fall gradually. In contrast to pion charge exchange and other photopion experiments, these results are well reproduced both in shape and in magnitude by distorted-wave impulse-approximation calculations.

Several experiments have been performed in the Δ(1236) region involving the charge exchange of one nucleon. The total cross sections for ^{7}Li(π^+, π^0), ^{10}B(π^+, π^0), and ^{13}C(π^+, π^0) have been measured and have been found to be much larger than predicted above T_π =80 MeV.[1,2] Recent differential-cross-section measurements to bound states for these same cases seem to support this discrepancy.[3] Measurements of ^{27}Al(γ, π^+) and ^{51}V(γ, π^+) from threshold to 1 GeV indicate total cross sections which are in very poor agreement with calculation below 500 MeV photon energy, the theories peaking much sooner and falling off much more rapidly than experiment.[4] Since these two cases sum over a large, unknown number of final states, it is not clear whether the disparity arises from the understanding of the nuclear structure or from the final-state interactions. Because of this uncertainty, we decided to study the reactions ^{12}C(γ, π^-)^{12}N and ^{7}Li(γ, π^-)^{7}Be, whose residual nuclei have only one and two bound states, respectively, and whose nuclear structures are well understood from recent magnetic form-factor measurements.[5,6] Both reactions have been previously investigated in the Δ region,[7,8] but because of their importance we decided to repeat them with better statistics and finer energy resolution on a modern linac. The ^{12}C(γ, π^-) reaction has been previously studied at the Bates linac in the region just above threshold.[9] The case of ^{14}N(γ, π^-)^{14}O also has one bound state for the final nucleus, but the cross section has been found to be very small[10] as expected from the strongly suppressed β-decay matrix element.[11] In this case the calculated value is found to be much larger than experiment, even though the wave functions used gave good fits to the available nuclear structure information, including the β-decay rate.[10]

The experiments were performed with electrons from the Massachusetts Institute of Technology–Bates Linear Accelerator which passed through a 2.6%-radiation-length tantalum radiator before impinging on an 800-mg/cm^2 ^{12}C target placed at

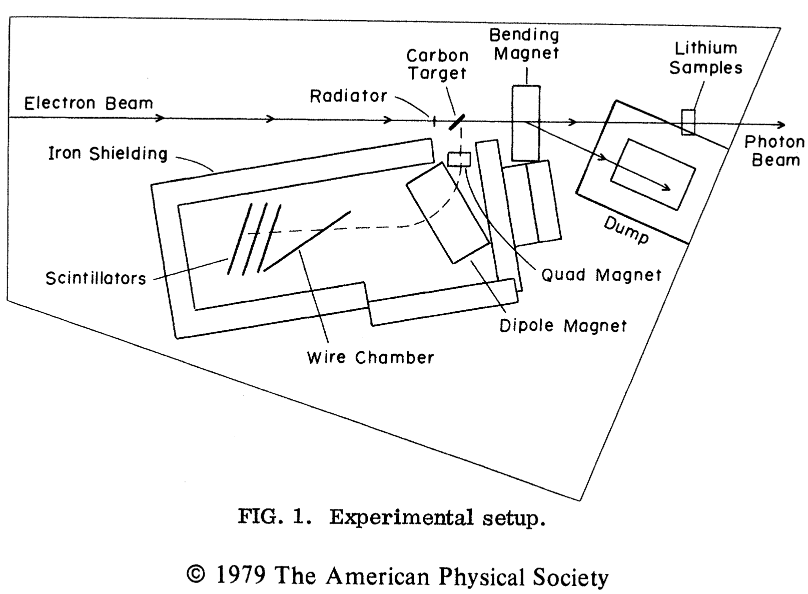

FIG. 1. Experimental setup.

45° with respect to the beam to minimize energy-loss effects. The beam was pulsed at 15 Hz which enabled us to measure the 10.97-msec half-life, 16.4-MeV endpoint[11] β^+ decay between beam bursts by bending the positrons with a magnet and registering the counts with a wire chamber in coincidence with three thin plastic scintillators (see Fig. 1). In order to reduce the background from the longer-lived activities of ^{9}C and ^{8}B,[11] both of which are produced in the target by photospallation reactions, the target was rotated past a slit at 65 rpm.

The experiment measures the yield $Y(E_0)$

$$Y(E_0) = \int_{E_{\mathrm{th}}}^{E} \varphi(EE_0)\sigma(E)\,dE,$$

where φ is the photon flux function and $\sigma(E)$ is the cross section. The experimental results for ^{12}C are shown in Fig. 2(a). The absolute normalization was done by fitting to the points at 170.2 and 191 MeV previously measured by Bernstein *et al.*[9] The results include only the contribution from the bremsstrahlung photons, with the contribution from electroproduction subtracted as explained below. There were roughly twice as many real photons as virtual ones in the experimental arrangement that was used. The dashed line represents the shape of the weakly energy-dependent ^{12}C(γ,p) yield. It was fitted to the below threshold (157.6 MeV) points which are nonzero due to the two-step process ^{12}C$(\gamma,p)^{11}$B followed by ^{12}C$(p,n)^{12}$N. The resulting background is unusually small for a radioactivity experiment because of the highly negative Q values for both reactions. Comparison with the data of Epaneshnikov *et al.*[7] shows that we are in good agreement up to 200 MeV, after which our yield is significantly higher. It is unlikely that this discrepancy is due to the two-step background because in this case it is so small.

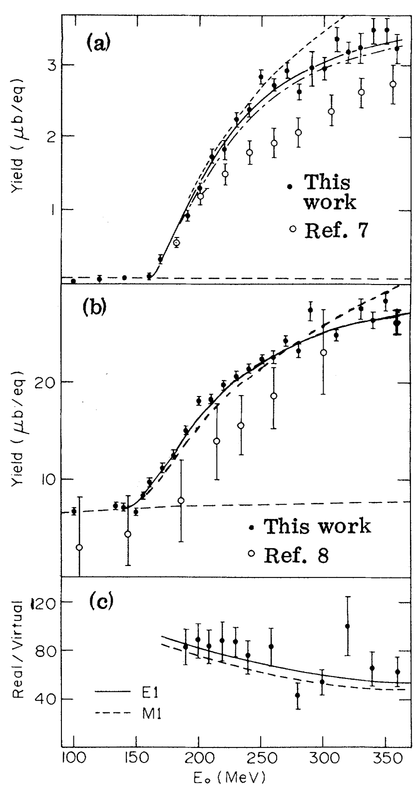

FIG. 2. Yields for (a) ^{12}C and (b) ^{7}Li as a function of incident electron energy. The theoretical curves are those calculated from the corresponding cross sections shown in Fig. 3 with the two-step background added back in. (c) Real-to-virual ratios per equivalent quantum (i.e., photoproduction-to-electroproduction ratios) for ^{12}C vs endpoint energy compared with Dalitz-Yennie predictions.

It is of interest to measure the relative efficacy of photons and electrons to induce (γ,π) reactions. This "real-to-virtual ratio" was measured for ^{12}C$(\gamma,\pi^-)^{12}$N by comparing the measured yields with and without the Ta radiator. The results as a function of energy are presented in Fig. 2(c). It can be seen that the virtual photons become less important at lower energies. This is consistent with a simple dipole form for the virtual spectrum given by Dalitz and Yennie.[12] The solid and dashed curves are obtained when the $E1$ and $M1$ forms of their spectra are folded with the theoretical cross section for ^{12}C(γ,π^-) of Epstein, Singham, and Tabakin (EST).[13] The predictions only change slightly when other shapes for the cross section that still reproduce the shape of the experimental photoproduction yield are used.

The electron beam was bent into a beam dump after passing through the carbon target, leaving only the photon beam to irradiate the $\frac{1}{2}$-in.-thick by $1\frac{1}{2}$-in.-diam ^{7}Li samples, which were each followed by a carbon disk of the same dimensions in order to monitor the beam intensity via the well-studied spallation reaction ^{12}C$(\gamma,3n2p)^7$Be.[8,14] The 478-keV γ's resulting from the 54-day half-life[11] decay of ^{7}Be were detected with a well-shielded NaI detector. The yield curve we obtained for ^{7}Li$(\gamma,\pi^-)^7$Be is shown in Fig. 2(b). It can be seen that the two-step background is much larger than for the ^{12}C case. An isochromat shape calculated from the known ^{7}Li(γ,p) cross section was fitted to the below-threshold (141.4 MeV) points. It is shown as the dashed line and was used to subtract this contribution. The contribution from ^{7}Li(γ,$p\pi^0$)^{6}He followed by ^{7}Li(p, n)^{7}Be is assumed to be small and is not included in the correction. Comparison with the results of Noga *et al.*[8] shows rough agreement in shape but a 30% disparity in the absolute magnitude. Because of this disagreement our results have been carefully checked and we believe that they are correct. Furthermore, we have also remeasured the reaction ^{9}Be(γ, 2n)^{7}Be in this energy region and find good agreement with their results.

The yield curves were unfolded by assuming that the cross section could be parametrized either as a polynomial in powers of the energy above threshold or as a sum of equally spaced Gaussians with widths at least twice as large as their spacing. We found the cross sections that gave the best χ^2 to be in good agreement with each other when the number of free parameters was between five and ten. The deduced cross sections are enclosed by the hatched regions shown in Figs. 3(a) and 3(b). It should be remembered that the errors represented by these zones are strongly correlated, so that a yield curve

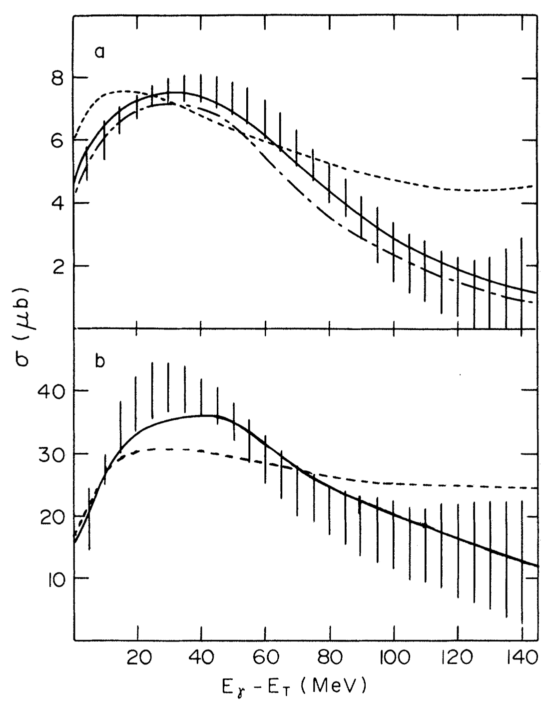

FIG. 3. Extracted cross sections for (a) ^{12}C and (b) ^{7}Li vs photon energy above threshold (shaded regions). Calculation of EST (see Ref. 13) shown as solid lines (full interaction) and dotted line (Coulomb only). Calculation of NU (see Ref. 15) shown as dash-dotted line.

calculated from a cross section skimming the top of the error zone would fall systematically high with respect to the original data points. An overall normalization uncertainty of 13.2% was not included in the ^{12}C cross section and yield points, whereas in the ^{7}Li case the systematic error is small compared to the statistical errors.

Two calculations exist for the case of ^{12}C(γ, π^-)^{12}N. That of Nagl and Überall[15] (NU) is shown in Fig. 3(a). The yield curve calculated from the cross section with the two-step contribution added back in is shown in Fig. 2(a). They have fitted the nuclear wave functions with the Helm model[16] and use the Berends parametrization of the elementary amplitude.[17] The EST calculation uses Haxton's wave functions[5] and the Blomqvist-Laget parametrization of the elementary amplitude.[18] Both calculations are done in coordinate space, and use optical-model parameters which adequately reproduce elastic pion scattering results. Also shown are EST's results with only Coulomb interactions in the final state. It can be seen that our data are in good agreement with the theoretical calculations which include sizable contributions due to the final-state interactions.

EST have also calculated the ^{7}Li(γ,π^-)^{7}Be cross section, obtaining the solid curve shown in Figs. 2(b) and 3(b). The two final states are found to contribute about equally near threshold, after which the ground-state contribution gradually becomes twice as large as that of the first excited state. It can be seen that in this case too there is reasonable agreement with the data.

In conclusion, we have found the pion photoproduction cross sections from threshold up to 150 MeV over threshold to be in agreement with distorted-wave impulse-approximation calculations for two cases for which the nuclear structure is well understood. This is in contrast to other photopion reactions whose nuclear structure is not as well understood, where large discrepancies with theory are found in the energy range we have studied.[4,10] The factor-of-2 discrepancies with calculations found in pion-charge-exchange reactions above T_π = 80 MeV may well be due to the more complicated reaction mechanism involved in these cases.[1,2]

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Photoproduction of 0–200-MeV Pions from ^{12}C and ^{7}Li

M. K. Singham,[a] G. N. Epstein,[b] and F. Tabakin
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania 15260
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Total cross sections for ^{12}C$(\gamma,\pi^-)^{12}$N and ^{7}Li$(\gamma,\pi^-)^7$Be are evaluated in the impulse approximation, with use of the Blomqvist-Laget photoproduction operator and pion distorted waves. A peak at low energies and the falloff of the cross section with increasing energy are found to be consequences of the changing overlap of pion waves with nuclear transition densities.

Total cross sections for photoproduction of energetic pions from light nuclei have recently been measured successfully by observing the radioactivity of the residual nuclei.[1] In ^{12}C$(\gamma,\pi^-)^{12}$N, the residual ^{12}N is in its 1^+ ground state, whereas ^{7}Be from ^{7}Li(γ,π^-)Be^7 appears in both its ground $(\frac{3}{2}^-)$ and first-excited $(\frac{1}{2}^-)$ states.

Our goal is to ascertain if an impulse-approximation approach (i.e., use of free production operators) can explain the trends for total and differential cross sections for production of 0–200-MeV pions. At threshold, parameter-free evaluations have already yielded reasonable agreement with data for ^{12}C and ^{6}Li, with use of just the free production operator.[2,3] Although in time more precise work will be needed at threshold, we concentrate here on the behavior of cross sections for energies approaching the resonance region. Input to these impulse-approximation calculations consists, first of all, of the basic operator for photoproduction from a nucleon, $H_{\gamma\pi}$, for which we adopt the Blomqvist-Laget model.[4] Their model was designed explicitly for use in nuclear problems. In addition to generating a reasonable fit to the basic data at relevant energies, they included simple isobar dynamics and the frame dependence needed for describing production from moving nucleons. Additional input information comes from recent analyses of pion elastic scattering, which provides the pion distorted waves.[5] (At threshold that information comes from pionic-atom studies.[6]) The nuclear structure aspect is obtained from shell-model calculations[7] and from $M1$ form factors extracted from studies of the inelastic electron scattering to the analog state of the initial nucleus.

With the above input, is it possible to explain the data? The main theoretical issues are the dependence of the predictions on the pion distorted waves, on the nuclear transition densities, and on the nonstatic terms in the photoproduction operator. By studying these sensitivities and by com-

