Photoemission of protons from $^4$He in the $\Delta$-resonance region


1 Institut für Kernphysik, Universität Göttingen, D-37073 Göttingen, Germany
2 Institut für Kernphysik, Universität Mainz, D-55099 Mainz, Germany
3 Department of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, Scotland

Received: 5 January 1996 / Revised version: 19 February 1996
Communicated by T. Walcher

Abstract. High resolution proton energy spectra from the $^4$He($\gamma,p$) reaction have been measured with tagged photons in the range $E_\gamma = 130 - 525$ MeV using the large Mainz NaI(Tl) spectrometer at $\theta_{\text{lab}} = 37.1^\circ$. Three separate reaction channels were identified, viz. $^4$He($\gamma,p$) two-body breakup, $^4$He photodisintegration via two-nucleon photon absorption processes and the quasifree pion production channel. Differential cross sections are presented for each of these channels as a function of photon energy. The sum of the two-nucleon photon absorption and the quasifree pion production differential cross sections, in the CM system, resembles that of the corresponding free-nucleon differential cross section when Fermi motion is taken into account.

PACS: 25.20.-X

1 Introduction

Photoproduction of pions on nucleons has been studied very intensely over the years and has led to a set of photomeson amplitudes [1] which are used as a tool for studies of the electromagnetic structure of the nucleon. For the deuteron the main modification of the photoproduction process in the $\Delta$ region is due to the fact that the meson may remain virtual so that photodisintegration may occur without a meson in the final state. The importance of meson exchange currents (MEC) and isobar configurations (IC) for "non-mesonic" photodisintegration of the deuteron emphasized by this simplifying view is well established [2, 3]. In a recent paper [4] non-mesonic photodisintegration of the deuteron in the $\Delta$-resonance region has been calculated very carefully and the results are compared with a selected set of recent experimental data [5]. It is shown that by introducing refinements to previous computational procedures it is possible to reproduce the experimental data satisfactorily.

In more complex nuclei MEC and IC are likely to make an even more significant contribution than in the deuteron. Modifications of the free-nucleon meson photoproduction process are expected due to (i) the initial Fermi motion of the nucleon, (ii) the exchange of virtual pions with immediate nucleon partners (quasideuteron or quasifree two-nucleon photodisintegration), (iii) final state nucleon interactions (FSI) (including the effects of Pauli blocking) and (iv) scattering or reabsorption of pions while traveling through the nuclear medium.

Two distinct theoretical approaches have been tried in recent years to model photodisintegration mechanisms in complex nuclei. The approach favoured by the Gent [6] and Pavia [7] groups is to perform microscopic quantum mechanical calculations of specific processes, e.g. p-n photon absorption or quasi-free pion production processes. Nucleon-nucleus FSI are included using an optical model. While this approach provides definite predictions for specific processes, it cannot account for the strong indirect processes, such as pion scattering or reabsorption which dominate the total cross section in the $\Delta$-resonance region. An alternative approach developed at Valencia [8] models initial photon interactions using a Fermi-gas model of the nucleus and employs a semi-classical Monte Carlo calculation to trace the particles produced through the nucleus and to treat secondary scattering and reabsorption processes. Although this approach includes nearly all of the processes contributing to the total photon absorption cross section and gives particularly good accounts of ($\gamma,pn$) processes, it tends to overestimate the weaker ($\gamma,pp$) channel [9]. The reasons for this are not presently understood. By the very nature of the model it is inapplicable to extremely light nuclei.

An experimental investigation of the photonuclear processes which occur in the $\Delta$-resonance region using the $^4$He nucleus offers several advantages. (a) $^4$He combines the high density of a complex nucleus with the well-known structure of a few-nucleon system. (b) The four nucleons are located in the same shell-model state so that cluster effects do not complicate the data interpretation. (c) All nucleons are lo-
cated more or less at the nuclear surface so that FSI are likely to be minimised. In particular reabsorption of pions traveling through the nuclear medium is likely to be strongly suppressed compared to heavier nuclei.

Three reaction channels are of specific interest in the present study; the direct knockout reaction,

\[ ^4\text{He} + \gamma \rightarrow p + ^3\text{H}, \]

the photodisintegration of quasifree two-nucleon systems, involving at least one proton, inside the \(^4\text{He}\) nucleus,

\[ 'p'n' + \gamma \rightarrow p + n \]
\[ 'pp' + \gamma \rightarrow p + p \]

and quasifree pion photoproduction processes in \(^4\text{He}\),

\[ 'p' + \gamma \rightarrow p + \pi^+ + \pi^- \]
\[ 'n' + \gamma \rightarrow p + \pi^0 \]

In addition, at high photon energies, more complex processes involving the emission of more than one pion become possible, e.g.

\[ 'p' + \gamma \rightarrow p + \pi^+ + \pi^- \]

High proton energy resolution is a prerequisite to separate these different reaction channels. However even very good energy resolution is insufficient to distinguish channels which have the same basic kinematics. In recognition of this the notation and description of the two-nucleon photon absorption channels (2) are combined under the common term of quasifree two-nucleon photodisintegration, denoted as

\[ 'p'n' + \gamma \rightarrow p + N. \]

Similarly, the two pion reaction channels (3) are amalgamated under the common term of quasifree pion photoproduction,

\[ 'N' + \gamma \rightarrow p + \pi. \]

Measurements of double pion photoproduction processes on the proton [10] show that these channels open up at \(E_\gamma \approx 400\) MeV, although their strength remains weak below 500 MeV. At all of the energies covered by the present experiment the total cross section for double pion production on the proton remains a small fraction of the single pion production cross section. Therefore the double pion photoproduction channel has been disregarded in the present analysis. This may lead to a slight overestimate of the single pion photoproduction cross sections at the very highest photon energies considered here.

There have been several previous photodisintegration experiments which have studied various aspects of photon reactions in light nuclei at energies similar to the present experiment. A brief overview is given here of those works which are most relevant to the present investigation. The reaction \(^3\text{He}(\gamma,p)d\) was investigated by Schumacher [15] and Emura et al. [19] at photon energies from 150 to 450 MeV. The differential cross sections were seen to be in a good agreement with the time-reversed reaction. Differential cross sections for the reactions \(^3\text{He}(\gamma,p)d\) and \(^4\text{He}(\gamma,p)t\) were measured by Argan et al. [12] for the photon energy range 150 to 450 MeV. The differential cross sections show a monotonically decreasing variation with photon energy with no indication of a \(\Delta\) peak. The same observation has been made by Kiergan et al. [13] who studied the \(^4\text{He}(\gamma,p)t\) reaction in the photon energy interval from 180 to 320 MeV. Arends et al. [14] studied the same reaction in the energy interval from 200 to 450 MeV and at proton centre-of-mass (CM) angles between 30° and 150°. The measured angular distributions show a strong forward peaking and again no indication of a \(\Delta\) peak on the monotonically decreasing differential cross section. In a more recent work R.A. Schumacher [15] investigated the emission of protons and neutrons for photon energies between 100 and 360 MeV at CM angles of 60°, 90° and 120° by detecting the recoil \(^3\text{H}\) and \(^3\text{He}\) nuclei with a magnetic spectrometer. The cross sections for the \((\gamma,p)\) and \((\gamma,n)\) reactions were seen to be very similar and were both forward peaked. The 60° data suggested a small bump near 300 MeV which might be an indication that the \(\Delta(1232)\) plays some role in the reaction. The recent work of Schmieden et al. [16] measured proton knockout from \(^4\text{He}\) in the lower energy range \(E_\gamma = 81 - 158\) MeV at proton laboratory angles between 55° and 125°. Data from a wide range of experiments were compared with the modified quasideuteron model of Schoch [17] in which the participating neutron is reabsorbed into the residual nucleus ground state, and with a simple quasifree knockout model. The analysis of Schmieden et al. shows some preference for the modified quasideuteron mechanism, although at photon energies above the \(\Delta\) resonance the data significantly exceed the modified quasideuteron predictions indicating the need for more complex processes at very high photon energies.

Single nucleon knockout investigations of type (1) have shown great similarity between proton and neutron emission, as expected by the modified quasideuteron mechanism. In addition, measurements on \(^4\text{He}\) have shown very little indication of the excitation of the \(\Delta\) resonance in these processes.

Measurements of two-nucleon emission from \(^4\text{He}\) have been carried out by Doran et al. [18] at photon energies 80–130 MeV, just below the present measurements. In addition Emura et al. [19] studied the four-body breakup of \(^4\text{He}\) at \(E_\gamma = 135 - 455\) MeV, similar to the present work. Doran et al. showed that the \(^4\text{He}(\gamma,p)n\) three-body-breakup channel dominated the four-body breakup channel and that the three-body breakup channel could be well described by a quasideuteron mechanism. On this basis the cross section for the \(^4\text{He}(\gamma,p)n\) channel was shown to rise from \(\sim 60\) \(\mu\)b at 88 MeV to \(\sim 90\) \(\mu\)b at 123 MeV. Emura et al. showed that the weaker four-body breakup cross section rose to a maximum of \(\sim 45\) \(\mu\)b at \(\sim 350\) MeV before falling slightly up to the highest photon energies measured.

More general experiments which investigated the interplay between non-mesonic two-nucleon emission processes (2) and quasifree pion production processes (3) in a range of light nuclei have been carried out by Homma et al. [20–25] for \(^3\text{H}\), \(^4\text{He}\), \(^6\text{Be}\), \(^12\text{C}\) and \(^16\text{O}\), by Baba et al. [26] for \(^8\text{Be}\) and \(^12\text{C}\), by Arends et al. [27] for \(^9\text{Be}\), \(^12\text{C}\), \(^16\text{O}\), \(^40\text{Ca}\), \(^40\text{Ti}\) and \(^208\text{Pb}\), and most recently by Cross et al. [9] for \(^12\text{C}\). These experiments all showed a distinct two-bump structure in the proton momentum (or energy) spectra, which is interpreted as arising from separate contributions from photon