The \((\gamma, p n)\) and \((\gamma, 3p 3n)\) Reactions in \(^{40}\text{Ca}\) at Intermediate Energies

K. Lindgren
Department of Nuclear Physics, Lund Institute of Technology, Lund, Sweden

Received January 14, 1976

The yields of the reactions \(^{40}\text{Ca}(\gamma, p n)^{38}\text{K}\) and \(^{40}\text{Ca}(\gamma, 3p 3n)^{34}\text{Cl}\) have been measured by the activation method in the energy range 80–800 MeV. From the measured yields the cross sections are deduced. The experimental cross sections are compared to calculations with a cascade-evaporation model for photo-induced reactions.

1. Introduction

Experimental studies of the \((\gamma, p n)\) process in various nuclei have been reported by several authors. In many experiments \(n-p\) coincidences have been measured (see Reference 1 and references therein). In other experiments, the activation method is used, i.e., the activity of the residual nucleus after \(np\) emission is measured. With the latter technique, Ferrero et al. [2] have measured the cross sections for \(^{32}\text{S}, ^{40}\text{Ca}\) and \(^{76}\text{Ge}\) from threshold up to 31 MeV. Extended measurements for \(^{40}\text{Ca}\) up to 140 MeV have been carried out by Kayser et al. [3]. In the energy region 50–300 MeV, measurements on \(^{32}\text{S}, ^{40}\text{Ca}\) and \(^{66}\text{Zn}\) have been made by van Hise et al. [4] and by Meyer [5].

The cross sections reported in References 4, 5 show an increase above about 100 MeV which is interpreted as an effect of pion production. However, these measurements cover only a small part of the region in which pion production processes are assumed to be of importance.

The reaction \((\gamma, 3p 3n)\) has been studied by Schupp et al. [6] at energies below 70 MeV and at energies up to 300 MeV by Meyer [5].

The first theoretical description of the energy region between the giant resonance and the pion threshold was given by Levinger [7] who introduced the quasi-deuteron model. In this model, the photon absorption cross section is proportional to the deuteron photodisintegration cross section. Since then, many attempts have been made to calculate the \((\gamma, p n)\) cross section by introducing short range nucleon-nucleon correlations into the single particle shell model, see e.g. Reference 8 and references therein. Most of these calculations have been carried out for light nuclei. The results are, however, not satisfactory. For \(^{40}\text{Ca}\) and \(^{32}\text{S}\), calculations have been carried out by Bramanis [9] and the results for \(^{40}\text{Ca}\) are compared with experiment in Reference 3. The most recent model for this energy region is given by Gari and Hebach [10] who introduce nucleon-nucleon correlations by means of meson exchanges. Their model can explain the dominance of the \((\gamma, p n)\) reaction.

The aim of the present investigation is to extend previous measurements on \(^{40}\text{Ca}\) to higher energies to see to what extent pion production processes contribute to the cross section. The measured cross sections will be compared with the results of calculations based on the cascade-evaporation model in which the primary photon interaction can take place either via quasi-deuteron absorption or via pion production on single nucleons. The quantitative calculations are carried out with the Monte Carlo programs of Gabriel and Alsmiller [11] and Dresner [12].

2. Experimental Details

The experiment was carried out at the 1.2 GeV electron synchrotron at the University of Lund. The calcium samples consisted of granular metallic calcium of natural isotopic composition. The grains were pressed together to form solid discs with 22 mm diameter and 4 mm thickness. The discs were placed in lucite containers. Graphite discs of the same dimensions were used for monitoring. The calcium and carbon samples were placed in an
uncollimated bremsstrahlung beam and irradiated for 20 min. After a 3 min delay, the \( \gamma \)-activity in the calcium sample was measured during a 20 min period with a 35 cm\(^2\) Ge(Li) detector. The decay data [13] of the studied products are given in Table 1. The measurement of the 511 keV annihilation radiation in the carbon samples started between 60 and 110 min after the end of the irradiation period and lasted between 3 and 10 min. The maximum bremsstrahlung energy was varied between 80 and 800 MeV and at each energy one irradiation was performed.

### Table 1. Decay data for the two nuclides studied

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Nuclide</th>
<th>Half-life (min)</th>
<th>( \gamma )-energy (MeV)</th>
<th>Intensity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( (\gamma, pn) )</td>
<td>( ^{38}\text{K} )</td>
<td>7.71</td>
<td>2.1668</td>
<td>100</td>
</tr>
<tr>
<td>( (\gamma, 3p 3n) )</td>
<td>( ^{34}\text{mCl} )</td>
<td>32.2</td>
<td>2.1280</td>
<td>29</td>
</tr>
</tbody>
</table>

#### 3. Analysis and Results

Using the yield curve for the \( ^{12}\text{C}(\gamma, n)^{11}\text{C} \) reaction measured by Hyltén [14], the absolute yields of the \( (\gamma, pn) \) and \( (\gamma, 3p 3n) \) reactions in \( ^{40}\text{Ca} \) were determined. The yields of the two reactions are shown in Figures 1 and 2, respectively. The yields measured also include contributions from the heavier calcium isotopes, but these were found to be negligible. The errors indicated in the figures are those due to counting statistics. The total systematic error is estimated to be about 15\%.

In the \( (\gamma, pn) \) yield curve, a marked increase is observed at the pion production threshold. To determine the cross section above 140 MeV, the yield from the cross section at lower energies was subtracted and for this purpose the data in Reference 3 were used. However, the overlap in the common energy region was found to be poor. To get a fit to our data, their cross section had to be reduced by a factor of 2.4. It should be noticed that in Reference 4 is given an integrated cross section at 140 MeV which is a factor of 2.2 smaller than that reported in Reference 3. The curve fitted to the present data below 140 MeV is shown by the solid curve in Figure 1. A zero cross section was applied at energies above 140 MeV. From the net yield curve, the cross section was calculated with the photon-difference method, using smoothing as described in Reference 15. The resulting cross section is shown in Figure 3 (solid curve) together with results from other.