Aust. J. Phys., 1996, **49**, 1075–80

De-excitation Gamma-ray Technique for Improved Resolution in Intermediate Energy Photonuclear Reactions

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Abstract

Use of residual-state decay γ-rays could be a powerful tool in the study of photonuclear reactions. The practicality of this technique in a tagged-photon experiment is demonstrated for the first time with data on the ^{12}C(γ, p) reaction.

1. Introduction

The reaction mechanism involved for photonuclear reactions between the giant resonance and the pion threshold is not fully understood. One outstanding problem is the role of photon absorption on two or more nucleons. Although great advances have been made since the advent of experiments with tagged photons, interpretation is in some cases hampered by inadequate energy resolution. The ^{12}C(γ, p) reaction studied at $E_\gamma \approx 60$ MeV is an example. The reaction was found to populate the excitation region at about 7 MeV in the residual ^{11}B nucleus, with known levels at 6·74 MeV ($\frac{7}{2}^-$), 6·79 MeV ($\frac{1}{2}^+$) and 7·29 MeV ($\frac{5}{2}^+$). While Springham *et al.* (1990) and recently Ruijter (1995) reported little strength to the 7·29 MeV ($\frac{5}{2}^+$) state, Van Hoorebeke *et al.* (1990) claimed appreciable population of this state. This point is important as Van Hoorebeke *et al.* interpreted their result as evidence for photon absorption on $T = 1$ pairs, rather than $T = 0$ pairs as in the simple quasideuteron model. By contrast the microscopic calculations of Ryckebusch *et al.* (1988, 1992) and Miller *et al.* (1995), which give a reasonable account of all measured (γ, p) cross sections for ^{12}C and ^{16}O, predict that the strength near 7 MeV is predominantly to the ($\frac{5}{2}^+$) state in ^{11}B at 7·29 MeV. On the other hand if only little strength goes into the ($\frac{5}{2}^+$) state, as found by Springham *et al.* (1990) and Ruijter (1995), the

0004-9506/96/061075$05.00

important question is how the remainder of the strength is divided between the $(\frac{7}{2}^-)$ and $(\frac{1}{2}^+)$ states. For instance, since a large admixture of 1f components in the wave function for ^{12}C can be ruled out the $(\frac{7}{2}^-)$ state has to be excited in a two step-process which also could result in excitation of the $(\frac{5}{2}^-)$ state at 4·45 MeV in ^{11}B. In fact Ruijter (1995) claimed to see a contribution from this latter state. However, in all the ^{12}C(γ,p) experiments performed so far the resolution is not really adequate to determine how the strength is distributed between the three states at 6·74, 6·79 and 7·29 MeV. In the case of ^{16}O, population of the positive-parity doublet in ^{15}N in the ^{16}O$(\gamma,\mathrm{p})^{15}$N reaction carried out at similar excitation energies, is well confirmed by Van Hoorebeke *et al.* (1990), Sims *et al.* (1992) and Miller *et al.* (1995). However, a consistent theoretical interpretation of the excitation of positive-parity states in ^{11}B and ^{15}N has not yet been achieved.

It is difficult to improve the resolution in (γ,p) experiments as it is dominated by the effects of target thickness. An alternative is to detect the decay γ-rays as well as the emitted protons. Then the resolution is little affected by target thickness, and depends mainly on the resolution of the γ-ray detector. For example, in ^{12}C a NaI γ-ray detector gives a resolution sufficient to distinguish the 7·29 MeV state from the two at 6·8 MeV. Furthermore, because of the different decay patterns from the states at 6·74 and 6·79 MeV (see Fig. 1) it is also possible to determine the relative population of these two states by measuring all the specific cascade γ-rays.

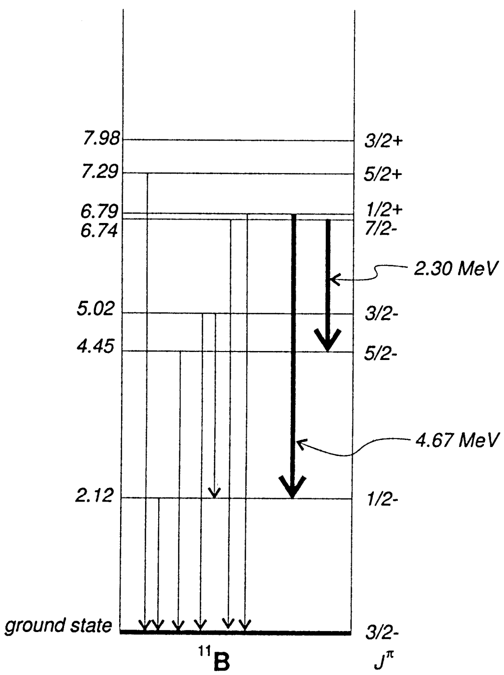

Fig. 1. Low-lying states of ^{11}B with relevant cascade γ-rays.

2. Experiment

In this experiment it has been possible to detect γ-rays emitted from the residual nucleus, in coincidence with photoprotons leading to the excited residual state. This technique has been carried out for the first time using a source of tagged photons. Although the proton energy resolution is still limited by the target thickness (the resolution is about 2 MeV for protons with energy 30–50 MeV and 1 mm carbon target), the 200 keV γ-ray resolution permits the identification of the residual states and allows off-line cuts to be made in order to identify the excitation region in ^{11}B from what particular de-excitation γ-rays are seen. In particular we have studied the ^{12}C(γ, p) reaction with the aim of resolving the relative population of the three states at 7 MeV.

The experiment was done at the MAX Laboratory of Lund University using tagged photons with energies between 50 and 70 MeV. The de-excitation γ-rays were detected using two well-shielded 25-cm diameter 30-cm deep NaI detectors placed perpendicular to the beam. The protons which provided the trigger to accept the NaI signal were detected in three proton spectrometers placed at different positions around the 235 mg cm^{-2} natural carbon target. Two 3 inch (7·6 cm) CsI detectors each with two thin ΔE detectors were placed about 15 cm from the target at angles of 65° and 120°. A third proton spectrometer, consisting of a matrix of small CsI crystals and with thin plastic ΔE detectors (see Annand *et al.* 1990), was placed at 70° approximately 15 cm from the target.

The excited states in ^{11}B and ^{10}B decay not only directly to the ground state, but also by cascade through intermediate states. Thus the relative intensity of de-excitation γ-rays will not necessarily represent the relative populations of the excited states. For this reason it was necessary to have a reasonably good-resolution proton spectrometer system, to determine the approximate energy of the excited residual state. This information, plus the known decay γ-ray branchings from Ajzenberg-Selove (1990), will allow the true relative populations to be found.

The purpose of this note is to report the practicality of this method, and foreshadow the likely clarification of the population of the states around 7 MeV in the ^{12}C(γ, p) reaction. At this stage the data analysis is far from complete, however, there are some important indications from the preliminary data.

Identification of the excitation energy in ^{12}C and the region in the residual nucleus that is being populated can be made by tagging the photon and cutting on the proton spectrum. The proton cut is best done by first identifying those protons that have led to the emission of de-excitation γ-rays. Fig. 2*a* shows the excitation-energy spectrum of the residual nucleus produced by tagged photons in the energy range 50 to 70 MeV. The energy scale is the missing energy less the absolute value of Q (−15·97 MeV) of the ^{12}C(γ, p) reaction. The peak at energies less than 3 MeV includes protons to the ground state of ^{11}B and to the 2·12 MeV state. The higher energy peak includes protons leading to higher states in ^{11}B; above this are protons to states in ^{10}B. The peak widths are about 3 MeV as expected from the target thickness. The entire spectrum rides on a smooth background due to random coincidences with the tagger. Fig. 2*b* shows the excitation-energy spectum derived from Fig. 2*a* by requiring a coincidence between a proton and a de-excitation γ-ray. Note that the spectrum no longer contains protons to the ground state of ^{11}B, and the region corresponding to excited low-lying states in ^{11}B is relatively enhanced.

Fig. 2*b* allows de-excitation γ-ray spectra to be obtained for specified excitation regions in the residual nuclei. Fig. 3*a* shows the de-excitation γ-ray spectrum triggered by protons leading to the lowest 3 MeV of the excitation-energy spectrum; thus it shows evidence only of population of the 2·12 MeV state in ^{11}B. In Fig. 3*b* the de-excitation γ-ray spectrum is triggered by protons contributing to the region of the excitation-energy spectrum between 5 and 8 MeV; so that excited states from 5·02 to 7·29 MeV are examined. The γ-rays at 2·3 and 4·44 MeV are assumed to be the result of cascade decay from the states at 6·74 MeV. Because of the relatively poor proton energy resolution there may be some additional strength in the population of 4·44 MeV state if it is populated directly in the ^{12}C(γ, p) reaction.

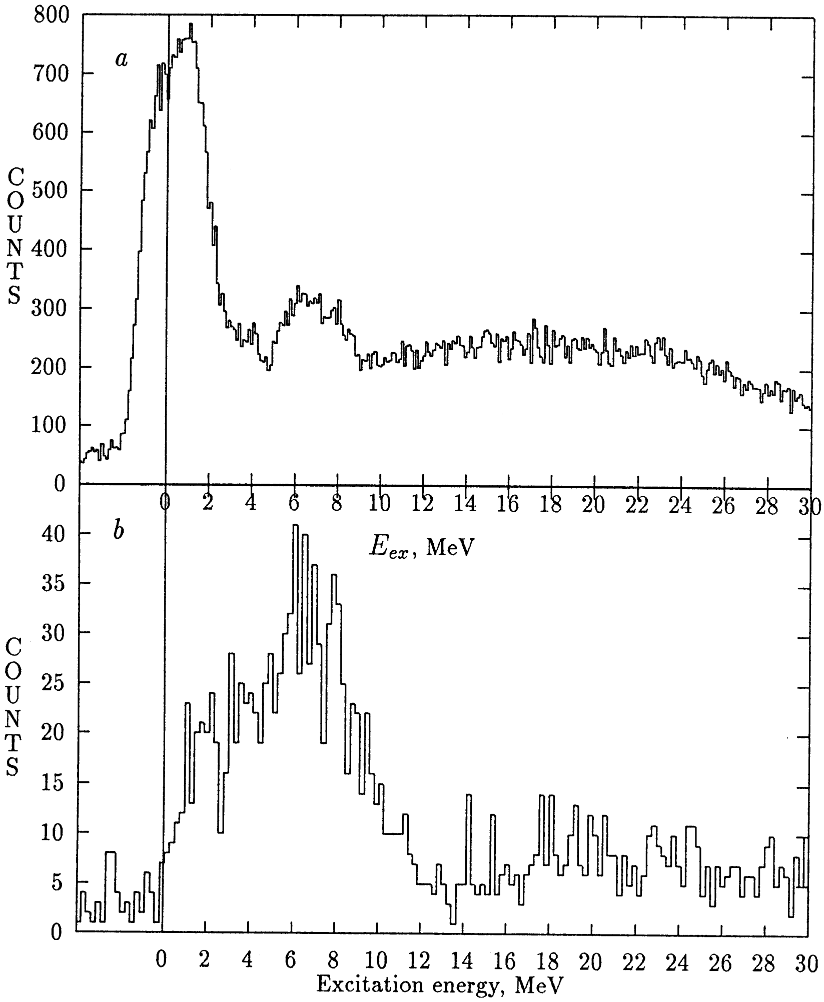

Fig. 2. A typical excitation-energy spectrum produced by tagged photons in the energy range 50 to 70 MeV. (*b*) The spectrum derived from that shown in (*a*) by requiring a coincidence between a proton and a de-excitation γ-ray.

It is clear that the population of the 7·29 MeV state is considerably weaker than one or both of the states at 6·8 MeV. This cannot be caused by the different decay branching because 87% of decays from the 7·29 MeV state are direct to the ground state according to Ajzenberg-Selove (1990).

This observation is in disagreement with Van Hoorebeke *et al.* (1990) but confirms the findings of Springham *et al.* (1990) and Ruijter (1995). It suggests that the theory by Ryckebusch *et al.* (1992) needs to be re-examined possibly to take account of two step mechanisms (see Ireland and van Steenhoven 1994), which can be expected to populate the $\frac{7}{2}^-$ 6·74 MeV state.

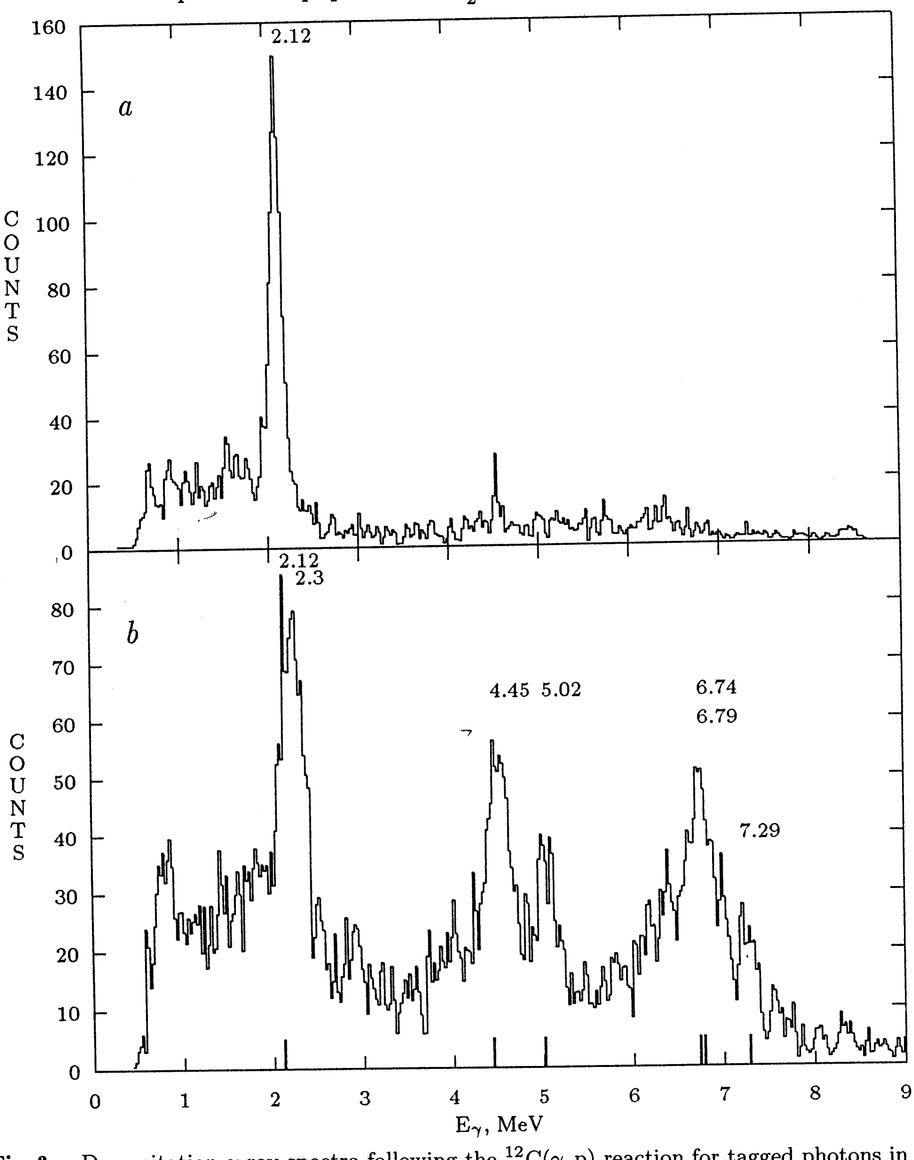

Fig. 3. De-excitation γ-ray spectra following the $^{12}C(\gamma, p)$ reaction for tagged photons in the energy range 50 to 70 MeV: (*a*) triggered by protons from the excitation-energy region less than 3 MeV; (*b*) triggered by protons from excitation-energy region between 5 and 8 MeV. The energies of the states in ^{11}B are shown by the tick marks on the energy axis.

3. Summary

We have successfully applied the de-excitation γ-ray technique to the study of photonuclear reactions at intermediate energies. Further analysis of the present data will clarify the relative population of the three states in ^{11}B at 6·74, 6·79 and 7·29 MeV. It is likely to resolve the question also of whether a $T=1$ quasideuteron needs to be introduced in the simple quasideuteron model, and will confront microscopic theories with more challenging data. The technique can also be used to overcome energy resolution problems in other photonuclear reactions, e.g. (γ,pn) in ^{12}C and in other nuclei. It has great potential to improve the understanding of photonuclear reaction mechanisms.

Acknowledgments

The diligence of the MAX Laboratory accelerator operators is gratefully acknowledged. This measurement was supported by grants from the Australian Department of Science and Technology, the UK Science and Engineering Research Council, the EC Human Capital and Mobility program, the Swedish Natural Science Research Council, the Knut and Alice Wallenberg Foundation and the Crafoord Foundation. One of the authors (AK) was supported by an Australian Postgraduate Research Award.

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Manuscript received 14 May, accepted 17 July 1996