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De-excitation gamma-ray technique for improved resolution in intermediate energy photonuclear reactions.

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The reaction mechanism involved for photonuclear reactions between the giant resonance and the pion threshold is not fully understood. The $^{12}C(\gamma,p)$ reaction studied [1, 2, 3, 4] 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.* [1] and recently Ruijter [3] report little strength to the 7.29 MeV $(\frac{5}{2}^+)$ state, Van Hoorebeke *et al.* [2] claim appreciable population of this state. This point is important, as Van Hoorebeke *et al.* interpret 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.* [5, 6, 7], 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 in [1, 3] the important question is how the strength is divided between the $(\frac{7}{2}^-)$ and $(\frac{1}{2}^+)$ states. However, in all the $^{12}C(\gamma,p)$ 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. It is difficult to improve the resolution in single arm experiments as it is dominated by the effects of the 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-rays detector. Furthermore, because of the different decay patterns from the states at 6.74 MeV and 6.79 MeV it is also possible to determine the relative population of these two states by measuring of the specific cascade γ-rays.

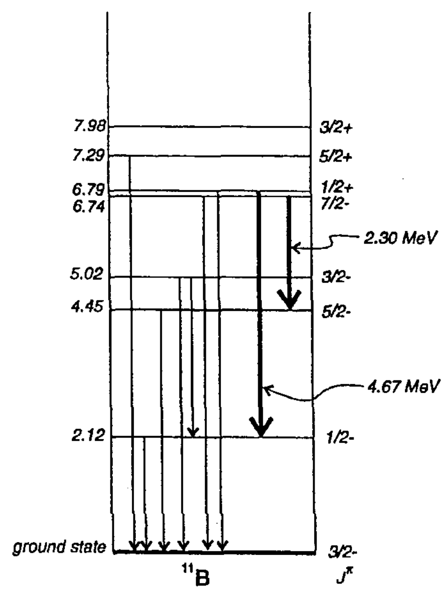

Figure 1: The low-lying states of ^{11}B with relevant cascade γ-rays.

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 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 excitattion region in ^{11}B from what particular de-excitation γ-rays are seen.

The experiment was done at the MAX Laboratory of Lund University using tagged photons with energies between 50 and 70 MeV, two 10" NaI γ-ray detectors, 235 $mg \cdot cm^{-2}$ natural carbon target, three 3" CsI detectors each with two thin ΔE detectors.

The excited states in ^{11}B shown in Figure 1 decay, not only directly to the ground state, but also by cascades 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 [8] will allow the true relative populations to be found. Figure 2 shows the excitation-energy spectrum of the residiual nucleus produced by tagged photons in the energy range 50 to 70 MeV for the forward angle (65°) detection of protons. The energy scale is the missing energy less the Q[15.97 MeV] of the $^{12}C(\gamma$,p) reaction. The peak at energies less than 3 MeV includes protons to the GS 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.

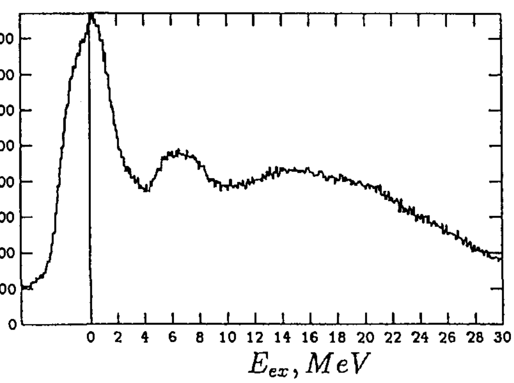

Figure 2: A typical excitation-energy spectrum produced by tagged photons in the energy range 50 to 70 MeV.

Figure 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 Figure 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.

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 [8]. This observation is in disagreement with Van Hoorebeke *et al.* [2] but confirms the findings of Springham [1] and Ruijter [3]. It suggests that the theory [6] needs to be re-examined possibly to take account of two step mechanisms [9], which can be expected to populate the $7/2^-$ 6.74 MeV state. The fitting routine using the least squares method was applied to unfold the spectrum to estimate populations of the peaks in question. After the peaks were fitted the relative populations were found as shown in Table 1.

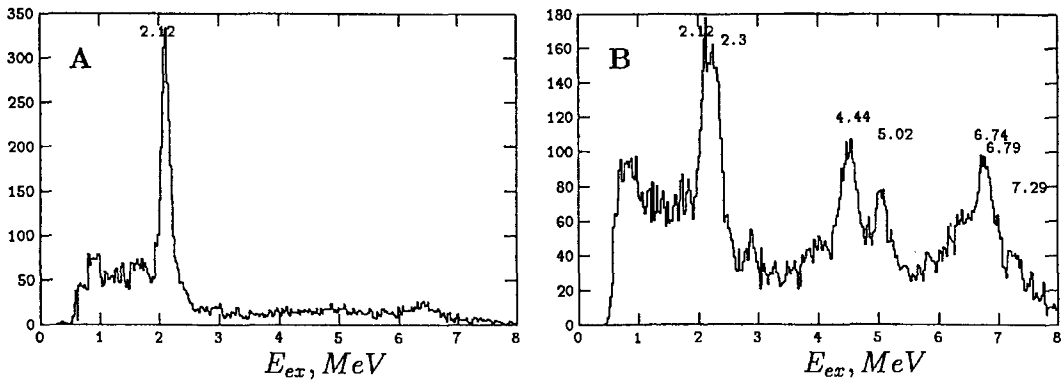

Figure 3: De-excitation γ-ray spectra following the $^{12}C(\gamma$,p) reaction for tagged photons in the energy range 50 to 70 MeV. (**A**) triggered by protons from excitation energy region less than 3 MeV. (**B**) triggered by protons from excitation energy region between 5 and 8 MeV. (the energies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

Spin	Energy	Relative population	Configuration			
			particle	^{10}B core		
$\frac{5}{2}^+$	7.29 MeV	1	$d_{\frac{5}{2}}$	2^+	T=1	5.16 MeV
$\frac{1}{2}^+$	6.79 MeV	2.4	$2s_{\frac{1}{2}}$	0^+	T=1	1.74 MeV
$\frac{7}{2}^-$	6.74 MeV	3.4	$1p_{\frac{1}{2}}$	3^+	T=0	G.S.

Table 1: Population of the states near 7 MeV in ^{11}B.

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 give information of the behaviour of the relative population of the three states in ^{11}B at 6.74, 6.79 and 7.29 MeV depending on energy of the incident photons and the angle of proton detection. It is likely to resolve the question also whether a T=1 quasi-deuteron needs to be introduced in the simple QDM, 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

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