Deuterons and Protons from ^{12}C and ^{13}C: What do they tell us?

M. J. BOLAND, R. P. RASSOOL, M. N. THOMPSON
School of Physics, The University of Melbourne, Melbourne, Australia

J. JURY
Trent University, Ontario, Canada

J-O. ADLER, K. HANSEN, B. SCHRÖDER, M. LUNDIN, M. KARLSSON, D. NILSSON
Department of Nuclear Physics, Lund University, Lund Sweden

T. DAVISON, S. A. MORROW, K. FOEHL
Department of Physics, University of Edinburgh, Scotland

J. R. M. ANNAND, J. C. MCGEORGE
Department of Physics and Astronomy, University of Glasgow, Scotland

The reactions $^{13}C(\gamma, d)$ and $^{13}C(\gamma, t)$ were studied using tagged photons in the intermediate energy range E_γ=50–70 MeV. An unexpectedly large number of deuterons and tritons were emitted from ^{13}C compared with the same reactions on ^{12}C. These results may be understood in terms of the break-up of the cluster nucleus ^{12}C by the addition of an extra neutron to form ^{13}C. The valence neutron in ^{13}C produces strong final state interactions with the ejected proton, enhancing the deuteron emission.

1 Introduction

A recent intermediate-energy photonuclear experiment on ^{13}C at E_γ=50–70 MeV indicates significantly more deuterons and tritons are emitted than from ^{12}C at the same energy. The reason for this is not clear, but may well be related to the differences induced in the ^{12}C ground-state wavefunction with the addition of the extra neutron. An understanding of the experimental observations may be relevant in understanding the photonuclear reaction mechanism in the intermediate-energy region.

The data presented was taken from measurements made at the MAX-Lab[5,6] at Lund University in 1998. It was made in collaboration with groups from Lund University, University of Glasgow, University of Edinburgh and Trent University.

2 Motivation

The idea for studying ^{13}C stemmed from the highly successful measurement of the $^{12}C(\gamma, p\gamma')^{11}B$ to residual states by Kuzin *et al.*[1] This experiment successfully measured the relative population of the previously unresolved states at $\frac{7}{2}^-$ (6.74 MeV), $\frac{1}{2}^+$ (6.79 MeV) and $\frac{7}{2}^+$ (7.29 MeV), thereby clarifying the relative importance of the various photon absorption mechanisms. It was argued that if in ^{13}C, the additional neutron was weakly coupled to a ^{12}C core, then the residual states populated in ^{12}B following the $^{13}C(\gamma,p)^{12}B$ reaction should be those populated in ^{11}B following the $^{12}C(\gamma,p)^{11}B$ reaction, coupled to the spectator neutron.

In reality this experimental aim proved difficult to achieve. However the observation of emission of heavier charged particles (deuterons and tritons) has provided data which has a bearing on the same theme: namely, the effect of the extra neutron on the wavefunction of ^{12}C. The differences in the results of photo-reaction experiments may thus throw some light on the nature of the reaction mechanism involved.

3 Experiment

The experiment was conducted at the MAX-Lab Tagged photon facility in Lund, Sweden. It was designed as a pilot measurement, *downstream* from the principal experiment, in an attempt to maximise the beam usage. A beam of real photons was used, and the tagging range was set to $E_\gamma \approx$ 50-70 MeV.

The 1 mm thick target of 99% enriched ^{13}C graphite powder was placed in the beam, and observed by three charged-particle spectrometers at 60°, 90° and 120°. Each spectrometer consisted of a thick intrinsic Ge detector and a thin Si detector. This combination of detectors allowed very clean particle identification with the Ge resolution measuring $< 1\%$. The detectors and targets were set in an evacuated chamber, specifically the GLUE chamber[3,4] which was originally built by Gent University. We are indebted to Dirk Ryckbosch for arranging its use.

4 Results

Because of limited statistics, the original aim of identifying the populated states in ^{12}B could not be achieved. However the emission of deuterons and tritons was higher than expected. The data shown in Figure 1 was taken at 90°, and includes tagged photons in the entire range from 50-70 MeV. The abscissa is in units of the familiar parameter T/a, which unambiguously distinguishes between particle types in the ΔE-E telescopes. For clarity, the electron signals have been removed from this figure and the deuteron and triton peaks have been raised by a factor of ten.

5 Comparison with ^{12}C

For comparison with the heavy charged-particle emission for ^{12}C, we were fortunate that the measurement by Ruijter *et al.* was made with a tagged-photon energy of 75 MeV. This data is shown in Figure 2.

The ^{12}C data is for $30° - 90°$ and E_γ= 75 MeV. It has been assumed here that the angular distribution of the proton, deuteron and triton cross-sections follow the same trend. A small correction may be required to compare the $30° - 90°$ data from ^{12}C with the 90° data from ^{13}C, however it would not explain the large discrepancy in the cross-sections.

From the plots it seems that the emission of deuterons and tritons relative to protons is grater in the case of ^{13}C than ^{12}C. These ratios are quantified in Table 1.

Element	$\frac{N_d}{N_p}$	$\frac{N_t}{N_p}$
^{12}C	0.0156	0.0123
^{13}C	0.0479	0.0224

Table 1. Ratios of the number of deuterons and tritons to the number of protons.

No absolute cross-sections were obtained, each value given in the table is relative to the proton counts for that element.

6 Discussion

We see that for ^{13}C there are nearly 3 times as many deuterons emitted per proton compared to ^{12}C, and approximately twice as many tritons. If the extra neutron in ^{13}C was just a spectator, we would not expect this. The ^{12}C would be the principle reaction object. So we conclude that the weak coupling model, which certainly explains photo-nuclear reaction data in the GDR region, is not applicable here.

For the case of triton emission, the momentum mismatch is much too large for one massive particle to be ejected from the nucleus on its own. The reaction is more likely to proceed via a two nucleon knockout mechanism. Comparing the Q value for the reactions (γ, nt), (γ, dt) and (γ, pnt) we find that for ^{12}C they are around 15 MeV above those for ^{13}C, reducing the channels for triton emission from ^{12}C. This is not the case for the Q values for deuteron emission.

If we assume the reaction mechanism can be explained by the QDM, we see some consistency. There are more p-n pairs, so that the deuteron emission might be expected to increase for ^{13}C. However, the changes induced by adding an extra neutron to ^{12}C are expected to be around 10% rather than factors of two or three.

In the ^{12}C results from Kuzin *et al.*, it was found that the inclusion of admixtures to the GS of carbon was not sufficient to explain the population of states in ^{11}B. A macroscopic calculation which includes MEC terms and uses RPA techniques does a reasonable job of predicting the magnitude of the (γ, p) cross-section, unfortunately the code cannot handle odd-A nuclei.

^{12}C can viewed as a strongly clustered nucleus consisting of three ^{4}He nuclei. The valence neutron added to make ^{13}C interacts with the ^{12}C core and might break up the clustering. This effect would make p-n pairs more readily available for photon absorption in ^{13}C than in ^{12}C resulting in the enhancement of the deuteron and triton channels.

These results could also be evidence for strong final state interactions. It is well know that the $^{12}C(\gamma, pn)$ channel is strong at intermediate energies. If in ^{13}C the photon interaction is predominantly with the ^{12}C core, then (γ, pn) emission would also be expected to be high in ^{13}C. However, the valence neutron will interact with the outgoing proton possibly forming deuterium in a pickup type reaction, enhancing the $^{13}C(\gamma, d)$ channel with respect to $^{12}C(\gamma, d)$.

Being unable to resolve populations to residual states in ^{12}B, we may not be able to judge the merits of the different mechanisms. A follow up measurement which clearly identifies the residual states is required to more fully understand the physics which is behind the photo-emission process.

7 Summary

In the intermediate-energy region, significantly more deuterons and tritons were emitted from ^{13}C than from ^{12}C. The mechanism by which these particles are emitted is not well understood. No calculations are currently able to deal with the ^{13}C system, however, these results may be important in explaining photonuclear reaction mechanisms.

Acknowledgements

We would like to thank all the staff at the MAX-lab for their help and support during this experiment.

References

1. A. Kuzin, *Phys. Rev.* C **58**, 2167 (1998).
2. H. Ruijter, PhD thesis, Lund University, 1995.
3. D. Nilsson *et al.*, *Z. Phys.* A **335**, 239 (1990).
4. D. Ryckbosch *et al.*, *Nucl. Phys.* A **568**, 52 (1994).
5. L.J. Lindgren and M. Eriksson, *Nucl. Inst. Meth. Phys. Res. A* **294**, 10 (1990).
6. J.-O. Adler *et al.*, *Nucl. Inst. Meth. Phys. Res. A* **294**, 10 (1990).

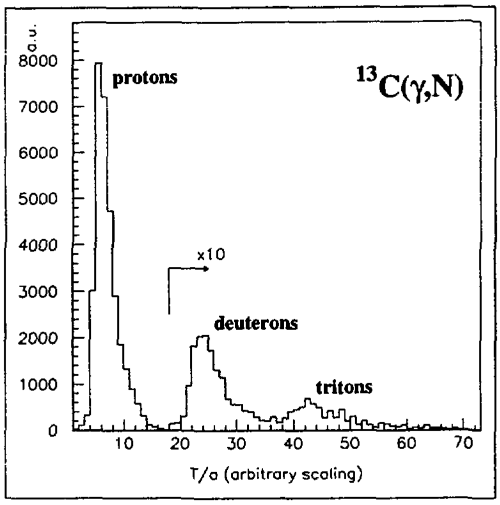

Figure 1. PI plot from the June 1998 experiment.

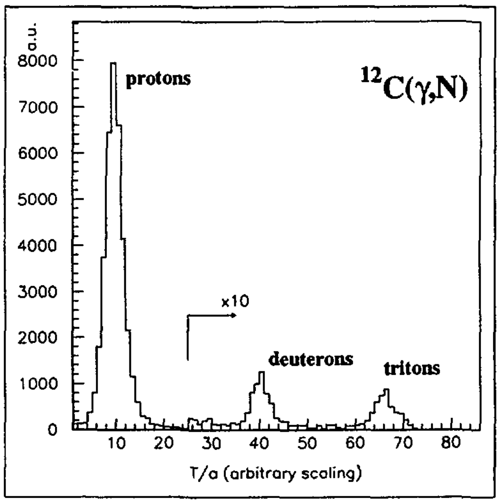

Figure 2. PI plot from Ruijter's PhD thesis, 1995.