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The $^{12}C(p,\gamma)^{13}N$ Cross Section near the $E_p = 0 \cdot 46$ MeV Peak

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Abstract

The $^{12}C(p,\gamma)^{13}N$ cross section in the neighbourhood of the $E_p = 0 \cdot 46$ MeV peak has been measured using thin and thick targets, and fitted using R-matrix formulae. The best value for the radiation width of the first excited state of ^{13}N is $0 \cdot 53 \pm 0 \cdot 05$ eV. Reanalysis of earlier thick-target data gives values consistent with this result.

1. Introduction

There has been considerable controversy over the value of the radiation width of the $\frac{1}{2}^+$ first excited state of ^{13}N, which is reflected in the values adopted in the compilations of Ajzenberg-Selove: $\Gamma_\gamma^0 = 0 \cdot 45 \pm 0 \cdot 05$ eV (1981), $0 \cdot 64 \pm 0 \cdot 07$ eV (1986) and $0 \cdot 50 \pm 0 \cdot 04$ eV (1991). The value of Γ_γ^0 is of interest in several areas: in astrophysics, since $^{12}C(p,\gamma)^{13}N$ is a key reaction in the CNO cycles (Rolfs and Rodney 1988); in isospin mixing and distortion, through comparison of E1 transition strengths in the mirror nuclei ^{13}C and ^{13}N (Barker and Ferdous 1980, and references given therein); in normalising related cross sections, such as that for $^{13}N(p,\gamma)^{14}O$ (Mathews and Dietrich 1984); and in testing models (Langanke *et al.* 1985).

Values of Γ_γ^0 have been obtained by fitting cross sections for the $^{12}C(p,\gamma)^{13}N$ reaction in the region of the peak centred at $E_p \approx 0 \cdot 46$ MeV. Other parameters determined in these fits are the resonance energy E_r, the level width Γ^0 and the peak cross section $\sigma_{\rm peak}$. Previous results are gathered in Table 1. Some quantities, such as the level width, have different definitions depending on the particular formula used to fit the data. The values in the table are for R-matrix fits, and the widths are 'observed' values (Lane and Thomas 1958). The above four parameters are not independent but satisfy

$$\sigma_{\rm peak} = 2 \cdot 826 \ {\rm MeV\,b} \times \Gamma_\gamma^0 / E_r \, \Gamma^0 \,, \tag{1}$$

where E_r is taken in the c.m. system. In Table 1, values derived using this relation are enclosed in braces. The lab and c.m. values of E_r, Γ^0 and Γ_γ^0 are related by the factor $0 \cdot 9226$ ($\approx$12/13)—values derived using this factor are in square brackets.

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The c.m. values of Γ_γ^0 given in Table 1 range from 0·45 to 0·67 eV, with most clustering near the higher end. We describe here a new measurement of Γ_γ^0, using both thin and thick ^{12}C targets.

Table 1. Parameter values from ^{12}C(p,γ)^{13}N data

Values in square brackets or braces are derived, as indicated in the text

E_r (keV)		Γ^0 (keV)		Γ_γ^0 (eV)		σ_{peak} (mb)	Ref.
lab	c.m.	lab	c.m.	lab	c.m.		
456(2)	[421]	35	[32]	0·63	[0·58]	0·12	A
		35	[32]	0·67	[0·62]	0·127	B
456·8(5)	[421·4]	37·6	[34·7]				C
460·5	[424·9]	36	[33]	{0·69}[a]	[0·63]	0·127	D
460	424	[35·2]	32·5	[0·682]	0·629	0·129	E
		34(1)[b]	[31]	[0·49]	0·45(5)		F
456·9	[421·5]	[36·1]	33·3(18)				G
457(1)	[422]	39(2)	[36]	{0·73}	[0·67]	0·125(15)	H

[A] Fowler *et al.* (1948); Fowler and Lauritsen (1949). [B] Seagrave (1951, 1952).
[C] Hunt and Jones (1953). [D] Hebbard and Vogl (1960); Vogl (1963).
[E] Fowler *et al.* (1967), fit to data of Vogl (1963). [F] Riess *et al.* (1968).
[G] Blatt *et al.* (1974). [H] Rolfs and Azuma (1974).

[a] Corresponds to formal width $\Gamma_\gamma = 1\cdot52$ eV.
[b] Identified as lab value by Clarkson (1973).

2. Experimental Procedure

Proton beams of up to 1 μA were accelerated in the Physics Department's 500 keV Van de Graaff generator. The beam spot size was 1·5 mm wide by 4 mm high. The energy was calibrated to an accuracy of ±1 keV using the 340 and 484 keV resonances in the ^{19}F(p,$\alpha\gamma$) reaction.

The effectiveness of beam current collection for the stopping targets used was checked using the plateau height method (Sargood 1982) applied to the spectrum measured with a surface barrier detector at a backward angle. The effectiveness of the Faraday cup used with thin targets was also checked using the same method. A very thin gold target was placed immediately in front of an aluminium stopping target. Protons scattered from the gold were also counted in the surface barrier detector, allowing the relative beam current to be monitored. The stopping target was then removed and the effectiveness of the Faraday cup was checked against this beam monitor. The difference between the charge collected and the charge inferred from the barrier height was usually less than 2% and at worst 3%.

The thicknesses of the thin self-supporting pure natural carbon targets were measured using Rutherford scattering. It was found that to get the Rutherford E^{-2} variation in scattering yield it was necessary to use a proton energy E_p of 250 keV or less, because of the effects of the ^{12}C + p resonance. Hence the measurements were made at 225 keV. The deduced thicknesses were checked by observing the loss of energy of protons scattered from very thin gold in a backward direction when one of the carbon targets was inserted immediately in front of the gold. The energy shift is about twice the carbon thickness and could be measured to about ±10%.

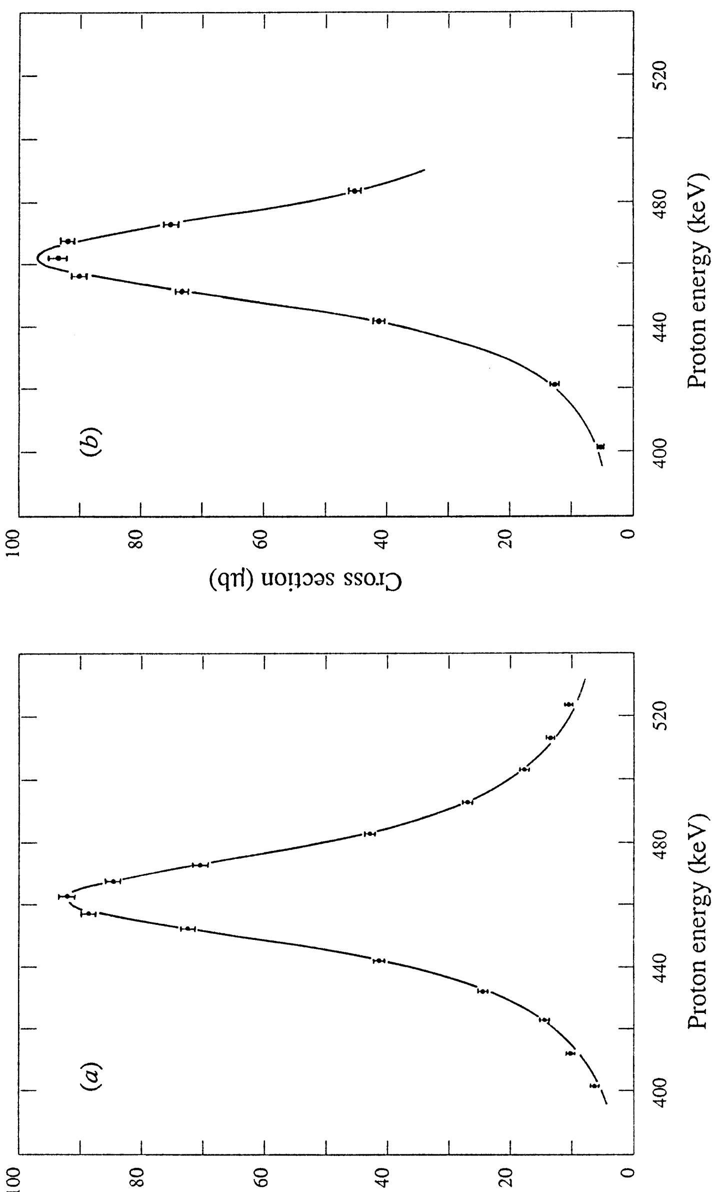

Fig. 1. Energy dependence of the $^{12}C(p,\gamma)^{13}N$ cross section. The experimental points are for the thin targets (*a*) C(1) and (*b*) C(2). The curves are best fits, using the *R*-matrix formula (2) including the Thomas factor.

The absolute photopeak efficiency of the 76 mm $\times$ 76 mm NaI(Tl) γ-ray detector was determined using several standard sources having γ-ray energies up to 2·6 MeV. This detector was at 90° to the beam direction and about 35 mm from the target beam spot. The γ-rays are isotropic because they originate from a $\frac{1}{2}^+$ state. The targets were also at 90° to the beam and were held in frames having negligible γ-ray absorption.

3. Results

Two thin carbon targets, taken from the same film, were used and each was measured to have a thickness of $20\cdot6\pm1\cdot5\ \mu g\,cm^{-2}$, corresponding to an energy loss of about 8·0 keV at the resonance energy. The two thin-target runs had slightly different geometries, leading to absolute photopeak efficiencies ($\pm$6%) of 0·0117 for C(1) and 0·0120 for C(2); the latter efficiency also applied to the thick-target measurements.

The γ-ray spectrum from the NaI(Tl) detector was simple because of the relatively high energy of the ^{13}N γ-ray (2·37 MeV) and also because the detector was well shielded. The only correction to the photopeak yield arose from the low-energy tail of the 2·6 MeV natural background γ-rays, and this was significant only when the ^{13}N γ-ray yield was very low, i.e. less than about 15 μb. At

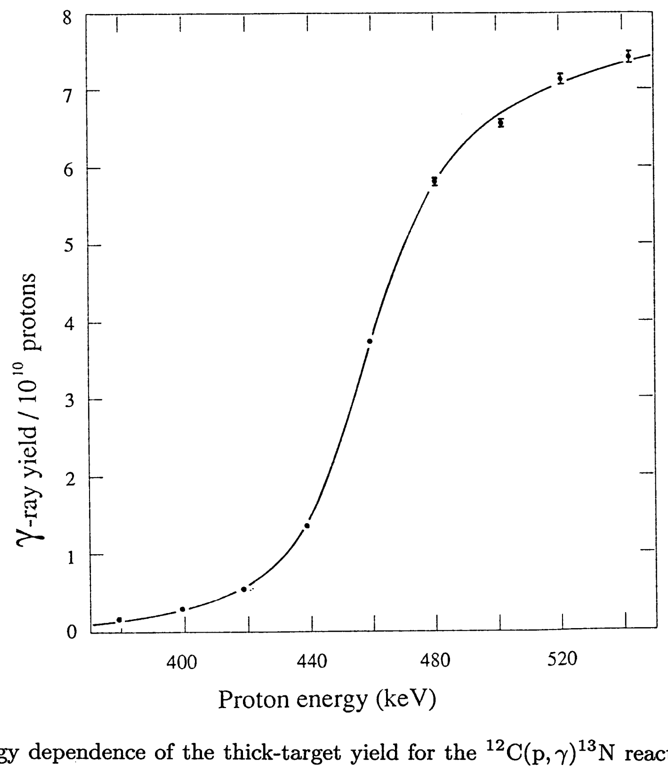

Fig. 2. Energy dependence of the thick-target yield for the $^{12}C(p,\gamma)^{13}N$ reaction. The best fits to the experimental points using the stopping powers of either Andersen and Ziegler or Janni are indistinguishable, and are shown by the curve.

these proton energies the yield due to the 1·1% of ^{13}C in the targets is utterly negligible (Hebbard and Vogl 1960).

The absolute cross section for the $^{12}C(p,\gamma)^{13}N$ reaction through the first resonance for the thin and thick targets is shown in Figs 1 and 2 respectively, where statistical errors only are shown and the curves are best fits as described in the following section.

4. Fits

Both R-matrix and complex-eigenvalue formulae have been used in previous fits to $^{12}C(p,\gamma)^{13}N$ data. In general, however, standard R-matrix formulae are not justified for reactions involving photons because the basic assumptions of R-matrix theory (Lane and Thomas 1958) are not satisfied. In addition to the internal contribution to the collision matrix, which resembles that for particle reactions, there should also be a channel contribution. Thomas (1952) showed that, in the one-level approximation, the channel contribution can be included by a slight modification of the standard cross-section formula. In this approximation, the $^{12}C(p,\gamma)^{13}N$ cross section may be written

$$\sigma(E)=\frac{\pi}{k_{\mathrm{p}}^2}\,\frac{2\gamma_{\mathrm{p}}^2\,P_{\mathrm{p}}(E)\,\Gamma_\gamma(E)\,[1\,+\,A(E_{\mathrm{r}}\,-\,E)]^2}{[E_{\mathrm{r}}\,-\,\gamma_{\mathrm{p}}^2\{S_{\mathrm{p}}(E)\,-\,S_{\mathrm{p}}(E_{\mathrm{r}})\}\,-\,E]^2+[\gamma_{\mathrm{p}}^2\,P_{\mathrm{p}}(E)]^2}\,. \qquad (2)$$

Here $P_{\mathrm{p}}(E)$ and $S_{\mathrm{p}}(E)$ are the penetration factor and shift factor of R-matrix theory, which are functions of the channel radius a, and γ_{p}^2 is the proton reduced width. The term involving A is the Thomas factor that takes account of the channel contribution. The formal proton width is

$$\Gamma_{\mathrm{p}}(E)=2\gamma_{\mathrm{p}}^2\,P_{\mathrm{p}}(E)\,, \qquad (3)$$

and we write the formal radiation width for the E1 transition as

$$\Gamma_\gamma(E)=2\gamma_\gamma^2\,E_\gamma^3\,, \qquad (4)$$

where γ_γ^2 is the gamma reduced width. We have assumed that $\Gamma_\gamma(E)/\Gamma_{\mathrm{p}}(E)\ll 1$. The observed widths are given by

$$\Gamma_{\mathrm{p}}^0(E)=\frac{\Gamma_{\mathrm{p}}(E)}{[1+\gamma_{\mathrm{p}}^2\,\mathrm{d}S_{\mathrm{p}}/\mathrm{d}E]_{E_{\mathrm{r}}}}\,,\qquad \Gamma_\gamma^0(E)=\frac{\Gamma_\gamma(E)}{[1+\gamma_{\mathrm{p}}^2\,\mathrm{d}S_{\mathrm{p}}/\mathrm{d}E]_{E_{\mathrm{r}}}}\,, \qquad (5)$$

and we denote the values of these at $E=E_{\mathrm{r}}$ by Γ^0 and Γ_γ^0, respectively. The formula (2) was used by Hebbard and Vogl (1960) and Fowler *et al.* (1967).*

Mahaux (1965), using formulae from complex-eigenvalue theory, found that he could not get a good fit to the $^{12}C(p,\gamma)^{13}N$ data in the one-level approximation,

* Fernandez *et al.* (1989) stated that Fowler *et al.* (1967) fitted the $^{12}C(p,\gamma)^{13}N$ data using only the three parameters E_{r}, Γ^0 and Γ_γ^0, but this is incorrect because Fowler *et al.* remarked, rather cryptically, that they used the Thomas (1952) factor.

but that this was possible if he included a constant background.

The thick-target yield is given by

$$Y(E)=\int_0^E \frac{\sigma(E')}{\epsilon(E')}\,\mathrm{d}E',\tag{6}$$

where $\epsilon(E)$ is the stopping power. The energy dependence of the γ-ray detection efficiency is not important because Γ^0 is small compared with $E_\gamma(E_r)=2\cdot37$ MeV. We use values of ϵ from the tables of either Andersen and Ziegler (1977) or Janni (1982), fitted by a quartic function of E over the range $E_p = 0\cdot2$ to $1\cdot0$ MeV. The integration in (6) is performed numerically.

In fitting the thin-target data, the cross section (2) must be averaged over the target thickness.

The thin-target data of Section 3 are fitted for fixed values of the channel radius a, with adjustable parameters E_r, γ_p^2, γ_γ^2 and A. From the best-fit values of these we calculate Γ^0 and Γ_γ^0 using equations (3)–(5). The values of E_r, Γ^0, Γ_γ^0 and A are insensitive to the choice of a; we give values for $a = 5\cdot0$ fm. The value of A is not well determined from these data alone, due to the limited range of E values; we take as a starting value that obtained by Hebbard and Vogl (1960), $A = 1\cdot185/0\cdot9226 = 1\cdot284\ \mathrm{MeV}^{-1}$, and the fitting process produces only small changes.

The results of fitting the data for targets C(1) and C(2) separately and together are given in Table 2, and the fits are shown in Fig. 1. With allowance for the uncertainties in the target thickness and gamma-detector efficiency, we take as the thin-target best value $\Gamma_\gamma^0 = 0\cdot50 \pm 0\cdot05$ eV.

Table 2. Parameters values (c.m.) from best fits to present thin- and thick-target $^{12}C(p,\gamma)^{13}N$ data

Target/ Stopping	a (fm)	E_r (keV)	γ_p^2 (MeV)	γ_γ^2 (10^{-8} MeV^{-2})	A (MeV^{-1})	Γ^0 (keV)	Γ_γ^0 (eV)	χ^2/DOF
Thin								
C(1)	5·0	424·3	1·324	3·87	1·24	35·6	0·491	1·42
C(2)	5·0	424·7	1·305	4·04	1·24	35·4	0·517	2·31
C(1) + C(2)	5·0	424·4	1·296	3·90	1·28	35·2	0·501	3·75
Thick								
A	5·0	423·3	1·465	4·65	1·24	36·9	0·559	2·63
B	5·0	423·2	1·495	4·93	1·24	37·2	0·586	2·80

[A] Andersen and Ziegler (1977). [B] Janni (1982).

In using equation (6) to fit the thick-target data of Section 3, we start from the thin-target values of Table 2 [C(1) fit] and adjust E_r, γ_p^2 and γ_γ^2. Separate fits are made using the stopping powers from either Andersen and Ziegler (1977) or Janni (1982). The resultant parameter values are included in Table 2, and the best fit is shown in Fig. 2. The thick-target best-fit value of Γ_γ^0 is taken as $0\cdot57{\pm}0\cdot05$ eV. There is a strong correlation between the values of γ_p^2 and γ_γ^2, or equivalently between Γ^0 and Γ_γ^0. If Γ^0 is fixed at the thin-target value, the best values of Γ_γ^0 are reduced by about $0\cdot01$ eV.

As the combined thin- and thick-target best value we take $\Gamma_\gamma^0 = 0\cdot53{\pm}0\cdot05$ eV.

5. Discussion

The best-fit values of E_r from Table 2, with an uncertainty of ± 1 keV from the beam energy calibration, are consistent with previous values given in Table 1 or obtained from ^{12}C + p elastic scattering and $^{12}C(^3He,d)^{13}N$ (Ajzenberg-Selove 1991). The values of Γ^0 in Table 2 are larger than most previous values, but similar values have been obtained, for example $\Gamma^0 = 36 \cdot 1 \pm 2 \cdot 8$ keV, determined from the $^{12}C(^3He,d)^{13}N$ reaction by Blatt *et al.* (1974).

Vogl's (1963) value of Γ^0_γ tends to have dominated previously adopted values (Rolfs and Azuma 1974; Fox *et al.* 1975; Mathews and Dietrich 1984; Langanke *et al.* 1985), because his table of cross section values shows a 3% uncertainty in the neighbourhood of the peak. This is, however, a relative error only, and Vogl normalised his cross section to Seagrave's absolute values. These various values of Γ^0_γ were discussed at greater length in Barker (1985).

Fowler *et al.* (1948) and Seagrave (1951) both made absolute thick-target measurements. They obtained yields at $E_p = 1 \cdot 00$ MeV of $7 \cdot 3 \times 10^{-10}$ and $7 \cdot 7 \times 10^{-10}$ γ/p, respectively. These may be compared with the yield obtained here of $7 \cdot 3 \times 10^{-10}$ γ/p for $E_p = 0 \cdot 54$ MeV. This corresponds to a yield at $E_p = 1 \cdot 00$ MeV of $8 \cdot 3 \times 10^{-10}$ γ/p for the stopping powers of either Andersen and Ziegler (1977) or Janni (1982). Although the present yield is higher, the extracted value of Γ^0_γ is smaller. Fowler *et al.* (1948), in their derivation of Γ^0_γ from equation (6), assumed that $\epsilon(E)$ is independent of E over the resonance, that $\sigma(E)$ can be written

$$\sigma(E) = \sigma_{\text{peak}} \frac{(\Gamma^0/2)^2}{(E_r - E)^2 + (\Gamma^0/2)^2} \tag{7}$$

with constant Γ^0, and that the lower limit of integration in (6) can be taken as $-\infty$. This leads to

$$Y(\infty) = \frac{\pi}{2} \frac{\sigma_{\text{peak}} \Gamma^0}{\epsilon}, \tag{8}$$

which, combined with (1), gives

$$\Gamma^0_\gamma = 0 \cdot 2253 \text{ MeV}^{-1} \text{ b}^{-1} \times \epsilon \, E_r \, Y(\infty) \, . \tag{9}$$

Fowler *et al.* equated their yield at $E_p = 1 \cdot 00$ MeV with $Y(\infty)$, and used values of ϵ calculated by Livingstone and Bethe (1937). Presumably Seagrave (1951, 1952) used the same approach. For $E_p = 0 \cdot 46$ MeV, Livingstone and Bethe gave $\epsilon_{\text{air}} = 9 \cdot 5 \times 10^{-15}$ eV cm^2 and $\epsilon_C/\epsilon_{\text{air}} \approx 0 \cdot 94$, suggesting $\epsilon = 8 \cdot 9 \times 10^{-15}$ eV cm^2. The numerical values given by Fowler *et al.* and Seagrave are consistent with equation (9) for $\epsilon \approx 8 \cdot 5 \times 10^{-15}$ eV cm^2. In comparison, at $E_p = 0 \cdot 46$ MeV Andersen and Ziegler (1977) and Janni (1982) gave $\epsilon = 7 \cdot 3 \times 10^{-15}$ and $7 \cdot 7 \times 10^{-15}$ eV cm^2, respectively. Our fits to the yield measured at $E_p = 1 \cdot 00$ MeV by Fowler *et al.*, made using equations (2) and (6) with our thin-target parameter values (apart from γ^2_γ) and with the $\epsilon(E)$ values of either Andersen and Ziegler or Janni, give $\Gamma^0_\gamma = 0 \cdot 49$ and $0 \cdot 51$ eV respectively, and similar fits to Seagrave's yield give $\Gamma^0_\gamma = 0 \cdot 51$ and $0 \cdot 53$ eV. These values are consistent with our best value of $\Gamma^0_\gamma = 0 \cdot 53 \pm 0 \cdot 05$ eV.

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