ANALYSIS OF THE $^{12}C(p, \gamma)^{13}N$ REACTION AT $E_p \leqslant 1$ MeV*

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The $^{12}C(p, \gamma)^{13}N$ reaction data are analyzed in terms of a modified direct-semidirect capture model, which accounts for the presence of broad resonances. The resonance at $E_p = 457$ keV is found to have to a good approximation pure single particle nature. Spectroscopic factor for the ground state of the ^{13}N nucleus is found to be equal 0.88 ± 0.11 and the astrophysical S-factor at 25 keV is found to be 1.74 ± 0.18 keV × barn.

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Among the subbarier radiative proton capture reactions the one on ^{12}C target nuclei is of particular interest from the astrophysical point of view as it constitutes the first step in the CNO cycle [1]. Direct measurement of its cross sections at solar energies, however, poses at present insurmountable experimental problems and therefore recourse to extrapolation of those cross section values from the experiments carried out at higher energies has to be made. In [2, 3] a new method of analyzing the radiative proton capture data has been suggested which seems to be particularly well suited for carrying out such a theoretical extrapolation. This method treats on equal basis as well the direct and semi-direct contributions to the cross section as the contribution from broad resonances and has proved its ability to describe the reaction cross sections in broad energy ranges [4–6]. Its main advantage over the traditional scheme of analysing such experimental data [7] consists in both numerical and conceptual simplicity. There is no longer a need for treating the shape resonance within the R-matrix approach with an energy dependent width and Thomas corrections of the tails in order to add (coherently) its contribution to that identified with the direct mechanism — a procedure involving adjustment of many parameters which

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in some instances only mock up physical processes and therefore could potentially lead to large extrapolation errors. In the present paper we demonstrate the ability of our method to describe the low energy $^{12}C(p, \gamma)^{13}N_{g.s.}$ reaction data over a range of 4.5 orders of magnitude in the cross section when effectively only two parameters are allowed to vary and the physical processes are treated explicitly, (although approximately) rather than simply mocked up. The impressive quality of the fit then lends credibility to the extrapolated to 25 keV value of the astrophysical S-factor as well as to the extracted value of the spectroscopic factor of the ground state of the ^{13}N nucleus.

It is well known that the gamma-yield from the $^{12}C(p, \gamma)^{13}N$ reaction at energies below 1 MeV is dominated by a $J^{\pi} = 1/2^+$ shape resonance located at $E_p = 457$ keV. It has been shown in [3] that such a resonance can be quantitatively understood in terms of the direct-semi-direct capture model when the interaction potential parameters in the entrance channel are properly chosen. In our approach the reaction amplitude is evaluated accordingly to the direct capture formula [8]. Resonances are generated by adjusting the geometry of the interaction potential well in the entrance channel and by imposing a particular energy dependence of the depth of this potential so as to account for the fact that the observed resonances not necessarily are of pure single-particle nature (see [3]). The semi-direct mechanism is accounted for by introducing an effective (polarization) charge which is both energy and radial distance dependent.

Our numerical studies have shown that in the present case, the observed position of the resonance ($E_p = 457$ keV) and its $1/2^+$ quantum characteristics require a combination of the values of the depth V_0 and the radius parameter r_0 of the (Saxon-Woods) interaction potential well at 457 keV which satisfy the equation:

$$V_0 \times r_0^{1.7} \simeq 89.6 \text{ MeV} \times \text{fm}^{1.7}. \tag{1}$$

These studies have shown also that the width of a pure single-particle resonance generated (using an energy independent interaction strength) at 457 keV depends linearly on r_0:

$$\Gamma_{s.p.}\,(\text{keV}) = 35.5 + 15.7 \times (r_0 - 1.2), \tag{2}$$

when r_0 is varied in a physically reasonable range and the diffuseness parameter a_V is kept equal 0.5 fm. Confronting Eq. (2) with the experimentally observed width of the resonance in question, $\Gamma_{exp} = 36.5 \pm 1.0$ keV [9, 10] allows us to assume that to a good approximation this resonance is of pure single-particle nature. So, in order to reproduce here within the framework of our approach the position and the width of the 2s resonance seen at 457 keV it is enough to take in the entrance channel an energy-independent Saxon-Woods interaction potential with $V_0 = 57.44$ MeV, $r_0 = 1.30$ fm and $a_V = 0.5$ fm. The full description of the measured excitation function requires additionally adjusting of the effective charge parameters. This charge was assumed to be given by the expression [4]:

$$e_{eff}(r) = 0.5e(1 + q(E_\gamma)f(r)), \tag{3}$$

where the energy dependence is given by

$$q(E_\gamma) = q_0 \tfrac{1}{2}\Gamma_{GDR}\{(E_\gamma - E_{GDR})^2 + \Gamma_{GDR}^2/4\}^{-1/2} \tag{4}$$

and the radial form factor $f(r)$ is taken either in Saxon-Woods or Saxon-Woods derivative form.

The achieved fit to the experimental data of Rolfs and Azuma [7] normalized in the peak to 102 μb (Barker and Ferdous [10]) is shown in Fig. 1. In the calculations only the E1 multipolarity transitions from the $s_{1/2}$ and $d_{3/2}$ partial waves were taken into account, the latter making less than 1% contribution to the yield for $E_p < 0.8$ MeV. The GDR parameters entering in the expression for $q(E)$ were taken accordingly to the paper of Berghofer et al. [11] as $E_{GDR} = 13$ MeV, $\Gamma_{GDR} = 9$ MeV. The coupling strength parameter

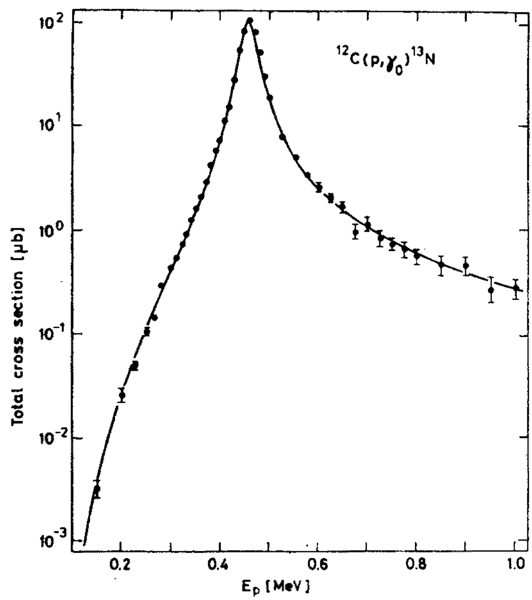

Fig. 1. Comparison of the experimental total cross section values with the theoretical excitation curve

q_0 was taken equal 9.0. For the final bound state of the captured proton a Saxon-Woods potential with $r_0 = 1.30$ fm, $a = 0.5$ fm and the depth adjusted to reproduce the separation energy was assumed. It is worth to note the excellent quality of the fit seen in Fig. 1 which goes over many orders of magnitude although only 2 parameters were allowed to vary.

From the fit shown in Fig. 1 we get for the spectroscopic factor of ^{13}N the value 0.88 which is in a reasonable agreement with those found in average by others. A summary of the values of this spectroscopic factor extracted by different experimenters and from different reactions is given in Table I.

For astrophysical purposes we have converted the cross section — theoretically extrapolated to 25 keV energy — into the so-called astrophysical S-factor [1]:

$$S(E) = \sigma(E)E \exp(2\pi\eta), \tag{5}$$

where η is the Sommerfeld parameter and E is the proton center-of-mass energy. The result is then $S_{E=25\,\mathrm{keV}} = 1.74$ keV × barn, a value which agrees within the experimental

TABLE I

Spectroscopic factors for the ^{13}N ground state from proton transfer reactions

S	Reaction	Reference
0.61	theory	[12]
0.56	theory	[13]
0.88 ± 0.11	$^{12}C(p, \gamma)$	present work
0.49 ± 0.15	$^{12}C(p, \gamma)$	[7]
0.53 ± 0.12	$^{12}C(d, n)$	[14]
0.74	$^{12}C(d, n)$	[15]
$0.78 - 1.35$	$^{12}C(d, n)$	[16]
0.48	$^{12}C(^{3}He, d)$	[17]
0.81	$^{12}C(^{3}He, d)$	[18]
0.68	$^{12}C(^{3}He, d)$	[19]
0.56–0.78	$^{12}C(^{3}He, d)$	[20]
0.70–1.48	$^{12}C(^{3}He, d)$	[21]
0.91	$^{12}C(\alpha, t)$	[22]
1.34	$^{12}C(\alpha, t)$	[23]
0.72	$^{12}C(^{7}Li, ^{6}He)$	[24]
0.25, 0.40	$^{12}C(^{10}B, ^{9}Be)$	[25]
0.62	$^{12}C(^{14}N, ^{13}C)$	[26]
0.29, 0.40	$^{12}C(^{16}O, ^{15}N)$	[27]

errors with those obtained by Rolfs and Azuma [7] (1.45 ± 0.20 keV $\times$ barn) and by Barker and Ferdous [10] ($1.54^{+0.15}_{-0.10}$ keV $\times$ barn).

In order to assess the possible errors of the extracted value of the spectroscopic factor for the ^{13}N nucleus as well as the values of q_0 and astrophysical S-factor we have performed a number of calculations in which we varied the values of the radius parameters r_0 both in entrance and in final bound channels, values of the GDR parameters and type of the effective charge radial form-factor. From these calculations we estimate the uncertainties of the extracted values of the spectroscopic factor on 13% and of the astrophysical S-factor on 10%. The value of the q_0 has an uncertainty of 20%.

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