ANC's for $^{14}N \rightarrow {}^{13}C + p$ and the Astrophysical S-factor for the $^{13}C(p,()^{14}N$ Reaction

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The $^{13}C(p,()^{14}N$ reaction is one of the important reactions of the CNO cycle. This reaction is a predecessor of the slowest CNO cycle reaction $^{14}N(p,()^{14}N$ which defines the rate of energy production in the CNO cycle. In addition, the $^{13}C(p,()^{14}N$ radiative capture turns out to be very important for the nucleosynthesis of the elements via the s-processes that use the helium burning reaction $^{13}C(\forall,n)^{16}O$ as a neutron generator [1]. A few measurements of $^{13}C(p,()^{14}N$ made to energies as low as E= 93 keV in the c.m. were reported in the literature before 1994 (see [2] and references therein). The extrapolation of the measured astrophysical S-factors down to zero energy led to the range of S(0)=5-12 keVb. In all the works previous to [2] only the capture to the ground state of ^{14}N was measured and the measured S-factor was renormalized to take into account the contributions ftom the captures to excited states. The most accurate and thorough measurements of the S-factor for $^{13}C(p,()^{14}N$, including the captures to the all first six excited states of ^{14}N, have been done in [2] leading to the values of S(0)=7.64 keVb and S(25 keV)=7.7 ± 1.0 keVb, which are higher than the recommended value of S(0)=5.5 keVb [3]. The higher value determined in [2] is due to the contribution of captures to the excited states.

There are two resonances in ^{14}N at c.m. energies below 1 MeV: E_{R1} = 417.9 keV and E_{R2} = 518.9 keV [2]. The first resonance is very narrow and does not affect the astrophysically important region of very low energies while the second resonance dominates the whole energy region around and below E_{R2} down to zero energy. There is also the third, very wide resonance in ^{14}N, located at E_{R3} = 1232 keV. This resonace also affects the low energy S-factor. The $^{13}C(p,()^{14}N$ reaction populates the first seven bounds states of ^{14}N [2] proceeding through resonant and direct captures. At zero energy the total direct capture S-factor is important [2]. Its extraction requires an accurate determination of the low energy direct contribution. In the conventional analysis applied in [2] the direct capture amplitudes were parametrized in terms of spectroscopic factors which cannot be determined experimentally. In addition, in the potential model applied to capture to tightly bound states, the capture amplitudes are very sensitive to the optical potentials describing the interaction of the colliding nuclei and the antisymmetrization effects, due to the contribution of the nuclear interior, are important.

In this work we reanalyzed the experimental data derived in [2] within the framework of the R-matrix approach. The R-matrix method allows us to treat in a consistent way, the resonant and nonresonant contribution, avoiding double counting. The R matrix nonresonant amplitudes are parametrized in terms of the asymptotic normalization coeiecients (ANC's) measured by us [4,5]. The only uncertainty in the nonresonant capture amplitudes comes from the dependence on the channel radius.

$$\sigma_{J_fJ_i} = \frac{\pi}{k^2}\frac{2J_i+1}{(2J_b+1)(2J_B+1)}\sum_{Il_i}|U_{J_fIl_i}|^2, \qquad (1)$$

where J_b *and* J_B are the spins of the colliding particles b, and I is the channel spin of the reaction, l_i is the initial relative orbital angular momentum of particles b and B and k is their relative momentum. It is important to note that the capture amplitude $U_{J_iIl_i} = U^R_{J_iIl_i} + U^{NR}_{J_iIl_i}$ is given by the sum of resonant and nonresonant amplitudes. It is clear ftom Eq. (1) that the interference between the resonant and nonresonant terms occurs only when both have the same channel spin I and initial orbital l_i what was not taken into account in [2].

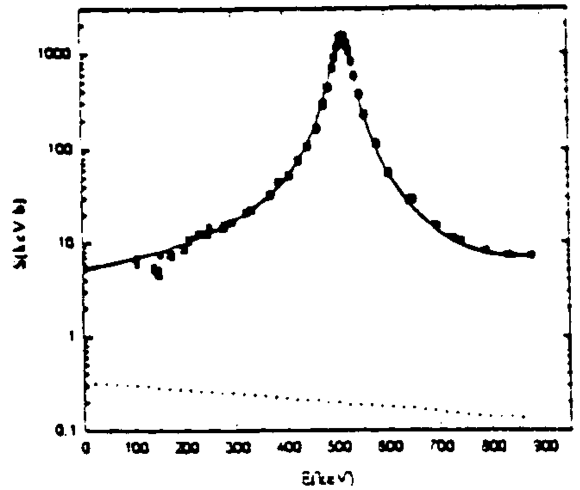

Figure 1: The astrophysical S-factor for the $^{13}C(p,()^{14}N$ radiative capture leading to the ground state in ^{14}N. The squares are the experimental data with error bars [2], the solid curve is the calculated S-factor, the dotted curve is the direct capture component.

The results of our analysis are as follows.

1. We find that the nonresonant captures are important to describe the data. Their effect is amplified due to interference with the resonance amplitudes.

2. 6 of 7 transitions to the bound states measured in [2] are reproduced using the ANC's determined in our previous works [4,5]. The fit is sensitive to the ANC values. Thus for the first excited state, for which the two measurements using the $^{13}C(^{14}N, ^{13}C)^{14}$N reaction [4] and the ^{13}C($^3He,d)^{14}$N reaction [5] gave conflicting results, the ANC can be extracted unambiguously. The ANC determined for the first excited state, E_x =2.3 1 MeV, $J^B = 0^+$, T =1, from the $^{13}C(^{14}N,^{13}C)^{14}$ N reaction is C_1^2 = 8.9 ± 0.9 fm^{-1} [4] while from the anaysis of the $^{13}C(^3He,d)^{14}N$ reaction the extracted ANC is significantly higher, C_1^2 = 16.0 ± 1.1 fm [5]. Note that a similar disagreement has also been found for the ANC's extracted from the heavy ion and (^3He, d) reactions for $^9Be+p \rightarrow {}^{10}B$ leading to the excited state of ^{10}B, when the isospin differs by 1 from the isospin of the ground state. The fit to the experimentally measured S-factor for the ^{13}C(p,()^{14}N capture allows us to state that the ANC for the first excited state, C_1^2=8.9 fm^{-1}, determined in [4], is preferred. For the third excited state, E_x = 4915 keV, $J^B = 0^-$, T= 1, we were not able to detemine the ANC from the heavy ion-induced proton transfer reaction [4]. The fit to the measured S-factor for the $^{13}C(p,()^{14}N$ capture to this excited

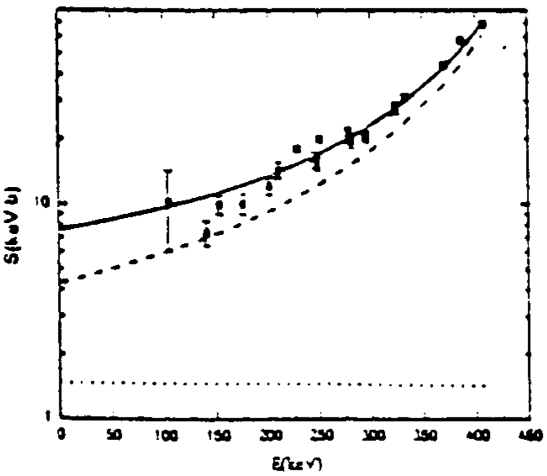

Figure 2: The total astrophysical S-factor for the $^{13}C(p,()^{14}N$ radiative capture leading to the ground and first six excited states in ^{14}N. The squares are the experimental data with error bars [2], the solid curve is the calculated S-factor, the dashed and dotted lines are the resonant and direct capture parts, correspondingly.

state allowed us to determine the ANC: C_3^2 25.4 fm^{-1}.

3. The results of the fits to the ground state capture S-factor and to the total S-factor allowing for the captures to the ground and first six excited states in ^{14}N at low energy are shown in Figs 1 and 2, respectively.

4. The calculated S-factor at zero energy, S(0)= 7.65 keVb, is in excellent agreement with the S(0)= 7.64 keVb determined in [2]. The total nonresonant S-factor at zero energy S(0)= 1.49 kevb contributes up to 35% of the the total resonance S(0)= 4.28 keVb value.

5. We confirm the higher value of the astrophysically important S(0)-factor for the $^{13}C(p,()^{14}$N capture. This means that there is less ^{13}C available for the reaction branch $^{13}C(\forall,n)^{16}O$ generating correspondingly fewer neutrons for the subsequent s-process nucleosynthesis.

6. The good description of experimental data by our calculations is another test of the indirect method which uses the ANC's determined from peripheral transfer reactions to extract astrophysical S-factors.

References

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