ELEMENTARY PARTICLE PHYSICS AND FIELD THEORY

RADIATIVE \(^{14}\text{N}\) CAPTURE AT ASTROPHYSICAL ENERGIES

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In the potential cluster model with forbidden states and classification of orbital cluster states according to Young’s schemes, the possibility is considered of describing the experimental data for the total cross sections of radiative \(^{14}\text{N}\) capture at energies from 25.0 meV (25 \(\times 10^{-3}\) eV) to 1.0 MeV. It is shown that on the whole it is possible to successfully explain the behavior of these cross sections outside the resonant energy region on the basis of the E1 transition from the \(^2S_{1/2}\) scattering wave with zero phase to the bound \(^2P_{1/2}\) state of the \(^{15}\text{N}\) nucleus in the \(^{14}\text{N}\) channel.

Keywords: nuclear physics, light atomic nuclei, low energies and astrophysical energies, elastic scattering, \(^{14}\text{N}\) system, potential description, radiative capture, astrophysical S-factors, total cross sections, thermonuclear reactions, primordial nucleosynthesis, potential cluster model, forbidden states, classification of orbital states according to Young’s schemes.

INTRODUCTION

References [1–4] considered astrophysical S-factors and total cross sections of some reactions of radiative capture of protons and neutrons in light atomic nuclei. In the analysis of such processes, we usually use calculational methods based on the potential cluster model (PCM) of light nuclei [5, 6]. In this approach the potentials of intercluster interactions for scattering processes [7, 8] are constructed on the basis of a description of the phases of elastic scattering. For bound states (BS) or ground states (GS) of nuclei in cluster channels, the intercluster potentials are constructed starting from a description of the binding energy and some important characteristics of such states. In this regard, for any system of nucleons the many-body nature of the problem is taken into account by a separation of the single-particle levels of such a potential into states that are allowed (AS) and states that are forbidden (FS) by the Pauli exclusion principle [1–6]. The choice of the PCM with FS in our consideration of such cluster systems and the thermonuclear processes associated with them is motivated by the fact that in many light atomic nuclei the probability of formation of nucleonic associations, i.e., clusters, and the degree of their isolation from one another are relatively high. This is confirmed by numerous experimental measurements and a number of theoretical calculations, obtained by different authors over the last 50–60 years [6].

The present paper is a continuation of a study of reactions of radiative capture of neutrons in light atomic nuclei that enter into various thermonuclear processes [9]. We direct our attention to the reaction \(^{14}\text{N}\rightarrow^{15}\text{N}\gamma\) of neutron capture at astrophysical energies. This process does not enter directly into any chain of primordial nucleosynthesis [10–12] underlying the formation and evolution of the observable Universe. However, it leads to the formation of the \(^{15}\text{N}\) nucleus, which is an intermediary in one of those reactions

\[ \ldots \text{^{14}C (n, \gamma) ^{15}C (\beta^-) ^{15}N (n, \gamma) ^{16}N} \ldots \]
and is supplementary to the $^{14}\text{C}(n,\gamma)^{15}\text{C}($β$)^{15}\text{N}$ process, increasing the number of $^{15}\text{N}$ nuclei taking part in further reactions of synthesis of heavier elements. Also, the total cross section of the $^{n}_{^1}\text{N}$ neutron capture process considered here is of the order of 1 mb at 1 keV, for example, and grows with decreasing energy as $1/\sqrt{E}$ whereas the cross section of the process $^{14}\text{C}(n,\gamma)^{15}\text{C}$ at the same energy is of the order of 1 μb and falls rapidly with decreasing energy as $E^{-1}$. The magnitudes of the cross sections of these reactions turn out to be comparable only at energies on the order of 100 keV and in both cases are about 10 μb. The two processes $^{14}\text{C}(n,\gamma)^{15}\text{C}$ and $^{14}\text{N}(n,\gamma)^{15}\text{N}$ demonstrate two types of behavior of capture cross sections as functions of energy – in the first case it falls while in the second case it grows with decreasing capture energy.

MODEL AND CALCULATIONAL METHODS

Moving on to an analysis of the total cross sections of $^{n}_{^1}\text{N}$-capture with formation of $^{15}\text{N}$, we note that the classification of orbital states of the $^{14}\text{N}$ nucleus according to Young’s schemes was qualitatively considered in [13]. Therefore, for the $^{n}_{^1}\text{N}$ system within the framework of the $1p$ shell, we have $\{1\} \times \{4442\} \rightarrow \{5442\} + \{4443\}$ [14]. The first of these schemes is consistent with the orbital angular momenta $L = 0, 2$ and is forbidden since there cannot be five nucleons in an $s$ shell, and the second scheme is forbidden and is consistent with orbital angular momenta 1 and 3 [14]. Thus, restricting ourselves to only the lower partial waves, we can say that a forbidden state is present in the potential of the $^2S_{1/2}$ wave whereas the $^2P_{1/2}$ wave has only an allowed state, which is found at the binding energy of the $^{n}_{^1}\text{N}$ system, –10.8333 MeV [15].

However, since we do not have complete tables of products of Young’s schemes for systems with number of particles greater than eight [16], which were used previously for such calculations [1–4, 17, 18], the above-obtained results must be taken only as a qualitative estimate of possible orbital symmetries in the ground state of the $^{15}\text{N}$ nucleus for the $^{n}_{^1}\text{N}$ channel. At the same time, it was specifically on the basis of this result that it was possible to provide a completely acceptable explanation for the available experimental data for radiative $p^{13}\text{C}$ [13] and $n^{13}\text{C}$ capture [1]. Therefore, we will also use here the above classification of states with respect to orbital symmetries, which gives a definite number of FS and AS in the partial intercluster interaction potentials.

The total cross sections of radiative capture $\sigma(EJ)$ in the potential cluster model have the following form (see, for example, [19] or [20–22]):

$$
\sigma_e(NJ, J_f) = \frac{8\pi Ke^2}{\hbar^2 q^3} \left(\frac{\mu}{(2S_1 + 1)(2S_2 + 1)}\right) \frac{J + 1}{J[(2J + 1)!]} A_J^2(NJ, K) \sum_{L_f, J_f} P_J^2(NJ, J_f, J_f) I_J^2(J_f, J_f),
$$

(1)

where we have the following expression for the orbital electric $EJ(L)$ transitions [19, 22]:

$$
P_J^2(EJ, J_f, J_f) = \delta_{S_f, S_i} \left[(2J + 1)(2L_f + 1)(2J_f + 1)(2J_f + 1)\right] \left(L_f J_f J_f\right)^2 \left[L_f S_f J_f\right]^2,
$$

$$
A_J(EJ, K) = K J^J \mu^J \left(\frac{Z_1}{m_1} + (-1)^J \frac{Z_2}{m_2}\right), I_J(J_f, J_f) = \left\langle \chi_i \right| R_J^J \left| \chi_i \right\rangle.
$$

Here $\mu$ is the reduced mass of the colliding particles, $q$ is the wave number of the particles in the initial channel, $L_f, L$, $J_f$ and $J$ are the angular momenta of the particles in the initial ($i$) and final ($f$) channels, $S_i$ and $S_f$ are spins, $m_1, m_2, Z_1, Z_2$ are the masses and charges of the particles in the initial channel, $K^J$ and $J$ are the wave number and angular momentum of the $\gamma$ photon in the final channel, $I_J$ is the integral over the wave functions of the initial and final states as functions of the relative motion of the clusters with intercluster distance $R$, and $N$ is the $E$ or $M$ transitions of the $J^J$ multipolarity from the initial $J$ to the final $J_f$ state of the nucleus [20]. We emphasize that in our calculations here and
previously [20] we never used such a concept as a spectroscopic factor (see, for example, [19]), i.e., its magnitude is simply taken to be equal to unity.

To perform our calculations of total cross sections, we rewrote our computer program based on the finite-difference method (FDM) [22]. The program was translated to the computing language Fortran-90, which made it possible to significantly increase the speed and accuracy of all the calculations and, for example, to obtain more accurate values of the binding energy of the nucleus in the two-particle channel. Besides the FDM, we also used the variational method (VM) with expansion of the wave function (WF) over a non-orthogonal Gaussian basis and independent variation of the expansion parameters [2, 22, 23]:

\[ \Phi_L(R) = \frac{\chi_L(R)}{R} = R^L \sum_i C_i \exp(-\beta_i R^2). \]

Here \( \beta_i \) are the variational parameters and \( C_i \) are the expansion coefficients. The variational program [22] was also translated into Fortran-90 and was used as a control of the calculational accuracy of the FDM of the binding energy and the form of the wave function of the BS.

Within the framework of the VM with expansion of the WFs over a non-orthogonal Gaussian basis, we solved the generalized matrix problem of eigenvalues and eigenfunctions of the form (see, for example, [22, 23]):

\[ \sum_i (H_{ij} - EL_{ij}) C_i = 0. \]

Here \( H_{ij} \) is the Hamiltonian matrix, \( L_{ij} \) is the matrix of overlap integrals, which for expansion of the WFs over an orthogonal basis leads to the unit matrix \( I_{ij} \), \( C_i \) are the eigenvectors of the problem, and \( E \) are the eigenenergies of the system. A simple numerical algorithm for solution of such a problem, having a simple programmatic implementation, was considered in [22, 24].

The calculations presented here gave an exact value for the mass of the neutron [25] with mass of the \( ^{14}\text{N} \) nucleus equal to 14.003074 amu [26]. The constant \( \frac{\hbar^2}{m_0} \) was taken to be equal to 41.4686 MeV·fm\(^2\).

**TOTAL CROSS SECTIONS OF \( n^{14}\text{N} \) CAPTURE**

To describe the total cross sections of radiative capture, as in our previous works [1–4], we consider the E1 transition from the non-resonant \( ^2S_{1/2} \) scattering wave at energies up to 0.5 MeV to the doublet \( ^2P_{1/2} \) bound state of the \( n^{14}\text{N} \) clusters in the \( ^{15}\text{N} \) nucleus. Here, it is namely the \( ^2P_{1/2} \) state that is being compared to the \( ^{15}\text{N} \) ground state with \( J^\pi, T = 1^+, 0 \) [15]. However, in general the \( ^{15}\text{N} \) ground state in the \( n^{14}\text{N} \) channel should be represented as a mixture of the doublet \( ^2P_{1/2} \) state and the quartet \( ^4P_{1/2} \) state, which in the given case is not explicitly taken into account as mean effective potentials are being used. In the calculations of the capture total cross sections the nuclear part of the intercluster potential of the \( n^{14}\text{N} \) interaction is represented, as usual, as a Gaussian [1]

\[ V(r) = -V_0 \exp(-\alpha r^2). \]

For the potential of the \( ^2S_{1/2} \) wave with one FS, we used the parameter values based on the assumption that its phase is equal to zero in the considered energy region:

\[ V_S = 22.15 \text{ MeV}, \ \alpha_S = 0.07 \text{ fm}^2. \quad (2) \]

Calculation of the \( ^2S_{1/2} \) phase with such a potential without a Coulomb interaction at energies from 0 to 0.5 MeV leads to values in the range \((0 \pm 2)^\circ\).
The potential without FS of the bound \( ^2P_{1/2} \) state should correctly reproduce the binding energy of the ground state of the \(^{15}\text{N} \) nucleus with \( J^\pi, T = 1/2–, 1/2 \) in the \(^{14}\text{N} \) channel at \(-10.8333 \) MeV \([15]\) and reasonably describes the root-mean-square radius of \(^{15}\text{N} \), whose experimental value is equal to 2.612(9) fm \([15]\) versus the experimental radius of \(^{14}\text{N} \) equal to 2.560(11) fm \([15]\) and zero charge radius of the neutron with its mass radius equal to the radius of the proton 0.8775(51) fm \([25]\). As a result, we obtain the following parameter values for the GS potential of the \(^{15}\text{N} \) nucleus in the \(^{14}\text{N} \) channel:

\[
V_{gs} = 55.44220 \text{ MeV}, \quad \alpha_{gs} = 0.1 \text{ fm}^{-2}. \quad (3)
\]

This potential leads to the binding energy \(-10.83330001 \) MeV for FDM accuracy \(10^{-8} \) MeV, root-mean-square charge radius 2.57 fm and mass radius 2.58 fm. For the asymptotic constant (AC), written in dimensionless form \([27]\) as \( \chi_l(R) = \sqrt{2k_0} C_0 W_{nl+1/2}(2k_0R) \) in the interval 7–13 fm, we obtained the value 4.94(1). The error in the constant is determined by averaging it over the above-indicated distance interval. Mukhamedzhanov and Timofeyuk \([28]\) give for this quantity the value 5.69(7) fm\(^{1/2}\), which after scaling to dimensionless form for \( \sqrt{2k_0} = 1.184 \) gives 4.81(6). Such a rescaling is needed since they used another definition of the AC: \( \chi_l(R) = CW_{nl+1/2}(2k_0R) \), which differs from the value used here by the factor \( \sqrt{2k_0} \).

For an additional check of the calculation of the GS energy, we used the variational method \([22]\), which already on a grid with \( N = 10 \) dimensions and independent variation of parameters for potential (3) allowed us to obtain the energy value \(-10.83330000 \) MeV. The parameters of the variational radial WF are listed in Table 1, where the magnitude of the errors does not exceed \(10^{-8} \) \([22]\). The AC in the region 7–14 fm is equal to 4.9(1), and the charge radius does not differ from the value obtained in the FDM calculations. Since the variational energy decreases with increase of the number of dimensions of the basis and gives an upper bound for the true binding energy while the finite-difference energy increases with decrease of the step size and increase of the number of steps \([1, 2, 22]\), it is possible to assign the mean value as the real binding energy in such a potential: \(-10.833300005(5) \) MeV. Thus, the accuracy of the binding energy of the nucleus, found by two methods (FDM and VM) using two different computer programs, is found to an accuracy of \( \pm 0.5 \cdot 10^{-9} \) MeV = \( \pm 5 \) meV.

Moving on to a direct description of the results of our calculations, we note that the available experimental data on the total cross sections of radiative \(^{14}\text{N} \) capture were obtained using the online database \([26]\), where the actual data are listed in \([29–31]\). They were obtained for the energy region 25 meV – 65 keV and are shown in Fig. 1 together with the results of our calculation (continuous curve) of the total cross sections of radiative \(^{14}\text{N} \) capture for energies below 1.0 MeV for transitions to the ground state of the \(^{15}\text{N} \) nucleus with the above-listed potentials (2) and (3) without allowance for resonances below 1.0 MeV. The experimental results of different research groups at 25 meV show values

| \( i \) | \( \beta_i \) | \( C_i \) |
|---|---|---|
| 1 | 2.763758336338713 \( \cdot 10^{-2} \) | \(-3.542736101468866 \cdot 10^{-4} \) |
| 2 | 5.252886535294879 \( \cdot 10^{-2} \) | \(-6.58446650462019 \cdot 10^{-3} \) |
| 3 | 9.444752983481111 \( \cdot 10^{-2} \) | \(-4.6797477384075 \cdot 10^{-2} \) |
| 4 | 1.088660404093062 \( \cdot 10^{-1} \) | \(1.318491526218144 \cdot 10^{-2} \) |
| 5 | 1.503846884800729 \( \cdot 10^{-1} \) | \(-1.087314408835770 \cdot 10^{-1} \) |
| 6 | 2.226413018972464 \( \cdot 10^{-1} \) | \(-8.992256982354141 \cdot 10^{-2} \) |
| 7 | 2.684402252313877 \( \cdot 10^{-1} \) | \(-5.74598590090638 \cdot 10^{-2} \) |
| 8 | 3.736191607656845 \( \cdot 10^{-1} \) | \(-2.834463978909703 \cdot 10^{-2} \) |
| 9 | 7.499707281247036 \( \cdot 10^{-1} \) | \(-1.302287964205851 \cdot 10^{-4} \) |
| 10 | 6.009438691088970 | \(2.060489845515652 \cdot 10^{-6} \) |

The potential without FS of the bound \(^{2}\text{P}_{1/2} \) state should correctly reproduce the binding energy of the ground state of the \(^{15}\text{N} \) nucleus with \( J^\pi, T = 1/2–, 1/2 \) in the \(^{14}\text{N} \) channel at \(-10.8333 \) MeV \([15]\) and reasonably describes the root-mean-square radius of \(^{15}\text{N} \), whose experimental value is equal to 2.612(9) fm \([15]\) versus the experimental radius of \(^{14}\text{N} \) equal to 2.560(11) fm \([15]\) and zero charge radius of the neutron with its mass radius equal to the radius of the proton 0.8775(51) fm \([25]\). As a result, we obtain the following parameter values for the GS potential of the \(^{15}\text{N} \) nucleus in the \(^{14}\text{N} \) channel:

\[
V_{gs} = 55.44220 \text{ MeV}, \quad \alpha_{gs} = 0.1 \text{ fm}^{-2}. \quad (3)
\]
of the total cross sections in the interval 75–80 mb, and are represented in Fig. 1 by a filled circle symbol. For example, in one of the most recent works [30] the value 80.3(6) mb was obtained. The results of our calculation with the above-listed potentials provide a complete description of the data on the capture cross sections to the GS at 25 meV, but do not reproduce the measurements of [31] at 65 keV since they do not take account of transitions to excited but bound states in the $^{14}$N channel of the $^{15}$N nucleus. Further experimental data for the energy region up to 1 MeV in the online database [26] are absent, and additional experimental results could not be found.

If for comparison we use the $^{2}\Sigma_{1/2}$ scattering potential with zero phases and zero depth, which does not contain FS, i.e., is not in agreement with the above-cited classification of FS and AS according to Young’s schemes, the calculated values of the cross sections we obtain for the same GS potential are found to be much higher than all the experimental data, as is shown in Fig. 1 by the dotted curve.

In order to correctly describe the data [31] at 65 keV, it is necessary to modify the potential of the $^{2}\Sigma_{1/2}$ wave and assign its depth as

$$V_S = 32.0 \text{ MeV}, \quad \alpha_S = 0.1 \text{ fm}^{-2}. \quad (4)$$

The phase of such a modified potential is also found to lie in the vicinity of zero, and the capture cross sections are shown in Fig. 1 by a dashed curve. However, the results of calculation with such a scattering potential no longer agree with the data in [29, 30] at 25 meV.

For the sake of an example, let us consider another variant of the GS potential of the $^{15}$N nucleus in the $n^{14}$N channel with a somewhat smaller width than in (3):

$$V_{gs} = 87.0071743 \text{ MeV}, \quad \alpha_{gs} = 0.2 \text{ fm}^{-2}, \quad (5)$$

which leads to the same binding energy $-10.83330002$ MeV, charge radius 2.57 fm, mass radius 2.55 fm, and AC equal to 2.65(1) in the interval 5–10 fm. Results of calculations for the total cross sections of $n^{14}$N capture with such a potential of the BS and scattering interaction in the form (4) are shown in Fig. 1 by the dash–dot curve, which lies

![Fig. 1. Total cross sections of radiative $n^{14}$N capture. Experimental points: $\bullet$ – [29, 30], $\circ$ – [31]. Curves: calculated values of the total cross sections for the potentials listed in the text.](image-url)
a little below the results for the first combination of potentials (2) and (3) and completely describes the available experimental data at 25 meV. However, it should be noted that the value of the AC for such a GS potential turns out to be almost two times smaller than the results of [28].

Since the calculated cross section is almost a straight line for energies from 25 meV to 10 keV, it can be approximated by a simple function of the form

$$\sigma_{ap}(\mu b) = \frac{445.0843}{\sqrt{E_e(\text{keV})}}.$$  

The value of the constant 445.0843 $\mu$b·$k$ev$^{1/2}$ was determined from one point in the calculated cross sections (the continuous curve in Fig. 1) for the minimum energy equal to 10 meV for the first variant of the $^2S_{1/2}$ elastic scattering potential with parameters (2) and BS (3). The absolute value

$$M(E) = \left| \frac{\sigma_{ap}(E) - \sigma_{theor}(E)}{\sigma_{theor}(E)} \right|$$

of the relative deviation of the approximate value of the cross section ($\sigma_{ap}$) given by the above function from the calculated theoretical cross section ($\sigma_{theor}$) in the region up to 10 keV does not exceed 0.9%. It is entirely realistic to suppose that this form of dependence of the total cross section on the energy will be preserved at lower energies. Therefore, we can estimate the magnitude of the cross section, for example, at 1 meV ($10^{-6}$ eV = $10^{-9}$ keV) to be on the order of 14.1 $\mu$b.

CONCLUSIONS

It is clear from the above obtained results that in the given system it is entirely possible to match the description of the total cross sections of radiative capture at low energies with the characteristics of the BS, including the AC, of the $^{15}$N nucleus in the $^{14}$N channel on the basis of the above-considered combination of GS potential (3) and scattering potential (2). In other words, if we fix the parameters of the GS potential of the $^{15}$N nucleus in the $^{14}$N channel on the basis of a correct description of its characteristics then it is entirely possible, on the basis of a classification of the FS and the AS according to Young’s schemes, to find a scattering potential that allows a correct description of both the elastic scattering phases, equal to zero in the given case, and the magnitudes of the total cross sections of the process of radiative $n^{14}$N capture at 25 meV.

Note that $n^{14}$N capture is already the seventh process of radiative capture of neutrons in light nuclei, whose cross section at astrophysical energies has been successfully described overall on the basis of the potential cluster model with FS and classification of cluster states according to Young’s schemes at astrophysical energies. Previously, we considered the reactions $n^2$H [32], $n^4$Li [33], $n^7$Li [34], $n^{12}$C, $n^{13}$C [35] and $n^{14}$C capture [36] and eleven reactions of charged particle capture in light nuclei with a 1p shell [2, 13]. All of them enter into various thermonuclear cycles and processes of primordial nucleosynthesis of the Universe.

However, having no experimental data for either the total capture cross sections or the differential cross sections of elastic $n^{14}$N scattering in the region up to 0.5–1.0 MeV, it is difficult to make any definite and final conclusions about the depth or even the shape of the elastic scattering potential in the $^2S_{1/2}$ wave. Apparently, its magnitude has a major effect on the results of calculations of the total cross sections of radiative $n^{14}$N capture since the GS potential is fixed via its characteristics completely unambiguously, as was obtained earlier, for example, for the $p^{13}$C channel in the $^{14}$N nucleus [13]. Future measurements of the differential cross sections of elastic $n^{14}$N scattering up to 0.5–1.0 MeV with minimal energy step would allow a detailed phase analysis, and on its basis to obtain a more accurate shape of the $^2S_{1/2}$ elastic scattering phase. This, in turn, would make it possible to more accurately determine the characteristics of the corresponding elastic scattering potential and more accurately calculate the total cross sections of radiative $n^{14}$N capture, especially with allowance for resonances below 1.0 MeV.
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