Radiative capture on neutron rich nuclei

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ABSTRACT

The \((n, \gamma)\)–cross sections for neutron–rich oxygen isotopes have been calculated in the direct capture model. The experimental data for \(^{18}\text{O}(n, \gamma)^{19}\text{O}\) can be reproduced using this model. Compared to previous work the cross section for \(^{19–21}\text{O}(n, \gamma)^{20–22}\text{O}\) are enhanced considerably by factors between four and 300.

1. INTRODUCTION

In the last years the importance of the direct–reaction (DI) mechanism in nucleosynthesis has been realized. The DI may even dominate over the compound–nucleus (CN) reaction mechanism in nuclear processes relevant for nucleosynthesis. This can be the case for primordial and stellar nucleosynthesis, f. i. in neutron–induced reactions in the inhomogenous big–bang scenario\(^1\–3\), in many solar nuclear reactions\(^4\), in the famous triple–alpha process leading to the creation of carbon\(^5\), or in nuclear reactions of the r–process involving magic–shell nuclei and nuclei far from stability\(^6\).

In this work we calculate cross sections of neutron–capture on oxygen isotopes. The reaction rates for these reactions are of importance in the inhomogeneous big–bang scenario\(^7\–8\) as well as in the \(\alpha\)–rich freeze out of the neutron–rich hot neutrino bubble in supernovae type II\(^9\–10\). We investigate the capture reaction \(^{18}\text{O}(n, \gamma)^{19}\text{O}\) at thermal (\(0.025\text{ eV}\)) and thermonuclear (30 keV) projectile energies and compare the calculated cross sections with the experimental data. Using the same methods we also calculate the cross sections for the neutron–capture reactions \(^{19–21}\text{O}(n, \gamma)^{20–22}\text{O}\) in the thermal and thermonuclear energy range.

In section 2 the folding procedure for the determination of the optical and bound–state potentials is introduced. In section 3 we discuss the model necessary for the calculation of direct capture (DC) cross sections. The method of bound states embedded into continuum (BSEC) allows including isolated CN–resonances in the DC–cross section. In section 4 the calculations and results for the neutron capture cross sections for some neutron–rich oxygen isotopes are presented and discussed. Finally, in the last section a short summary is given.

2. FOLDING PROCEDURE

The folding procedure is used for calculating the nucleon–nucleus potentials in order to describe the elastic scattering data and the bound states. This method was already applied successfully in describing many nucleon–nucleus systems. In the folding approach the nuclear density \(\rho_A\) is folded with an energy and density dependent NN interaction \(v_{\text{eff}}\)\(^\text{11,12}\):

\[
V(R) = \Lambda v_{\text{eff}}(R) = \lambda \int \rho_A(\vec{r}) v_{\text{eff}}(E, \rho_A, |\vec{R} - \vec{r}|) d\vec{r}
\]

with \(\vec{R}\) being the separation of the centers of mass of the two colliding nuclei. The normalization factor \(\lambda\) is adjusted to elastic scattering data and to bound– and resonant–state energies. The potential obtained in this way ensures the
correct behavior of the wave functions in the nuclear exterior. At the low energies considered in nucleosynthesis the imaginary parts of the optical potentials are small and can often be neglected.

In the folding approach the nuclear densities $\rho_A$ for stable nuclei are derived from experimental charge distributions. For unstable nuclei these densities are determined with the help of the relativistic mean field theory (RMFT). The RMFT describes the nucleus as a system of Dirac nucleons interacting via various meson fields. In the last few years this theory has turned out to be a very successful tool for the description of many nuclear properties (for example binding energies and charge radii for stable isotopes).

3. REACTION MECHANISMS AND MODELS

In nuclear reactions two extreme types of reaction mechanisms can exist: the compound–nucleus (CN) and the direct (DI) process. In the CN mechanism the projectile merges in the target nucleus and excites many degrees of freedom of the CN. The excitation proceeds via a multistep process and therefore has a reaction time typically of the order $10^{-16}$ s to $10^{-20}$ s. After this time the CN decays into various exit channels. The relative importance of the decay channels is determined by the branching ratios to the final states. In the DI process the projectile excites only a few degrees of freedom (e.g. single–particle or collective). The excitation proceeds in one single step and has a characteristic time scale of $10^{-21}$ s to $10^{-22}$ s. This corresponds to the time the projectile needs to pass through the target nucleus; this time is much shorter than the reaction time of CN processes.

In thermonuclear scenarios the projectile energy is well below the Coulomb and/or centrifugal barrier. At these energies the competition between different reaction mechanisms is quite complicated. At these energies the CN formation may be suppressed, because there may exist no CN levels that can be populated, especially in light, magic and far–off–stability nuclei.

In this work the theoretical cross sections are given through the DC–contribution. The theoretical cross section $\sigma^{th}$ is obtained from the DC cross section $\sigma^{DC}$ by

$$\sigma^{th} = \sum_i C_i^2 S_i \sigma_i^{DC} .$$

The sum extends over the ground state and excited states in the final nuclei, where the spectroscopic factors $S_i$ are known. The isospin Clebsch–Gordan coefficients are given by $C_i$. The DC cross sections $\sigma_i^{DC}$ are essentially determined by the overlap of the scattering wave function in the entrance channel, the bound–state wave function in the exit channel and the multipole transition–operator. The radial dependence of the DC–integral is in our case determined uniquely by the folding potentials.

Isolated CN–resonances with known resonance energy and width can be incorporated into the nonresonant DI cross section by BSEC which allows a simultaneous calculation of the resonant and non–resonant contributions of the cross sections. In this approach the scattering wave function is calculated using an adequate energy–dependent potential generating single–particle resonances and reproducing effects caused by their coupling with complicated bound states into the continuum.

4. CALCULATIONS AND RESULTS

The density distributions of $^{18}$O to $^{22}$O were derived with the help of RMFT. In the entrance channel the normalisation factor $\lambda$ given in Eq. of $^{18}$O+n was adjusted to reproduce the total cross section. For the other
Figure 1: Level scheme for the reaction $^{18}\text{O}(n,\gamma)^{19}\text{O}$ and comparison of the DC cross section for $^{18}\text{O}(n,\gamma)^{19}\text{O}$ with the experimental data\textsuperscript{24,26,27}.

Reactions the $\lambda$ were adjusted to reproduce the same volume integral $J = 578.33\text{MeV fm}^3$ as for the folding potential for $^{18}\text{O}+n$ elastic scattering. In the exit channels the $\lambda$ were fixed by the neutron separation energy from the final nuclei. The folding potentials of Eq. 1 were determined with the help of the computer code DFOLD\textsuperscript{20}.

The spectroscopic factors for one–nucleon transfer of the oxygen isotopes were determined from shell–model calculations in the sd–shell with an effective nucleon–nucleon interaction derived by Wildenthal\textsuperscript{21}. For these calculations the programs GENESIS, RITSSCHIL, DIA\textsuperscript{22} and SPECTROS\textsuperscript{23} were used. The resonance energies and widths of $^{19}\text{O}$ used for the BSEC–calculations of $^{18}\text{O}(n,\gamma)^{19}\text{O}$ are listed in Ref. 24. For the direct–capture calculations Eq. 2 the code TEDCA\textsuperscript{25} was used. For the BSEC–calculations the code TEDCA was generalized to include this approach.

Let us first discuss the reaction $^{18}\text{O}(n,\gamma)^{19}\text{O}$. For this reaction experimental reaction data at the thermal energy (0.025 meV) and around the $3/2^-$–resonance at 625 keV are available. The value of the cross section at 23.3 keV is given by $\approx 8 \pm 1\mu\text{barn}$\textsuperscript{26,27}. We consider this reaction as a test for our DC–model.

The level scheme for this reaction is shown on the left side in Fig. 1. There are two types of E1–transitions relevant for the energy range between thermal and thermonuclear energies. The first one is from an s–wave in the entrance channel exciting the negative–parity state $3/2^-$ in the final nucleus which is just bound by about 12.1 keV. Even so this transition has a very low Q–value it still reproduces the experimental cross section $\sigma_{\text{therm}} = 0.16\text{mb}$ at 0.025 eV with a reasonable spectroscopic factor of 0.331. In this case the transition matrix has contributions up to 500 fm and has a maximum at about 100 fm. This transition gives the well–known $1/v$–behavior (see Fig. 1). The second type of transition comes from an initial p-wave and excites the positive–parity states $5/2^+, 3/2^+, 1/2^+$ in the final nucleus. These transitions have a $v$–behavior (see Fig. 1). Furthermore as can be seen from Fig. 1, the resonance $3/2^-$ at 625 keV can be described by the BSEC which was discussed before.

The contributions of the different transitions to the cross section at 30 keV and their sum for the $^{18–21}\text{O}(n,\gamma)^{19–22}\text{O}$ reactions are shown in table 1. Also the spectroscopic factors obtained from the shell–model calculations are listed. One can see, that the cross sections calculated in this work are enhanced by factors between four and 300. The reasons are that in previous work\textsuperscript{8} spectroscopic factors have been assumed too low and important transitions to
Table 1: Comparison of the contributions of different transitions to bound–states and their spectroscopic factors between previous work and this work for the reactions $^{18-21}$O(n,γ)$^{19-22}$O

| reaction               | final state | spectroscopic factor | transition | previous work | this work |
|------------------------|-------------|----------------------|------------|---------------|-----------|
| $^{18}$O(n,γ)$^{19}$O | $5/2^+$     | 0.687                | $p \rightarrow d$ | 8.85          | 53.33     |
|                        | $3/2^+$     | 0.013                | $p \rightarrow d$ | 0.13          |           |
|                        | $1/2^+$     | 0.830                | $p \rightarrow s$ | 44.43         |           |
|                        | total       |                      |            | 52.40$^1$     | 53.33     |
| $^{19}$O(n,γ)$^{20}$O | $0^+$       | 3.427                | $p \rightarrow d$ | 0.54          | 2.72      |
|                        | $2^+$       | 0.731                | $p \rightarrow d$ | 1.94          | 2.63      |
|                        |            | 0.142                | $p \rightarrow s$ | 4.15          | 5.16      |
|                        | $4^+$       | 1.021                | $p \rightarrow d$ | 4.63          |           |
|                        | $2^+$       | 0.574                | $p \rightarrow s$ | 15.58         |           |
|                        | total       |                      |            | 6.63          | 30.72     |
| $^{20}$O(n,γ)$^{21}$O | $5/2^+$     | 0.345                | $p \rightarrow d$ | 11.02         | 5.40      |
|                        | $1/2^+$     | 0.811                | $p \rightarrow s$ | 40.23         |           |
|                        | total       |                      |            | 11.02         | 45.63     |
| $^{21}$O(n,γ)$^{22}$O | $0^+$       | 5.222                | $p \rightarrow d$ | 0.16          | 4.81      |
|                        | $2^+$       | 0.821                | $p \rightarrow s$ | 22.42         |           |
|                        | $3^+$       | 0.771                | $p \rightarrow s$ | 21.44         |           |
|                        | total       |                      |            | 0.16          | 48.67     |

$^1$ Determined with the help of the experimental value of the cross section at 23.3 keV.

some excited final states have been neglected.

5. SUMMARY

Direct–capture calculations using the folding procedure can reproduce excellently the experimental data for neutron–rich nuclei in the thermal as well as in thermonuclear energy region. Isolated resonances can also be incorporated successfully in the direct capture model. The cross sections calculated in our model for neutron–rich oxygen isotopes are for some reactions considerably higher than the ones given previously. Such changes should lead to modifications of existing reaction network calculations.

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