NUCLEAR HALO EFFECTS IN NEUTRON–CAPTURE REACTIONS OF ASTROPHYSICAL INTEREST

H. Oberhummer, H. Herndl and R. Hofinger
Institut für Kernphysik, TU Wien,
Wiedner Hauptstr. 8–10, A–1040 Vienna, Austria

Y. Yamamoto
Department of Physics, Tokyo Metropolitan University,
1–1, Minami–osawa, Hachioji, Tokyo, 192–03, Japan

Abstract: The halo effect in the final states of astrophysically relevant direct neutron–capture reactions by neutron–rich nuclei is discussed. As an example, we calculate the cross sections for $^{18}$O$(n,\gamma)^{19}$O at thermonuclear and thermal energies.

1 Introduction

The neutron halo, one of the most prominent recent discoveries in nuclear physics [1, 2, 3, 4, 5, 6], is characteristic for neutron–rich nuclei. A halo effect can also be observed in direct neutron–capture reactions leading to final states with a loosely bound neutron [7]. This halo effect can be important for astrophysically relevant neutron–capture reactions by neutron–rich nuclei in the α– and r–process occurring in supernovae as well as in inhomogenous big–bang scenarios.

2 Direct capture and nuclear halo effects

In astrophysically relevant nuclear reactions two opposite reaction mechanisms are of importance, compound–nucleus formation and direct reactions. At the low reaction energies occurring in primordial and stellar nucleosynthesis the direct mechanism often cannot be neglected and can even be dominant. The reason for this behavior is that only a few levels exist for low excitations of the compound nucleus. For instance, this is the case for neutron capture by neutron–rich nuclei. The importance of direct capture has already been demonstrated for magic nuclei and at the border of the region of stability (e.g., for neutron capture by neutron–rich nuclei).

The projectile–energy dependent factors in the Direct–Capture (DC) cross–section $\sigma_{\text{DC}}$ for an electric dipole (E1) transition are given by [9, 10, 11, 12]:

$$\sigma_{\text{E1}}^{\text{DC}} \propto \frac{E^3}{k} \left( \int dr r^2 R_{\ell i}(r) O_{\text{E1}}(r) \chi_{\ell i}(kr) \right)^2 . \tag{1}$$

In this expression the cross section is proportional to the square of the radial overlap integral (direct–capture integral). The photon energy is given by $E_\gamma$. The scattering wave function in the entrance channel and the bound–state wave function in the exit channel are given by $\chi_{\ell i}(kr)$ and $R_{\ell i}(r)$, respectively. The kinetic energy $E$ in the entrance channel is related to the wave number $k$ by $E = \hbar^2 k^2/(2M)$, where $M$ is the reduced mass. The radial part of the E1–transition operator is given in the long wavelength approximation that is appropriate for our low–energy (thermal and thermonuclear energies) case by $O_{\text{E1}} \simeq 1$. For direct capture to weakly bound final states, the bound–state wave function $R_{\ell i}(r)$ decreases only very slowly in the nuclear exterior, so that the contributions come predominantly from far outside the nuclear region, i.e., from the nuclear halo.

For this asymptotic region the scattering and bound wave functions in Eq. (1) can be approximated by their asymptotic expressions neglecting the nuclear potential:

$$\chi_{\ell i}(kr) \propto j_{\ell i}(kr) \quad \text{and} \quad R_{\ell i}(r) \propto h_{\ell i}^{(+)}(i\mu r) , \tag{2}$$

where $j_{\ell i}$ and $h_{\ell i}^{(+)}$ are the spherical Bessel, and the Hankel function of the first kind, respectively. The separation energy $S_n$ in the exit channel is related to the parameter $\mu$ by $S_n = \hbar^2 \mu^2/(2M)$.

1Tel.: +43/1/58801/5574, E-mail: ohu@ds1.kph.tuwien.ac.at, FAX: +43/1/5864203
3 An example: $^{18}\text{O}(n,\gamma)^{19}\text{O}$

As an example we investigate the reaction $^{18}\text{O}(n,\gamma)^{19}\text{O}$. The level scheme of $^{19}\text{O}$ is shown in Fig. 1. The cross section for this reaction at thermonuclear energies has been measured recently [13] and is also known from experiment at thermal energies [14]. The cross section has also been calculated using the direct–capture model [13, 15]. The calculated direct–capture cross section is in excellent agreement with the thermonuclear and thermal experimental cross section (compare thick solid curve with the experimental data [13, 14] in Fig. 2). The calculations for the three main transitions to the positive–parity final states in this work (the three broken curves labeled 1, 2 and 3 in Fig. 2) are the same as in Ref. [15], except that we used the spectroscopic factors extracted from the $^{18}\text{O}(d,p)^{19}\text{O}$–reaction [16]. For the transitions to the negative–parity $3/2^-$–state just below the neutron threshold (the two solid curves labeled 4 and 5 in Fig. 2), the spectroscopic factor was adjusted to the experimental thermal cross section [15].

The halo effect shows up in the transition to the final $3/2^-$–state in $^{19}\text{O}$, which is only bound by 12 keV with respect to the neutron threshold (Fig. 1). In this case the main contributions come from a region of about 75 fm (s–wave) and 160 fm (d–wave) at thermal energies, and about 45 fm (s–wave) and 85 fm (d–wave) at thermonuclear energies. The direct–capture calculations result in two main transitions to this state starting from an s– and d–wave, respectively (the two solid curves labeled 4 and 5 in Fig. 2). In this case the two curves show a totally different behavior for below and above a projectile energy that is equal to the neutron separation energy $S_n = 12$ keV of the $3/2^-$–state.

This behavior can be readily described by the halo effect. For the (s→p)–transition and (d→p)–transition, we insert the specific expressions for the Bessel– and Hankel functions

\[
j_{\ell=0}(x) = \frac{\sin x}{x} \quad (3)
\]

\[
j_{\ell=2}(x) = \left( \frac{3}{x^3} - \frac{1}{x} \right) \sin x - \frac{3}{x^2} \cos x
\]

\[
h_{\ell=1}^{(+)}(y) = \left( \frac{1}{y^2} - \frac{i}{y} \right) \exp(iy)
\]

where $x = kr$ and $y = i\mu r$. The E1 direct–capture cross section is then given by

\[
\sigma_{\text{DC}}^{E1}(s \rightarrow p) \propto \frac{1}{\sqrt{E}} \frac{(E + 3S_n)^2}{E + S_n}
\]

\[
\sigma_{\text{DC}}^{E1}(d \rightarrow p) \propto \frac{E^2}{E + S_n}
\]
Figure 2: Comparison of direct-capture calculations with the experimental data for the cross section of $^{18}$O(n,γ)$^{19}$O. Explanation see text.

For $E \ll S_n$ we recover the normal behavior at low energies for an incoming $s$– or $d$–wave:

\[
\sigma_{\text{DC}}^{\text{El}}(s \rightarrow p) \propto \frac{1}{\sqrt{E}} \propto \frac{1}{v}
\]

(5)

\[
\sigma_{\text{DC}}^{\text{El}}(d \rightarrow p) \propto E^2 \propto v^3
\]

where $v$ is the relative velocity in the entrance channel.

However, for $E \gg S_n$ the energy behavior changes completely, and we obtain:

\[
\sigma_{\text{DC}}^{\text{El}}(s \rightarrow p) \propto \sqrt{E} \propto v
\]

(6)

\[
\sigma_{\text{DC}}^{\text{El}}(d \rightarrow p) \propto \sqrt{E} \propto v
\]

Exactly this halo behavior is obtained for the transition to the $^{19}$O(3.945 MeV)–state, as can be seen easily from the solid curves in Fig. 2. For low energies the $s$–wave has an $1/v$–behavior and the $d$–wave a $v^3$–behavior. This is the normal energy dependence for low energies. However, at about 12 keV this behavior changes gradually in both cases to a $v$–behavior. This effect has not been taken into account in previous publications [4,5] of $^{18}$O(n,γ)$^{19}$O, where the $s$–wave was extrapolated using an $1/v$–behavior from the thermal cross section and the $d$–wave has been neglected.

The contribution of the transition to the $^{19}$O(3.945 MeV)–state to the whole cross section of $^{18}$O(n,γ)$^{19}$O is about 5% in the astrophysically relevant range (10–250) keV (compare broken and solid curves in Fig. 2). Therefore, the halo effect does not play a large role in the reaction rate for $^{18}$O(n,γ)$^{19}$O already given in Ref. [4]. However, from the astrophysical point of view, when investigating neutron–capture reactions further away from the region of stability this halo effect will be of relevance in special cases, especially when approaching the drip lines.

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