LLNL-PROC-625713

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ScienceDirect

Nuclear Data Sheets 118 (2014) 292–294

Nuclear Data Sheets

www.elsevier.com/locate/nds

Coupled-Channel Models of Direct-Semidirect Capture via Giant-Dipole Resonances

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Semidirect capture, a two-step process that excites a giant-dipole resonance followed by its radiative de-excitation, is a dominant process near giant-dipole resonances, that is, for incoming neutron energies within 5–20 MeV. At lower energies such processes may affect neutron capture rates that are relevant to astrophysical nucleosynthesis models. We implement a semidirect capture model in the coupled-channel reaction code FRESCO and validate it by comparing the cross section for direct-semidirect capture ^{208}Pb(n,γ)^{209}Pb to experimental data. We also investigate the effect of low-energy electric dipole strength in the pygmy resonance. We use a conventional single-particle direct-semidirect capture code CUPIDO for comparison. Furthermore, we present and discuss our results for direct-semidirect capture reaction ^{130}Sn(n,γ)^{131}Sn, the cross section of which is known to have a significant effect on nucleosynthesis models.

I. INTRODUCTION

Low-energy nucleon capture rates are an important input to the astrophysical nucleosynthesis models, fueling a need for improved capture models that take into account various nucleon capture mechanisms. Besides nucleosynthesis, other applications need capture cross sections at higher energies, and therefore the entire spectrum of captures is desirable. Usually, capture mechanisms are divided into three broad categories: 1) Direct capture, 2) Semi-direct capture, and 3) Statistical or Compound capture.

The direct-capture (DC) process takes place in a single-step electro-magnetic (EM) transition that is conventionally modeled as a first-order perturbation that involves an EM transition matrix-element between the incoming wave-function and the final bound state. The initial and final wave-functions are approximated by single-particle wave functions that are solutions of a Schrödinger equation with a one-body potential: usually an optical potential is used to calculate the former, and a real bound-state potential to determine the latter, although some variations on this theme exist. This model has been implemented in codes like CUPIDO [1], FRESCO [2], and TEDCA [3], and their computations of DC are in generally good agreement. Direct capture can occur at various neutron energies, and is very sensitive to the spectroscopy of the capturing bound states (their quantum numbers and energies). In relative terms, DC matters more for light and medium mass nuclei, as well as for neutron-rich nuclei.

Semi-direct (SD) capture via a giant-dipole resonance (GDR) becomes a dominant process between 5 and 20 MeV incoming neutron energy. It is a two-step process, where a giant dipole resonance is excited in the first step, followed by a γ-ray de-excitation in the second step. In some particular nuclei, the SD processes have been known to affect even the low-energy capture, where they may interfere (constructively or destructively) with DC. The first models of semi-direct capture, proposed in the 1970's, accounted for the the essential feature of direct-semidirect capture by adding to the single-particle EM operator a Lorentzian whose position and width are those of the GDR. One such model was successfully implemented in the direct-semidirect nucleon capture code CUPIDO.

Statistical or compound capture involves the formation of an intermediate (compound) nucleus in statistical equilibrium. Compound capture dominates for cases with high level densities, which occur typically in medium-mass and heavy nuclei. They are described in the framework of a Hauser-Feshbach model [4] that relies on level density and gamma-ray strength function models.

Compound-nuclear contributions to the total neutron-capture cross sections are typically assumed to be dominant for nuclei close to the valley of stability, and are expected to decrease when considering more neutron-rich isotopes, as these are characterized by lower level densities. How and where the transition from the compound to direct reaction regime occurs, however, is an open question [5, 6]. It is therefore relevant to investigate possible contributions from other capture mechanisms, including DSD capture via GDR and PDR (pygmy dipole resonance) excitations. We have begun to implement DSD

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http://dx.doi.org/10.1016/j.nds.2014.04.061
0090-3752/2014 Published by Elsevier B.V.

capture in the coupled-channel framework of FRESCO, in order to enable systematic studies that can include also deformed nuclei. A similar attempt has been made in [7]. Here, we present the coupled-channels formalism for DSD capture, comparisons with existing codes using on-shell approximations, and first results for capture in the tin region, which is of interest for the astrophysical r-process.

II. FORMALISM

The transition matrix element for direct-semidirect capture of a nucleon is

$$T_{\rm fi}(E,E_\gamma) = \langle \Psi_{\rm f}(E,E_\gamma)|O^{\rm n}_\lambda + O^{\rm c}_\lambda|\Psi_{\rm i}(E)\rangle, \qquad (1)$$

where $O^{\rm n}_\lambda$ and $O^{\rm c}_\lambda$ are single-particle and core multipole electromagnetic operators of multipolarity λ. The (on-shell) initial and final states in the coupled-channels approximation that incorporates a giant-dipole resonance (GDR) excitation of the core are

$$\begin{aligned} \Psi_{\rm i}(E) &= \chi^{E}_{\rm n}(r_{\rm n})\phi_{\rm gs}(\xi) + \chi^{E-E_{\rm d}}_{\rm d}(r_{\rm n})\phi_{\rm d}(\xi) \qquad (2)\\ \Psi_{\rm f}(E,E_\gamma) &= [\chi^{E-E_\gamma}_{\rm b}(r_{\rm n})\phi_{\rm gs}(\xi) \\ &+ \chi^{E-E_{\rm d}-E_\gamma}_{\rm e}(r_{\rm n})\phi_{\rm d}(\xi)]\zeta_\gamma(r_\gamma), \end{aligned}$$

where $\chi^{E}_{\rm n}(r_{\rm n})$ is the incoming neutron wave-function at energy E, E_γ is the γ-ray energy, $E_{\rm d}$ is the GDR energy, $\chi^{E-E_\gamma}_{\rm b}(r_{\rm n})$ is the neutron bound-state wave function, $\chi^{E-E_\gamma}_{\rm d}(r_{\rm n})$ is a single-particle component in the GDR, $\phi_{\rm gs}(\xi)$ is the target ground state, $\phi_{\rm d}(\xi)$ is the collective GDR state of the target nucleus. With these definitions, and after suppressing energy labels, the transition matrix element becomes

$$\begin{aligned} T_{\rm fi} &= \langle\chi_{\rm b}|O^{\rm n}_\lambda|\chi_{\rm n}\rangle + \langle\chi_{\rm e}|O^{\rm n}_\lambda|\chi_{\rm d}\rangle \qquad (3)\\ &+ \langle\chi_{\rm b}|\chi_{\rm d}\rangle\langle\phi_{\rm gs}|O^{\rm c}_\lambda|\phi_{\rm d}\rangle + \langle\chi_{\rm e}|\chi_{\rm n}\rangle\langle\phi_{\rm d}|O^{\rm c}_\lambda|\phi_{\rm gs}\rangle, \end{aligned}$$

and the coupled-channel equations may be written as

$$(H_\gamma - E_\gamma)\zeta_\gamma(r_\gamma) + V_{\gamma{\rm d}}(r_\gamma)\chi_{\rm d}(r_{\rm n}) + V_{\gamma{\rm n}}(r_\gamma)\chi_{\rm n}(r_{\rm n}) = 0, \qquad (4)$$

where $V_{\gamma{\rm d}}(r_\gamma) = \langle\chi_{\rm b}|O^{\rm n}_\lambda + \langle\phi_{\rm d}|O^{\rm c}_\lambda|\phi_{\rm gs}\rangle\langle\chi_{\rm b}|$, and $V_{\gamma{\rm n}}(r_\gamma) = \langle\chi_{\rm b}|O^{\rm n}_\lambda + \langle\phi_{\rm d}|O^{\rm c}_\lambda|\phi_{\rm gs}\rangle\langle\chi_{\rm e}|$. The two dominant terms in the $T_{\rm fi}$ matrix

$$T_{\rm fi} \approx \langle\chi_{\rm b}|O^{\rm n}_\lambda|\chi_{\rm n}\rangle + \langle\chi_{\rm b}|\chi_{\rm d}\rangle\langle\phi_{\rm gs}|O^{\rm c}_\lambda|\phi_{\rm d}\rangle, \qquad (5)$$

are implemented in FRESCO.

A second-order distorted-wave Born Approximation (DWBA) expression for the DSD capture T-matrix element is

$$T^{(\lambda)}_{\rm fi} = \langle\chi_{\rm b}\phi_{\rm gs}|O^{\rm n}_\lambda + O^{\rm c}_\lambda|\Psi_{\rm i}\rangle, \qquad (6)$$

which can be derived in a second-order perturbation approximation. To this end, the total Hamiltonian is separated into a core part H_0, a neutron part H_n, and a collective term $V_{\rm coll}$ representing coupling between core and neutron: $H = H_0 + H_n + V_{\rm coll}$. Here $H_0\chi_{\rm n} = E\chi_{\rm n}$ and $H_n\chi_{\rm b} = E_b\chi_{\rm b}$, so $E_\gamma = E - E_{\rm b}$ is the γ-ray energy, the difference between the energy E of the entrance channel and the (negative) final bound state energy. With this Hamiltonian one solves for the initial wave-functions as a first-order perturbation in $V_{\rm coll}$

$$|\Psi_{\rm i}\rangle = |\chi_{\rm n}\phi_{\rm gs}\rangle + \frac{1}{E - H_0 - H_n}V_{\rm coll}|\chi_{\rm n}\phi_{\rm gs}\rangle. \qquad (7)$$

Inserting this into Eq. (6) yields $T^{(\lambda)}_{\rm fi} = T_{\rm D} + T_{\rm SD}$, where

$$\begin{aligned} T_{\rm D} &= \langle\chi_{\rm b}|O^{\rm n}_\lambda|\chi_{\rm n}\rangle \qquad (8)\\ T_{\rm SD} &= \langle\chi_{\rm b}\phi_{\rm gs}|O^{\rm c}_\lambda\frac{1}{E - H_0 - H_n}V_{\rm coll}|\chi_{\rm n}\phi_{\rm gs}\rangle. \qquad (9) \end{aligned}$$

If an excited core state satisfies $H_0\phi_{\rm d} = E_d\phi_{\rm d}$, and is the sole intermediate channel in the two-step process, then

$$T_{\rm SD}{=}\langle\phi_{\rm gs}|O^{\rm c}_\lambda|\phi_{\rm d}\rangle\langle\chi_{\rm b}|\frac{1}{E{-}E_{\rm d}{-}H_{\rm n}}\langle\phi_{\rm d}|V_{\rm coll}|\phi_{\rm gs}\rangle|\chi_{\rm n}\rangle. \qquad (10)$$

In second order, this is equivalent to the second term of Eq. (5), and can thus be calculated with FRESCO [2] as the second-order iteration of a coupled-channel system.

One may perhaps make an on-shell approximation for the intermediate neutron state, i.e. one replaces the operator H_n in the Greens function in Eq. (7) by the pole energy E_b for the final neutron bound state. This gives the expression

$$T^{\rm os}_{\rm SD}{=}\langle\phi_{\rm gs}|O^{\rm c}_\lambda|\phi_{\rm d}\rangle\frac{1}{E{-}E_{\rm d}{-}E_{\rm b}}\langle\chi_{\rm b}\phi_{\rm d}|V_{\rm coll}|\phi_{\rm gs}\chi_{\rm n}\rangle, \qquad (11)$$

which was implemented previously in the CUPIDO code.

In all cases, a finite width of the excited state (GDR or PDR) may be easily included by using a complex energy,

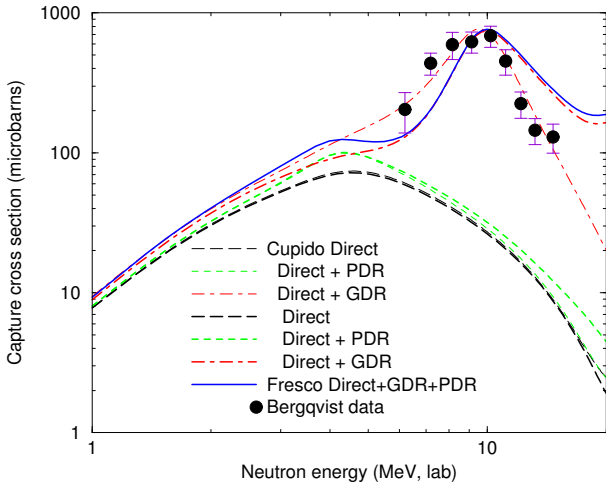

FIG. 1. Calculated capture cross sections for ^{208}Pb(n,γ). Contributions from direct and semi-direct capture via the GDR and PDR were obtained in second-order DWBA, using Eq. (10), as implemented in FRESCO [2], and Eq. 11, implemented in CUPIDO [1]. The data are from [8].

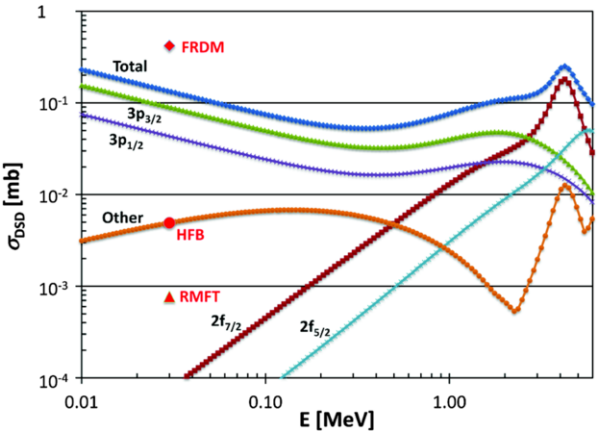

FIG. 2. ^{130}Sn(n,γ) reaction [10, 11] computed using the CUPIDO code [1] for real parts of a phenomenological Koning-Delaroche [12] optical model potential. Shown for comparison (single points) are the calculations of Rauscher et al. [13] for 30 keV neutrons using the finite range droplet (FRDM), the Hartree-Fock-Bogoliubov (HFB), and relativistic mean field theory (RMFT) models.

$E_{\rm d} = E_{\rm R} + i\Gamma/2$, where the real ($E_{\rm R}$) and imaginary (Γ) parts give the resonance position and width. We observe that the semidirect (SD) term peaks around $E_\gamma \sim E_{\rm R}$.

III. APPLICATIONS

A. ^{208}Pb(n,γ)^{209}Pb$_{\rm g.s.}$

We performed DSD capture calculations using FRESCO and CUPIDO and compared to the measured data, finding good agreement at energies for which data is available (Fig. 1). We have also modeled the effect of the so-called pygmy-resonance, a low-energy aggregation of electric-dipole strength that occurs in neutron-rich nuclei. Semi-direct capture via the GDR is clearly dominant (and in agreement with measurement) in the high-energy regime above about 7 MeV. For lower energies, the various contributions do not exhibit such different magnitudes, i.e. here it becomes important to properly describe the contributions from all reaction mechanisms. Presently, we have not included compound-nuclear contributions. Their significance, relative to DSD capture depends strongly on the level density in the nucleus under consideration. This aspect is not a focus of the present study, but it clearly deserves more detailed consideration, as has also been recognized in earlier work [9].

B. ^{130}Sn(n,γ)

Fig. 2 shows calculations for DSD capture on ^{130}Sn carried out with CUPIDO. This case plays an important role in astrophysical models of nucleosynthesis [14]. Only very recently, spectroscopic data has become available for the first time from a (d,p) reaction in inverse kinematics [10]. The SD capture in this case was only a small correction to the direct capture.

Although conventional applications of Hauser-Feshbach statistical capture predict cross sections that are substantially larger than DSD capture, a recent analysis of (d,p) data raises a question whether the level density in ^{131}Sn is sufficiently high to use conventional statistical theory. We plan to investigate this issue in more detail in future work.

Acknowledgements: The authors thank Frank Dietrich (LLNL) for useful suggestions and the CUPIDO code and Arthur Kerman for useful discussions. This work was funded by the DOE Topical Collaboration TORUS (www.reactiontheory.org). This manuscript has been authored by the Oak Ridge National Laboratory, managed by UT-Battelle LLC under Contract No. DE-AC05-00OR22725, and by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344, with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes.

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