Calculation of astrophysical reaction rate of ^{82}Ge(n,γ)^{83}Ge*

WANG Mian(王勉)[1)] CHEN Yong-Shou((陈永寿) LI Zhi-Hong(李志宏)
LIU Wei-Ping(柳卫平) SHU Neng-Chuan(舒能川)

(China Institute of Atomic Energy, Beijing 102413, China)

Abstract The neutron capture reaction on a neutron-rich near closed-shell nucleus ^{82}Ge may play an important role in the r-process following the fallout from nuclear statistical equilibrium in core-collapse supernovae. By carrying out a DWBA analysis for the experimental angular distribution of ^{82}Ge(d, p)^{83}Ge reaction we obtain the single particle spectroscopic factors, $S_{2,5/2}$ and $S_{0,1/2}$ for the ground and first excited states of ^{83}Ge=^{82}Ge$\otimes$n, respectively. And then these spectroscopic factors are used to calculate the direct capture cross sections for the ^{82}Ge(n, γ)^{83}Ge reaction at energies of astrophysical interest. The optical potential for neutron scattering on unstable nucleus ^{82}Ge is not known experimentally. We employed a real folding potential which was calculated by using the proper ^{82}Ge density distribution and an effective nucleon-nucleon force DDM3Y. The neutron capture reactions on neutron-rich closed-shell nuclei are expected to be dominated by the direct capture to bound states. We will show that the direct capture rates on these nuclei are sensitive to the structure of the low-lying states.

Key words neutron capture, spectroscopic factor, astrophysical reaction rate

PACS 24.50.+g

1 Introduction

The neutron capture reaction plays an important role for the r-process in the explosive nuclear astrophysics events. It is one of the main mechanisms for the synthesis of nuclei heavier than iron. The path of the r-process is through the neutron rich region. However, there is only a little information known for the neutron capture on neutron rich nuclei. The neutron capture of neutron-rich closed-shell nucleus^{82}Ge is one of important reactions that determine the r-process abundances.

In this paper, we carry out a DWBA analysis for the new experimental angular distribution of ^{82}Ge(d, p)^{83}Ge reaction[1] to obtain the spectroscopic factors for the ground and first excited states of ^{83}Ge=^{82}Ge$\otimes$n. By using the obtained spectroscopic factors and the real folding potential calculated with the density dependent two-body force DDM3Y[2], the cross section and reaction rate of direct neutron capture of ^{82}Ge were calculated.

2 The spectroscopic factors

As the nucleus ^{82}Ge is unstable, the neutron capture reaction on it can not be measured directly, the neutron transfer reactions may be employed to obtain the capture cross section indirectly. The spectroscopic factor (SF) can be obtained by carrying out a DWBA analysis for the experimental angular distribution. The experimental differential cross section of the (d,p) reaction can be expressed as

$$\left(\frac{\mathrm{d}\sigma^{lj}}{\mathrm{d}\Omega}\right)_{\mathrm{exp}} = S_d S_{l,j} \sigma^{lj}_{\mathrm{DW}}(\theta), \tag{1}$$

where S_d is the spectroscopic factor of deuteron, known having a value of 0.859, and $S_{l,j}$ denotes the spectroscopic factor for the state of ^{83}Ge=^{82}Ge$\otimes$n with orbital angular momentum l and total angular momentum j, and $\sigma^{lj}_{\mathrm{DW}}(\theta)$ is the distorted wave Born

Received 3 September 2008
* Supported by NSFC of China (10475115, 10775182, 10435010) and MSBRDP of China (2007CB815000)
1) E-mail: mwang@ciae.ac.cn

approximation (DWBA) differential cross section.

The ground and first excited states of ^{83}Ge have been measured recently as $5/2^+$ and $1/2^+$ (0.28 MeV), respectively, see Ref.[1]. The experimental ^{82}Ge(d,p)^{83}Ge cross section involves two components, transferring to the ground (l=2, j=5/2) and first excited (l=0, j=1/2) states of ^{83}Ge=^{82}Ge⊗n. The DWBA code DWUCK4 was used to compute the angular distribution. In the calculation neutron transfers to the $2d_{5/2}$ and $3s_{1/2}$ orbits were taken into account. Two sets of the entrance channel optical potential parameters were taken from Refs.[1,3], and three sets of the exit channel parameters were taken from Refs.[1,3,4], then six sets of parameters are obtained by combining the entrance and exit sets and used in the calculation. As an example, Fig.1 presents the normalized angular distribution for one set of optical potential parameters. The spectroscopic factor can be extracted by normalizing DWBA differential cross section to the experimental data. The average value of spectroscopic factors were found to be $S_{2,5/2}$=0.45±0.13 and $S_{0,1/2}$=0.50±0.14, which are in consistent with those obtained in Ref.[1], where a different code TWOFNR was used in the DWBA calculation. The uncertainties of the spectroscopic factors result mainly from the difference of the optical potentials used in the calculation.

It is interesting to note that the observed low-lying level scheme of the neutron rich nucleus ^{83}Ge indicates that the single particle structure around N=50 is different from the usual one which leads to the ground and the first excited states of ^{83}Ge to be $1g_{7/2}$ and $2d_{5/2}$, respectively. It was found that by using the $1g_{7/2}$ and $2d_{5/2}$ configurations the calculated DWBA angular distributions can not coincide with the experimental data, see Fig.1.

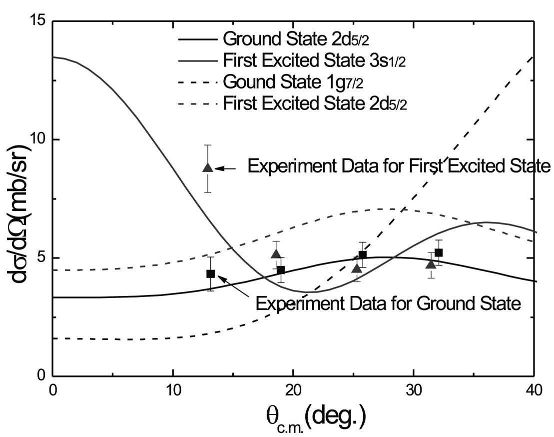

Fig. 1. Experimental angular distribution of ^{82}Ge(d, p)^{83}Ge at $E_{\mathrm{c.m.}}$=7.9 MeV, together with a DWBA calculation (curves).

3 Reaction rate of ^{82}Ge(n,γ)^{83}Ge

The E1 transition dominates the direct capture process, the cross section and the rate of the E1 direct neutron capture of ^{82}Ge may be calculated by

$$\sigma_{(\mathrm{n},\gamma)}=\frac{16\pi}{3}\left(\frac{E_\gamma}{\hbar c}\right)^3\frac{e_{\mathrm{eff}}^2}{k^2}\frac{1}{\hbar v}\frac{(2j_{\mathrm{f}}+1)}{(2I_1+1)(2I_2+1)}$$
$$\frac{\max(l_1,l_2)}{2l_2+1}S_{l_f j_\mathrm{f}}\times\left|\int_0^\infty r^2\omega_{l_i}(kr)u_{l_f}(r)\mathrm{d}r\right|^2, \quad (2)$$

where E_γ is the γ-ray energy, v is the relative velocity between particles 1 (neutron) and 2 (^{82}Ge), k is the incident wave number, $e_{\mathrm{eff}}=-eZ/(A+1)$ is the neutron effective charge for the E1 transition in the potential of the target nucleus $(Z,A), j_\mathrm{f}$ is the total angular momentum of ^{83}Ge, I_i is the spin of particle i, l_1 and l_2 are the orbit angular momenta of incident and captured neutrons in ^{83}Ge. The $\omega_{\mathrm{li}}(kr)$ is the distorted radial wave function in the entrance channel, and $u_{\mathrm{lf}}(r)$ is the radial wave function of bound neutron state in ^{83}Ge. The optical potential for the neutron scattering on unstable nucleus ^{82}Ge is unknown experimentally. We employed a real folding potential calculated by using the proper ^{82}Ge density distribution and an effective nucleon-nucleon force DDM3Y,

$$U(R)=\lambda\int\mathrm{d}\boldsymbol{r}_1\int\mathrm{d}\boldsymbol{r}_2\rho_1(\boldsymbol{r}_1)\rho_2(\boldsymbol{r}_2)g(E,s)f(E,\rho_1,\rho_2), \quad (3)$$

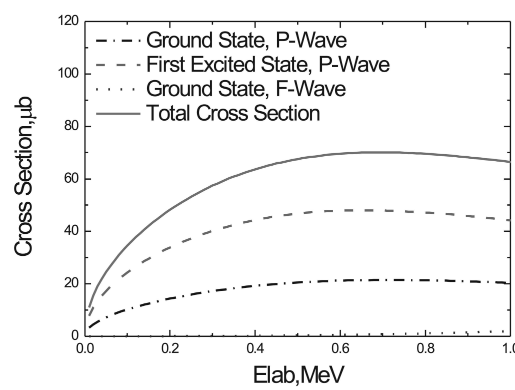

Fig. 2. The cross sections of the direct neutron capture of ^{82}Ge on the ground and first excited states.

where $\rho_1(\boldsymbol{r}_1)$ and $\rho_2(\boldsymbol{r}_2)$ denote the density distributions of incident neutron and target ^{82}Ge, respectively, $g(E,s)f(E,\rho_1,\rho_2)$ stands for the density dependent two-body interaction[2]. The depth of the real potential, λ, was scaled to the volume integral of potential per nucleon J_V/A=437 MeV·fm^3 which was obtained from the systematic studies[5, 6]. The density distribution of neutron is in Gauss-form[7]. The density distribution of ^{82}Ge is in Fermi-form with the radius and diffusion parameters leading to a folding Woods-Saxon potential with r_0=1.21 fm, a=0.67 fm and $V_0 = -50.74$ MeV, which is similar to usually used potentials, such as Wahlborn potential[8]. With this potential for the entrance channel the direct E1 capture cross sections were calculated with Eq.(2), the results are shown in Fig.2.

The rate of the direct neutron capture reaction on ^{82}Ge was calculated from the total cross section, and fitted with Eq.(4) with residues less than 10% over the temperature range from 0.03 to 10 GK.

$$N_A < \sigma v >= \exp(15.81292 - 0.02511 \times T_9^{-1} + 0.01686 \times T_9^{-1/3} + 0.51686 \times T_9^{1/3} - 0.40379 \times T_9 + 0.33869 \times T_9^{5/3} + 0.89117 \times \ln T_9). \quad (4)$$

References

1 Thomas J S et al. Phys. Rev. C, 2005, **71**: 021302
2 Kobos A M et al. Nucl. Phys. A, 1984, **425**: 208
3 Perey C M et al. Phys. Rev., 1963, **132**: 755
4 Becchetti F D et al. Phys. Rev., 1969, **182**: 1190
5 Krausmann E et al. Phys. Rev. C, 1996, **53**: 469
6 HU Ji-Min et al. The Nuclear Theory (Volume II). Beijing: Atomic Energy Press, 1987. 113 (in Chinese)
7 Radcap. for. Edited by Bertulani C A, 2003
8 Blomgvisl J et al. Ark. Fys., 1960, **16**: 543