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The Asymptotic Normalization Coefficient (ANC) of $\langle {}^{12}\mathrm{C} + n | {}^{13}\mathrm{C}^*(1/2^+) \rangle$ state have been determined by measuring the differential cross sections of the $^{12}\mathrm{C}(d,p)^{13}\mathrm{C}^*(1/2^+)$ reaction at very forward angles. The radiative capture cross section evaluated from the present ANC value is in good agreement with the recent experimental data obtained in the direct measurements, indicating the validity of the ANC method for this reaction process.

1. Introduction

The cross sections of radiative capture reactions at astrophysical energies are fundamental quantities required for understanding the paths of nucleosynthesis. It is difficult, however, to determine these cross sections precisely with direct measurements because they are very small at astrophysically relevant energies. To overcome this difficulty, use of peripheral transfer reactions have been recently proposed as one of the experimental tools to extract radiative proton capture cross sections [1]. This method, called the Asymptotic Normalization Coefficient (ANC) method, has been applied for several (p,γ) reactions (e.g. Ref. [2]). In order to extend the applicability of this method to radiative *neutron* capture reactions, we have investigated the $^{12}\mathrm{C}(n,\gamma)^{13}\mathrm{C}^*(1/2^+)$ cross sections through the (d,p) measurement.

This (n,γ) reaction is one of the nice candidates for this purpose. Experimentally, these cross sections at astrophysical energies have been directly measured [3], which can be compared with those deduced by the ANC method. In addition, this reaction may satisfy the peripherality. The binding energy of the valence neutron in the residual bound state is as low as 1.85 MeV, mainly consisting of the $\left|{}^{12}\mathrm{C}(0^+)\otimes\nu(2s_{1/2});1/2^+\right\rangle$ configuration. Moreover, the incident neutron undergoing the E1 transition is in p-wave relative motion with respect to the target nucleus so that this reaction would take place mainly outside the nucleus [4]. Hence this cross section can be described as

$$\sigma_{n,\gamma} \simeq C^2 \cdot \left|\langle\frac{e^{-\kappa r}}{r}\left|\hat{O}(r)\right|\psi^+(r)\rangle\right|^2, \tag{1}$$

where C is the ANC, $\hat{O}$ is the E1 operator and ψ^+ is the incident wave function. The ANC represents the normalization constant for the tail of the overlap function between ${}^{12}\mathrm{C}+n$ and ${}^{13}\mathrm{C}^*(1/2^+)$.

In the framework of the zero-range distorted wave Born approximation (DWBA) analysis, the differential cross sections of the peripheral transfer reaction can be written with the same ANC as

$$\frac{d\sigma}{d\Omega}_{exp} \simeq D_0^2 \cdot C^2 \cdot \left|\langle\chi_f\frac{e^{-\kappa r}}{r}\left|\delta_{pn}\right|\chi_i\rangle\right|^2, \tag{2}$$

where χ_i (χ_f) is the initial (final) distorted wave and D_0^2 is 1.53×10^4 [MeV^{2}fm^3]. The ANC can be deduced from the comparison between the differential cross sections and the DWBA calculation. However, a DWBA analysis has uncertainties arising from the choice of input parameters such as optical potentials and bound state potentials. These uncertainties should be estimated.

According to the simple DWBA analysis, the transfer process at 2 degrees at around 12 MeV is predominantly peripheral enough. We have measured the differential cross sections of the ${}^{12}\mathrm{C}(d,p){}^{13}\mathrm{C}^*(1/2^+)$ reaction at very forward angles by use of a 11.8-MeV deuteron beam, since there were no experimental data at angles smaller than 10 degrees around this energy region.

2. Experiment

The experiment was performed at SF-cyclotron facility of Center for Nuclear Study at University of Tokyo. The thickness of the self-supporting carbon target was 185.0±5.0 μg/cm^2. Outgoing particles were momentum-analyzed using a QDD type spectrograph [5] and detected with a focal plane detector system which consisted of four sets of single wire drift chambers and a plastic scintillator. A typical energy spectrum of deuterons on the focal plane is shown in Fig. 1. The overall energy resolution achieved was about 20 keV (FWHM). The elastic scattering have been also measured to deduce the optical potential set of the entrance channel.

The differential cross sections of the transfer reaction were measured at angles down to 2.0 degrees. During the measurements at angles larger than 10 degrees, a Faraday cup placed at 0 degree in the scattering chamber was used for determining the beam current. At angles smaller than 10 degrees, instead of the Faraday cup, two SSD's placed at ± 60 degrees were used for monitoring the beam current.

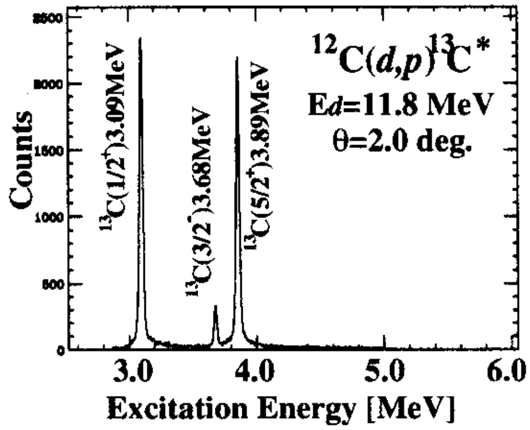

Figure 1. The energy spectrum of deuterons from the ^{12}C(d,p) reaction measured at 2 degrees.

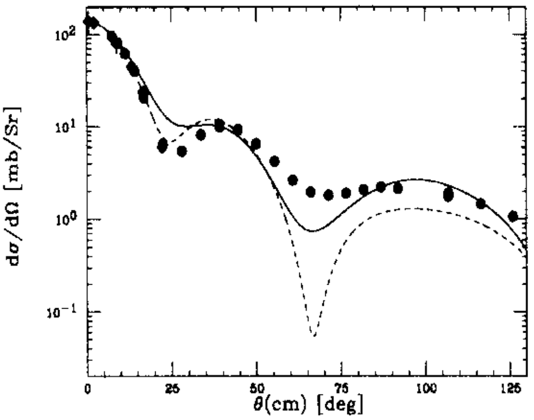

Figure 2. The differential cross sections of the transfer reaction ^{12}C(d,p)^{13}C($1/2^+$) measured at E = 11.8 MeV. Only statistical errors are included for the data points. Two typical DWBA curves are also plotted for reference.

3. Results and discussions

Figure 2 shows the angular distribution of the measured differential cross sections of the transfer reaction. The experimental systematic error mainly derived from the the beam current calibration of beam monitors was estimated to be 8%. The ANC value has been obtained from the comparison between the experimental differential cross section and DWBA calculation using the code DWUCK4 [6] with evaluating the ambiguities arising from the DWBA analysis.

In order to estimate the uncertainty derived from the choice of the optical potentials, ANC values have been deduced with several optical potential sets. For the entrance channel, two types of optical potential sets were used.

For an imaginary part, either a volume or a surface Woods-Saxon potential shape was used. In both cases, real parts were volume Woods-Saxon forms. Three different optical potential sets of each type were searched for to reproduce the angular distribution of the measured elastic scattering. For the exit channel, we adopted three global optical potential sets [7–9]. As the result of this analysis, it has been found that the differential cross sections at 2 degrees converged to an average value within a 6.4 % deviation.

The ANC can be defined as $C = S \cdot b$, where S is the spectroscopic factor and b is the normalization constant for the asymptotic part of the bound state wave function of the neutron in ^{13}C. To estimate the uncertainty derived from the choice of the bound state potentials, several model-space parameter sets consisting of size and diffuseness, (r_0, a), were tested. The bound state potentials of Woods-Saxon shape have been examined in the region of $1.1 \leq r_0 \leq 1.3$ fm and $0.5 \leq a \leq 0.7$ fm. The depth of the potential was adjusted to reproduce the binding energy of the neutron for each value of the pair (r_0, a).

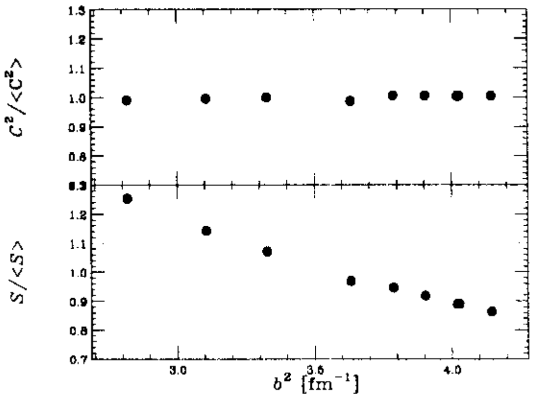

Figure 3. The variation of the spectroscopic factor S (lower panel) and the ANC C (upper panel) as a function of the single asymptotic amplitude ANC b^2.

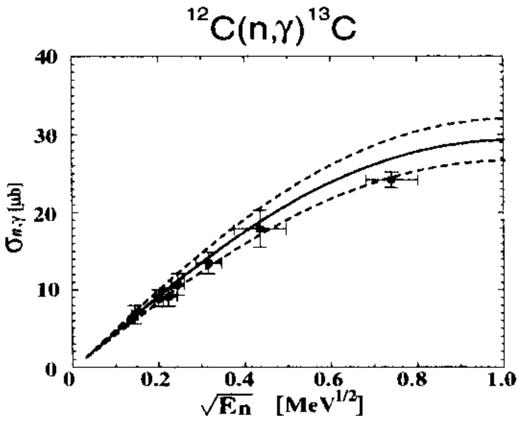

Figure 4. The (n,γ) cross sections as a function of $\sqrt{E_n}$. The points indicate the experimental data [3]. The solid line is the deduced cross sections with the ANC mean value and the dashed lines shows the range of the systematic error.

The single particle asymptotic amplitude, b, was deduced fitting the single particle wave function to the Yukawa functions at large relative distances ($r \gg r_0$). Figure 3 shows the dependence of the ANC and of S on the bound state potential parameters. In contrast to the observed strong dependence of the S values, the ANC values varies by less than 1% over full range of b values investigated in this analysis.

By comparing the DWBA calculation with the measured differential cross section at 2 degrees, the ANC value for the ^{13}C($1/2^+$) have been determined to be 3.65 ± 0.34 (statistical error) ± 0.35 (systematic error) fm^{-1}. The (n,γ) cross sections calculated using the obtained ANC value are compared with those determined by the direct measurement [3] in Fig. 4. They show a good agreement within the errors.

4. Conclusion

We have derived the ANC of the $\langle ^{12}\mathrm{C} + n | ^{13}\mathrm{C}^*(1/2^+)\rangle$ state from a transfer reaction at very forward angles. The dependence of the ANC value on the DWBA parameters used in the analysis is shown to be relatively small. This method may therefore be considered to be a powerful tool for deducing direct neutron radiative capture cross sections.

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