The $S_{E1}$ factor of radiative $\alpha$ capture on $^{12}$C in effective field theory

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Abstract. The $S_{E1}$ factor of radiative $\alpha$ capture on $^{12}$C is studied in effective field theory. We briefly discuss the strategy for the calculation of the reaction and report a first result of $S_{E1}$ at the Gamow-peak energy, $E_G = 0.3$ MeV.

Keywords: Radiative alpha capture on carbon-12, $S_{E1}$ factor, effective field theory

1 Introduction

The radiative $\alpha$ capture on carbon-12, $^{12}$C($\alpha$, $\gamma$)$^{16}$O, is a fundamental reaction in nuclear-astrophysics, which determines the C/O ratio created in the stars [1]. The reaction rate, equivalently the astrophysical $S$-factor, of the process at the Gamow peak energy, $E_G = 0.3$ MeV, however, cannot be determined in experiment due to the Coulomb barrier. A theoretical model is necessary to employ in order to extrapolate the reaction rate down to $E_G$ by fitting model parameters to experimental data typically measured at a few MeV. In constructing a model for the study, one needs to take account of excited states of $^{16}$O [2], particularly, two excited bound states for $l_{\pi i-} = 1^-$ and $2^+$ just below the $\alpha$-$^{12}$C breakup threshold at $E = -0.045$ and $-0.24$ MeV, respectively, as well as two resonant (second excited) $1^-_2$ and $2^+_2$ states at $E = 2.42$ and $2.68$ MeV, respectively. The capture reaction to the ground state of $^{16}$O at $E_G$ is expected to be $E1$ and $E2$ transition dominant due to the subthreshold $1^-_1$ and $2^+_1$ states. See Refs. [2,3] for review.

Theoretical frameworks employed for the previous studies are mainly categorized into two [3]: the cluster models using generalized coordinate method [4] or potential model [5] and the phenomenological models using the parameterization of Breit-Wigner, $R$-matrix [6], or $K$-matrix [7]. A recent trend of the study is to rely on intensive numerical analysis, in which a large amount of the experimental data relevant to the study are accumulated, and a significant number of parameters of the models are fitted to the data by using computational power [8,9]. In the present work, we discuss an alternative approach to estimate the $S$-factor at $E_G$; we employ a new method for the study and briefly discuss a calculation of the $S_{E1}$ factor at $E_G$ based on an effective field theory [10,11].

1 The energy $E$ denotes that of the $\alpha$-$^{12}$C system in center of mass frame.
In the study of the radiative capture process, $^{12}$C($\alpha$, $\gamma$)$^{16}$O, at $E_G = 0.3$ MeV employing an EFT, one may regard the ground states of $\alpha$ and $^{12}$C as point-like particles whereas the first excited states of $\alpha$ and $^{12}$C are chosen as irrelevant degrees of freedom, from which a large scale of the theory is determined [12]. Thus the expansion parameter of the theory is $Q/A_H \sim 1/3$ where $Q$ denotes a typical momentum scale $Q \sim k_G$; $k_G$ is the Gamow peak momentum, $k_G = \sqrt{2\mu E_G} \simeq 41$ MeV, where $\mu$ is the reduced mass of $\alpha$ and $^{12}$C. $A_H$ denotes a large momentum scale $A_H \simeq 150$ MeV obtained from the first excited energy of $\alpha$ or $^{12}$C. An effective Lagrangian for the study is obtained in Eq. (1) in Ref. [14].

The capture amplitudes are calculated from the Feynman diagrams depicted in Figs. 1 and 2. One can find an expression of the amplitudes in Eqs. (6), (7), (8), and (9) in Ref. [14]. We note that the loop diagrams (a) and (b) in Fig. 1 are finite whereas those (d), (e), and (f) diverge. The divergence terms are renormalized by a counter term $h^{(1)}$ in a contact vertex in the diagram (c). Six parameters remain in the amplitudes. Four of them are effective range parameters of elastic $\alpha$-$^{12}$C scattering for $l = 1$ [13]. One of them is fixed by using the binding energy of the subthreshold $l = 1$ state of $^{16}$O, and the others are fitted to the phase shift data of the elastic scattering [15].
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3 Result

In the left panel of Fig. 3 we show the data and the fitted curve of the phase shift and find that the fitted curve well reproduces the data. The remaining two parameters, $h^{(1)}R$ and $y^{(0)}$, in the amplitudes are fitted to the $S_{E1}$ data [3], and we obtain $h^{(1)}R = -6.95(11) \times 10^2$ MeV$^3$ and $y^{(0)} = 0.495(18)$ MeV$^{-1/2}$, where the number of the data is $N = 151$ and $\chi^2/N \simeq 1.72$. In the right panel of Fig. 3 we show the data and the fitted curve for $S_{E1}$. At the Gamow peak energy, $E_G = 0.3$ MeV, thus, we obtain $S_{E1} \simeq 58$ keV b. An error estimate of $S_{E1}$ is now under investigation.

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