R-matrix analysis of $^{12}C(\alpha,\alpha)^{12}C$ reaction at low energies

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Introduction

The $^{12}C(\alpha,\gamma)$ reaction at 300 KeV [1] in helium burning stars determines the ratio of ^{16}O to ^{12}C abundance. This reaction is however almost impossible to measure at the Gamow energy owing to very small cross-section. The usual technique is to extrapolate the cross-section or astrophysical S-factor data at higher energies by R-matrix extrapolation.

In R-matrix extrapolation the information of some of the unbound states in terms of its position (energy) and/or the Asymptotic Normalization constant (ANC) can pose a great challenge for the analysis. The ANC of the sub-threshold states close to the threshold are thought to influence the capture cross-section if the tails of the wavefunction of these states extend above the threshold. In the $^{12}C(\alpha,\gamma)$ reaction the 7.12 and 6.92 MeV states have been found to influence the capture cross-section significantly. The determination of the ANC of these states are important in this reaction is thus important as they form the inputs for the R-matrix calculations.

The ANC is generally determined from transfer reactions [2]. In this method, the measured transfer angular distribution is compared with some direct reaction model calculation to determine the ANC. The main source of uncertainty in this method is the uncertainty in the nuclear potentials used in the direct reaction model calculations. The entrance and exit channel potential dependence can be reduced by measuring the transfer cross-sections at sub-Coulomb energies.

An alternate approach is the $^{12}C(\alpha,\alpha)$ elastic scattering. There are some extensive studies of $^{12}C(\alpha,\alpha)$ scattering at low energies to determine the spectroscopic properties of the bound states. At such energies resonance scattering can compete with Rutherford scattering. In a resonance scattering process the elastic channel is opened after the two interacting nuclei reside in a resonance state. Also they can interact through a non-resonant continuum but the latter can be overshadowed by Rutherford scattering. As for the gamma channel the non-resonant or direct capture as it is termed is influenced by the ANC of low lying subthreshold states. It is interesting to investigate whether these states play any role in the elastic scattering cross-section fit.

In this work, we have analyzed the data of Radovic et al [2] in terms of the R-matrix theory. We have used the phenomenological R-matrix program AZURE2 [3] that has been widely used for such analysis. In these analysis, only the resonance states are included. The question is whether the very close lying sub-threshold states have any effect on elastic scattering.

R-matrix phenomenology

In this method, the cross-sections are fitted with structure of the compound nucleus incorporated. The structure information are the energies and level widths (for unbound states) and ANC (for bound states) of ^{16}O. The level widths are measurable and are obtained from the nndc database. The ANCs of the different unbound states considered in AZURE2 calculations are given in the following table with references from where they are obtained.

Table 1: ANC (C^2) of various bound states of ^{16}O used in the AZURE2 calculations

Energies(MeV)	ANC(C^2) fm^{-1}	Ref
6.05(0^+)	$2.43*10^6$	[5]
6.13(3^-)	$1.93*10^4$	[5]
6.92(2^+)	$1.81*10^{10}$	[6]
7.12(1^-)	$76.8*10^{28}$	[6]

The best fit calculations of the data at two angles are shown in figs 1 and 2.

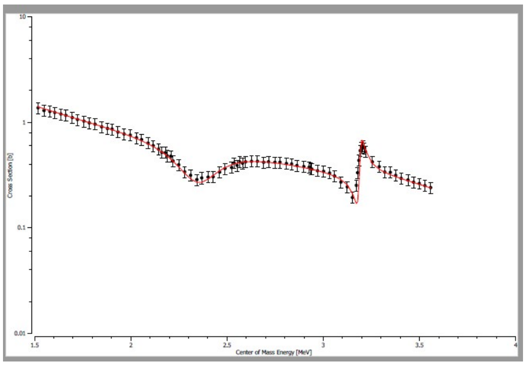

Fig. 1 (Color online) R-matrix (AZURE) fit (red line) to the low energy $^{12}C(\alpha,\alpha)^{12}C$ excitation function data of Ref.[2] (black symbol) at the angle 45 deg.

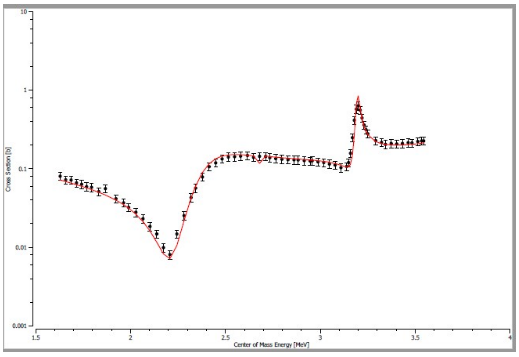

Fig. 2 (Color online) R-matrix (AZURE) fit (red line) to the low energy $^{12}C(\alpha,\alpha)^{12}C$ excitation function data of Ref.[2] (black symbol) at the angle 150 deg.

Results and Discussions

As the figures suggest, a reasonably good result can be obtained by considering both the bound and unbound state and one background pole. A unpublished analysis obtains a fit with several background poles and two unbound states (9.84 MeV and 10.32 MeV) excluding the bound states for the elastic scattering problem.

Interestingly the -45keV subthreshold state shows no effect on the fit whereas the -245 keV shows effect on the fit in terms of its ANC values. This interesting effect needs to be investigated in more detail in future.

References

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