Nuclear astrophysics with indirect methods

Shubhchintak*
Department of Physics and Astronomy,
Texas A&M University-Commerce, Commerce, TX - 75428, USA

In the area of astrophysics, it is well known that several different type of nuclear reactions are involved in the production of elements and for energy generation in stars. The knowledge of rates and cross section of these reactions is necessary in order to understand the origin of elements in the Universe. Particularly, interests are there in the processes like pp-chain, CNO cycle, r-process and s-process, which are responsible for the formation of majority of the nuclei via various reactions like (p, γ), (n, γ), (α, γ) etc.

Direct measurements in this direction, though preferable, are often very difficult to perform because the reaction cross sections are very small at astrophysical energies (tens or hundreds of keV/u), yields are low and unstable nuclei are involved. Furthermore, these measurements at low energies can also be affected by electron screening, which needs a difficult and uncertain treatment. An alternative way is to perform experiments at higher energies (few MeV/u) and then extrapolate the results down to the desired energies. But this procedure also involves considerable uncertainties. To overcome these difficulties alternative indirect methods are being used depending on the type of reaction involved. The Asymptotic Normalization Coefficient method the Coulomb dissociation method, the Trojan horse method, (d, p) and charge-exchange reactions are the ones which are being developed as indirect methods in nuclear astrophysics [1, 2].

In this talk I would discuss, the use of 'Trojan horse' method (THM) as an indirect method for calculating the cross section of the reaction having sub-threshold bound state in the initial channel and a real resonance in the exit channel.

The THM has been used in many theoretical and experimental studies of capture reactions with success. Although, initially it has been used for charged particle capture reactions, now it has also been extended to study direct neutron and resonant capture reactions. In the THM a suitable two-body to three-body reaction ($A + a \to x + B + y$) [called Trojan horse (TH) reaction] is used to extract the cross section of a relevant binary reaction ($A + s \to x + B$) at stellar energies. The particle $a = (sx)$ in the TH reaction is called TH particle and has dominant cluster structure. Kinematical conditions are set in a way that the cluster s interacts with target A, whereas the other cluster x remains as spectator. For this, the TH reaction is performed in Quasi-Free (QF) regime, which require that the relative momentum between the cluster s and x in the three-body phase space should be zero or small compared to the bound state (sx) wave number. Consequently, the interaction between the clusters s and x, would be small and they stay at large distance from each other. In addition to it, it is also required that the ground state angular momentum of the TH nucleus a should be small (preferably zero), which results in narrow momentum distribution and hence a large separation of the fragments $s-x$ and therefore x can be treated as a spectator.

In this method the TH particle is accelerated at energies above the Coulomb barrier so that a can dig into A and there is no possibility of additional Coulomb barrier between A and s. Therefore, the cross sections of the binary sub-process ($A + s \to x + B$) extracted from the TH processes do not contain the related Coulomb barrier and are free from electron screening and hence one can go

*Electronic address: Shub.Shubhchintak@tamuc.edu

even down to the relevant ultra-low stellar energies. The transfer particle s in the TH reaction acts as a virtual particle and therefore its energy and momentum are not related by the on-shell relation $E_s = k_s^2/2m_s$. As a consequence of this one can measure cross section of the binary reaction even at negative relative energies E_{sA}. One can obtain the half-off-energy-shell (HOES) cross section for the binary reaction from the measured cross section of TH reaction. This binary HOES cross section is then used to extract the quantity of interest, namely, the on-energy-shell cross section by normalization to the direct data available at higher energies. For more details of this method, one is referred to review article [1].

As an application of this method, I will discuss the case of α + ^{13}C $\rightarrow$ ^{17}O$^*(1/2^+, E =$ 6.356 MeV) $\rightarrow$ n + ^{16}O reaction. This reaction is a neutron generator in asymptotic giant branch stars and is a source of neutron for s-process. Here the $1/2^+$ state at 6.356 MeV is a subthreshold bound state with binding energy of -3 keV in the α + ^{13}C channel and is a resonance in the exit channel n + ^{16}O. The asymptotic normalization coefficient and astrophysical S factor for this reaction using the TH method for the first time has been obtained in Ref. [3]. In this talk our new findings for this reaction would be discussed.

I would also discuss about our ongoing work on (d, p) reaction study using the generalized Faddeev equations in Alt-Grassberger-Sandhas formalism [4], where the target excitations and Coulomb interactions are explicitly included. (d, p) reaction is also a type of TH reaction where the deuteron act as TH particle and here our goal is to get the information about neutron-induced reactions which are often difficult in direct measurements.

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