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STUDY OF COULOMB DISSOCIATION FOR NUCLEAR ASTROPHYSICS WITH SPECIAL REFERENCE TO THE NUCLEOSYNTHESIS

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ABSTRACT

This paper gives the knowledge about fragmentation of a fast moving loosely bound projectile (stable/radioactive) on to some light/heavy target is an important reaction channel. The fragments are produced either due to coulomb or nuclear or both interaction depending upon how close the projectile was to the target at the instant of dissociation. In case of light target and small impact parameter the break up occurs mainly through the nuclear interaction between the projectile and the target. The nucleosynthesis of the heavier elements in stellar environments have attracted much attention in nuclear astrophysics. The first two elements and their stable isotopes H and He emerged from high temperature and high density state of the expanding universe, the so called “Big-bang”. A small amount of Li was also produced in the Big–bang but the remainder of the Li isotopes and all of Be and B isotopes were produced by the interaction of cosmic radiation with the constituents of the inter stellar medium between stars .

Key Words: 1.Nuclear 2.Big-Bank,3.Astrophysics . 4.Nuclear Energy 5.Nucleosynthesis
Sub-Area: Nuclear Astrophysics
Broad-Area: Physics

Introduction

The fragments are produced either due to coulomb or nuclear or both interaction depending upon how close the projectile was to the target at the instant of dissociation. In case of light target and small impact parameter the break up occurs mainly through the nuclear interaction between the projectile and the target[4,5]. While, in a peripheral nuclear collision with impact parameter larger than the sum of the radii of colliding partners, the nuclear forces do not come into play and the projectile experiences, in the projectile frame of reference, a time varying electromagnetic field produced due to relative motion.

Problem of Solar Neutrino

According to standard solar model (ssm) the main source of energy production in the sun is the nuclear fusion reactions which in turn involve the emission of the neutrinos (ν_e)from several of nuclear β-decay or electron capture reactions. The ^{8}B β-decay is the major source of high energy neutrinos in the solar center. The discrepancy between the values of measured and predicted high energy neutrino flux is often referred to as the ^{8}B Solar Neutrino problem and is closely related to ^{7}Be(p,γ)^{8}B radiative capture reaction[6].

Nucleosynthesis of Heavier Elements in Stars

However, there exists ideas that some heavier nuclei might be produced in the inhomogeneous Big-bang scenarios leading to the production of ^{14}C [7,8,9] which is bottleneck for the production of other heavier nuclei. The various nuclear processes occurring in stars and in supernova are responsible for the formation of the heavy elements [10-14]. Two distinct neutron capture processes namely the s-process and r-process have been identified on the basis of quit different astrophysical environments [15]. The distinction is made largely on the basis of the relative life times for neutron capture (τ_n) and beta decays (τ_β). The condition $\tau_n > \tau_\beta$, ensures that the neutron capture path will itself remain close to the valley of beta stability. This defines the astrophysical s-process of neutron capture. In the limit of large neutron density $\tau_n << \tau_\beta$, it follows that successive neutron capture will proceed into the neutron rich region well off the beta stable valley and this process is termed as astrophysical r-process of neutron capture. This r-process neutron capture mechanism is expected to operate in an environment characterized by a very high neutron flux. The quantitative details of these processes can be obtained by knowing energy averaged neutron capture cross sections. Such data provide information on the mechanism of neutron capture process and time scales, as well as temperature involved in the process. The data should also shed light on neutron sources, required neutron fluxes and possible sites of the processes [3].

Besides neutron capture reactions (n,γ) two particles capture reactions are also important for the synthesis of heavy elements [4,5]. It is believed that the formation of the heavy elements take place via the recombination of free alpha particles, neutrons and protons. This generates an alpha-process leading to the formation of massive isotopes (upto A≈100) largely via alpha capture. Besides $^{4}\mathrm{He}(2\alpha,\gamma)\,^{12}\mathrm{C}$ and $^{4}\mathrm{He}(\alpha n,\gamma)\,^{9}\mathrm{Be}$, recombination of alpha particles is also possible via alternative three body reactions, depending on the initial neutron proton ratio X_n/X_p. Two-neutron capture reactions are not the only two particle capture reaction, the two-proton capture reactions are also of immense importance. The hot CNO cycle and the rp-processes have been proposed as the dominant nucleosynthesis processes in explosive hydrogen burning, which take place most notably in novae and X-ray bursts. At high temperature and density conditions the CNO cycles and the rp-process are linked by the capture reaction sequence $^{15}\mathrm{O}\,(\alpha,\gamma)\,^{19}\mathrm{Ne}(p,\gamma)\,^{20}\mathrm{Na}$ and the initial CNO material can be processed towards heavier nuclei as massive as Fe, Ni and beyond. Besides the above mentioned reactions the $^{12}\mathrm{C}(\alpha,\gamma)\,^{16}\mathrm{O}$ reaction [16] is a key one in the synthesis of heavier elements. Helium burning through $^{12}\mathrm{C}(\alpha,\gamma)\,^{16}\mathrm{O}$ at thermonuclear energies is a key process for the evolution of massive stars and for the nucleosynthesis of $^{16}\mathrm{O}$ and heavier elements up to Fe.

Process of Energy Production in Stars

Another astrophysical problem is related with the process of energy production in stars by hydrogen burning through CNO cycle. In the normal CNO cycle, the principle nuclear reaction sequence converts four hydrogen nuclei into an alpha particle [1]

$^{12}\mathrm{C}(p,\gamma)\,^{13}\mathrm{N}(\beta^{+},\nu)\,^{13}\mathrm{C}(p,\gamma)\,^{14}\mathrm{N}(p,\gamma)\,^{15}\mathrm{O}(\beta^{+},\nu)\,^{15}\mathrm{N}(p,\alpha)\,^{12}\mathrm{C}$

This hydrogen burning process is believed to be the principal source of energy in the core of main sequence stars in the temperature range $20\times10^{6}\,\mathrm{K}\leq T<10^{8}\,\mathrm{K}$ [17,18]. For higher temperature, in the range $T\approx1\text{-}2\times10^{8}$ K, it is expected that the $^{13}\mathrm{N}(p,\gamma)\,^{14}\mathrm{O}$ reaction will become faster than β decay of $^{13}\mathrm{N}$ [19,20]. The cycle then turns into the "hot" or β-limited CNO cycle, where the main sequence of reactions is [21]

$^{12}\mathrm{C}(p,\gamma)\,^{13}\mathrm{N}(p,\gamma)\,^{14}\mathrm{O}(\beta^{+},\nu)\,^{14}\mathrm{N}(p,\gamma)\,^{15}\mathrm{O}(\beta^{+},\nu)\,^{15}\mathrm{N}(p,\alpha)\,^{12}\mathrm{C}$

The "hot" CNO cycle is triggered when the mean life time for proton capture on $^{13}\mathrm{N}$, $\tau_p(^{13}\mathrm{N})$, becomes smaller than the positron decay life time , $\tau_{\beta}+(^{13}\mathrm{N})$. The mean life time $\tau_p(^{13}\mathrm{N})$ of $^{13}\mathrm{N}$ for interaction with protons is given by [22]

Where ρ is the matter density; N_A is the Avogadro's no; X_H is the hydrogen fraction by mass, and A_H=1.0078 amu is the hydrogen atomic mass. The term <σv> is the product of the reaction cross section σ(E) and the relative velocity v averaged over the Maxwellian velocity distribution at temperature T. Knowledge of the radiative capture cross section σ(E) at low energy is thus essential for an accurate description of the stellar environment where hydrogen burning through the β-limited CNO cycle can occur. Besides the above mentioned reactions there are various astrophysical phenomena where detailed information on rates of radiative capture reactions is needed as listed in the Table 1.1. Typically one needs to know these cross sections at very low collision energies corresponding to the relevant astrophysical temperature and at such low energies these cross sections are very small and very difficult to measure in the laboratory. The small value of the cross section may be attributed to the presence of coulomb barrier between the charged nuclei. Such small cross sections are accessible experimentally only after long data collection periods and painstaking attention to background and stability problems. Thus the direct experimental determination of the cross sections at astrophysically relevant energies under laboratory conditions is rather difficult or even precluded, mainly as the coulomb barrier strongly suppresses the cross sections for the reactions of interest. Therefore at present it is not possible to measure directly the reaction cross section at such a low energy. However, the coulomb dissociation process has recently attracted a great deal of attention as an alternative method, first suggested by G. Baur et al. [23] to study radiative capture reactions of astrophysical interest.

In the present work we use the nuclear coulomb field as a source of photo- disintegration process. In fact, instead of studying directly the radiative capture reaction
$b+c \rightarrow a+\gamma$
one may consider the time reversal process
$a+\gamma \rightarrow b+c$
Which is now known as coulomb dissociation reaction and occurs because of the relative motion between projectile ‘a’ and the target.
The coulomb breakup cross-section is now related to photo-disintegration cross section by the relationPhotoσ= γγγσdEdnECD, with is the virtual photon number, which in turn is related to radiative capture cross section via the detailed balance theorem [24]. γn
)()12)(12()12(2)(22cbakKjjjacbPhotocbacap+→++++=+→+γσγσγ,
where j_a, j_b and j_c represent the spin of a, b and c respectively while the wave number k of b+c system is given by 2..22ηmcbcEkμ= with reduced massbcμand the wave number associated with photon iscQEcEKmcηη)(..+==γγwith Q as Q-value of the capture reaction.
The differential scattering cross section is given by Rutherford law
Ω=−dadR)(sin412420σ 202vmeZZaTp=om , where θ is the scattering angle in the center of mass system and is half the distance of closest approach. The reduced mass of the projectile and the target is denoted by and v is the velocity of the target in **Table 1.1** Radiative capture reactions of astrophysical interest

Reactions	**Astrophysical Applications**
He (α, γ) ^{7}Be	^{3}He abundancy
^{7}Be (p, γ) ^{8}B	Solar Neutrino problem
^{4}He (d, γ) ^{6}Li	Primordial nucleosynthesis of Li, Be and B-isotopes
^{6}Li (p, γ) ^{7}Be	
^{6}Li (α, γ) ^{10}B	
^{4}He (t, γ) ^{7}Li	
^{7}Li(α, γ) ^{11}B	
9Be (p, γ) 10B	
^{7}Li (n, γ) ^{8}Li	Primordial nucleosynthesis in inhomogeneous Big-Bang
^{8}Li (n, γ) ^{9}Li	
^{12}C(n,γ) ^{13}C	
^{14}C(n,γ) ^{15}C	
14C(α,γ)18O	
^{12}C(p,γ) ^{13}N	CNO Cycle
^{16}O(p,γ) ^{17}F	
^{13}N(p,γ) ^{14}O	
20Ne(p,γ)21Na	
^{11}C(p,γ) ^{12}N	Hot p-p Chain
^{31}S(p,γ) ^{32}Cl	rp-process
^{16}O(α,γ) ^{20}Ne	Helium burning
14N(α,γ)18F	

projectile frame of reference and and ZpZ$_{T}$ denote the atomic numbers of projectile and the target respectively.

where P is the probability of excitation of projectile (coulomb break up state).

The probability P can be expressed in terms of the amplitudes for a transition from the initial nuclear state to the various final states and is given by ifa=PifΣ+fiMMifiaI2)12(1,

where is the spin of the initial nuclear state, and are the magnetic quantum numbers of the initial and final states and the transition amplitude by using first order time dependent perturbation theory is given by [25] iIiMfMifa dteitHfiatiiffiω∫∞∞−−〉 〈 =)()('1η, where fiω defines the Bohr’s angular frequency with and as the energies of the initial and final nuclear states respectively. represent the total interaction energy.

The total excitation cross section of orderλE, obtained by integration over all scattering directions is given by
),()(2221ξλσλλλEEfEBaveZd+−□□□□□□□=η
whereΩΩ=∫dddffEE),()(ξθξλλ = ∫Σ+πθθλμμλθξθπλπ02322233sincos),()0,2()12(16dIYE
andλEB() represents the reduced transition probability associated with a radiative transition of multipole order λE and
[]ωωωωξθμλμωωξλμdieIi∫∞∞−++∈ +∈ −∈ +∈ +=)1cosh(sinh)1(cosh),(212)sinh(.
The parameter ξ represents the ratio between collision time and nuclear excitation time and is thus measure of extent to which the process is adiabatic.
As mentioned earlier the dominating transition in radiative capture reactions is electric dipole one. Thus we concentrate only on the predominant electric dipole transition in the coulomb excitation also. The matrix element corresponding to this transition conveniently obtained within the cluster model of the projectile wherein it is given as [26]
⟨ ⟩ ffiiMIEmMI),(μλ=e=
⟩ ⟨ iiffMIEmMI),(*μλ[][]).()()1(2!)2()(122121qYqqZZixxbbλμλλλλλλληββλπη+++×−+×−
Now capσcan be connected with astrophysical S-factor through the relation
)2.(exp)(....πησMCcapMCEES=,
with and ..MCEη as the relative energy and coulomb parameter respectively.
The coulomb break up reactions have been investigated theoretically by several authors using different approaches such as First Order Perturbation Theory [27], Virtual Photon Method [28], Distorted Wave Born Approximation(DWBA) [29], Coupled Channel Theory [30], Eikonal Approximation [31], Sudden Approximation Theory [31] etc. In the present work, we have adopted the most frequently used first order perturbation theory to describe the coulomb breakup mechanism.

As an example, we have calculated the astrophysical S-factor for ^{8}Li(n,γ)^{9}Li reaction as a function of relative energy and the result so obtained has been presented in figure. The contribution of electric dipole and electric-quadrupole transition towards S-factor is also shown in the same figure which indicates that the coulomb breakup reactions predominately occur due to the dipole transition and the contribution of electric quadrupole transition is ignorable at low energy while it does become relevant at higher energies.

CONCLUSIONS

We have reviewed the current experimental work on the coulomb dissociation reactions and drawn the following important conclusions. The astrophysical S-factor of ^{7}Be(p,γ)^{8}B reaction was deduced from 0.6 to 1.7 MeV center-of-mass energy leading to $S_{17}(0) = 16.7 \pm 3.2$ eVb which is appreciably smaller than the value obtained through the Standard Solar Model (SSM). The experimentally extracted E2 component for $^{208}Pb(^{8}B, ^{7}Be\text{-}p)^{208}Pb$ reaction was found to be considerably smaller than any theoretical prediction for $E_{rel} < 1.75$ MeV. The $S_{17}(0)$ was modified for the E2 component, when the dominant theoretical uncertainty in ^{8}B coulomb breakup measurement was properly accounted. The S-factors extracted from breakup data, even exceed 0.15 KeVb with considerable uncertainties below 100 KeV because of the measurements suffered from degradation of the energy resolution in this region.

Role of nuclear and nuclear-coulomb interference effects in the dissociation mechanism. Higher order effects of multipole transitions in the process of coulomb excitation. Effects of higher order dynamical processes like post acceleration etc.

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