ISSN 0976 – 1411

Available online at www.internationaleJournals.com

International eJournals

INTERNATIONAL eJOURNAL OF MATHEMATICS AND ENGINEERING

www.InternationaleJournals.com

International eJournal of Mathematics and Engineering 20 (2010) 203 - 211

IMPORTANCE OF COULOMB DISSOCIATION FOR NUCLEAR ASTROPHYSICS

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Abstract

To understand various nuclear processes like generation of energy during evolutions of stars, supernova explosions, big-bang, solar neutrino problem etc., one need to know nuclear reaction cross sections at very low collision energies corresponding to the relevant astrophysical temperatures. Most of the astrophysical processes are related to some radiative capture reactions at low energies. Thus the knowledge of some specific radiative capture reaction cross-section is a key to explain these processes. Some astrophysical problems of current importance along with the associated radiative capture reactions are listed. This paper gives the knowledge about fragmentation of a fast moving loosely bound projectile (stable/radioactive) onto 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. 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 of the

Key Words: 1.Nuclear 2.Astrophysics 3.Component 4.Energy 5.CNO Cycles 6.Nucleosynthesis.
Sub-Area: Nuclear Astrophysics
Broad-Area: Engineering 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. 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.

Nucleosynthesis of Heavier Elements in Stars

The nucleosynthesis of the heavier elements in stellar environments have attracted much attention in nuclear astrophysics [4,5]. 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 [6]. 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 $A \approx 100$) largely via alpha capture. Besides

$^{4}He(2\alpha,\gamma)^{12}C$ and $^{4}He(\alpha n,\gamma)^{9}Be$, 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 $^{15}O(\alpha,\gamma)^{19}Ne(p,\gamma)^{20}Na$ and the initial CNO material can be processed towards heavier nuclei as massive as Fe, Ni and beyond. Besides the above mentioned reactions the $^{12}C(\alpha,\gamma)^{16}O$ reaction [16] is a key one in the synthesis of heavier elements. Helium burning through $^{12}C(\alpha,\gamma)^{16}O$ at thermonuclear energies is a key process for the evolution of massive stars and for the nucleosynthesis of ^{16}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]

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

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

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

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

$$\tau_p\left(^{13}N\right)=\left[\rho N_A\frac{X_H}{A_H}<\sigma v>\right]^{-1}.$$

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 $<\sigma v>$ 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 relation $\sigma_{Photo} = \frac{E_\gamma}{n_\gamma}\frac{d\sigma_{CD}}{dE_\gamma}$, with n_γ is the virtual photon number, which in turn is related to radiative capture cross section via the detailed balance theorem [24].

$$\sigma_{cap}(b+c \rightarrow a+\gamma) = \frac{2(2j_a+1)}{(2j_b+1)(2j_c+1)}\frac{K_\gamma^2}{k^2}\sigma_{Photo}(a+\gamma \rightarrow b+c),$$

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 $k^2 = \frac{2\mu_{bc}E_{c.m.}}{\eta^2}$ with reduced mass μ_{bc} and the wave number associated with photon is $K_\gamma = \frac{E_\gamma}{\eta c} = \frac{(E_{c.m.}+Q)}{\eta c}$ with Q as Q-value of the capture reaction.

The differential scattering cross section is given by Rutherford law

$d\sigma_R = \frac{1}{4}a^2\sin^{-4}(\theta/2)d\Omega$, where θ is the scattering angle in the center of mass system and $a = \frac{Z_p Z_T e^2}{m_0 v^2}$ is half the distance of closest approach. The reduced mass of the projectile and the target is denoted by m_o and v is the velocity of the target in

Table 1.1 Radiative capture reactions of astrophysical interest

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

projectile frame of reference and Z_p and Z_T denote the atomic numbers of projectile and the target respectively. As orbit of particle is not appreciably affected by the excitation, the differential cross section is given by

$$d\sigma_{BU} = P d\sigma_R ,$$

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

The probability P can be expressed in terms of the amplitudes a_{if} for a transition from the initial nuclear state i to the various final states f and is given by $P = \frac{1}{(2I_i + 1)} \sum_{M_i M_f} |a_{if}|^2$,

where I_i is the spin of the initial nuclear state, M_i and M_f are the magnetic quantum numbers of the initial and final states and the transition amplitude a_{if} by using first order time dependent perturbation theory is given by [25]

$$a_{if} = (i\eta)^{-1} \int_{-\infty}^{\infty} \left| \langle f \left| H^{'}(t) \right| i \rangle \right| e^{i\omega_{fi} t} dt ,$$

where ω_{fi} defines the Bohr's angular frequency with E_i and E_f as the energies of the initial and final nuclear states respectively. $H^{'}(t)$ represent the total interaction energy which is given as

$$H^{'}(t) = H_E(t) + H_M(t)$$

with $H_E(t)$ and $H_M(t)$ as the electric and magnetic interaction energy respectively.
The total excitation cross section of order $E\lambda$, obtained by integration over all scattering directions is given by

$$d\sigma_{E\lambda} = \left(\frac{Z_1 e}{\eta v}\right)^2 a^{-2\lambda+2} B(E\lambda) f_{E\lambda}(\xi),$$

where $f_{E\lambda}(\xi) = \int \frac{df_{E\lambda}(\theta,\xi)}{d\Omega} d\Omega \; = \; \frac{16\pi^3}{(2\lambda+1)^3} \sum_{\mu} \left| Y_{E\lambda}(\frac{\pi}{2},0) \right|^2 \int_0^{\pi} \left| I_{\lambda\mu}(\theta,\xi) \right|^2 \frac{\cos \theta/2}{\sin^3 \theta/2} d\theta$

and $B(E\lambda)$ represents the reduced transition probability associated with a radiative transition of multipole order $E\lambda$ and

$$I_{\lambda\mu}(\theta,\xi) = \int_{-\infty}^{\infty} e^{i\xi(\in \sinh \omega + \omega)} \frac{\left[\cosh \omega + \in + i(\in^2 - 1)^{1/2} \sinh \omega\right]^{\mu}}{(\in \cosh \omega + 1)^{\lambda+\mu}} d\omega \, .$$

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]

$$\begin{aligned} \langle I_i M_i | m(E\lambda,\mu) | I_f M_f \rangle &= \langle I_f M_f | m^*(E\lambda,\mu) | I_i M_i \rangle \\ &= e(-i)^{\lambda} (2\pi\eta)^{1/2} \lambda! 2^{\lambda+1} \times \left[Z_b \beta_b^{\lambda} + (-1)^{\lambda} Z_x \beta_x^{\lambda} \right] \times \left[q^{\lambda} / (\eta^2 + q^2)^{\lambda+1} \right] Y_{\lambda\mu}(q). \end{aligned}$$

Now σ_{cap} can be connected with astrophysical S-factor through the relation

$$S(E_{C.M.}) = \sigma_{cap} E_{C.M.} \exp.(2\pi\eta) \, ,$$

with $E_{C.M.}$ and η 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 $^{8}Li(n,\gamma)^{9}Li$ 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.

(1) 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).

(2) The experimentally extracted E2 component for ^{208}Pb(^{8}B,^{7}Be-p)^{208}Pb reaction was found to be considerably smaller than any theoretical prediction for $E_{rel} < 1.75$ MeV.

(3) The $S_{17}(0)$ was modified for the E2 component, when the dominant theoretical uncertainty in ^{8}B coulomb breakup measurement was properly accounted.

(4) The angular correlation of the particles emitted in the coulomb breakup ^{7}Be(p,γ)^{8}B reaction at 254*A*MeV demonstrated that E1 multipolarity dominates and that E2 multipolarity can be neglected.

(5) Projectile breakup near particle thresholds may provide indirect access to radiative- capture-processes at astrophysical energies where extrapolation has been known to be the major cause of associated uncertainties.

(6) By setting tight constraints to the scattering angle and analyzing p-^{7}Be angular correlations, a significant contribution from E2 multipolarity can be excluded.

(7) The S_{17} distribution as a function of the p-^{7}Be relative energy agree well with lower group of the (p,γ) results and coulomb dissociation results at low E_{rel}. The discrepancy at higher E_{rel} may be due to neglects of an E2 component which in a proper theoretical treatment might affect the high E_{rel} data points.

(8) 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.

Further, for more accurate determination of the S_{17} factor by the use of coulomb dissociation, the following issues are to be addressed properly.

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

As a result, a lot of work both theoretical as well as experimental is being carried out all over the world even now to extract more accurate and precise information about astrophysical problems through coulomb breakup reactions.

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