Chapter 1

Introduction

“It is of particular interest to study the simplest nuclear system i.e. the diplon which almost certainly consists of a proton and a neutron. In dealing with such a two body problem, the wave equation can be rigorously solved if the forces are known and this problem therefore has the same importance for nuclear mechanics as the hydrogen atom has for atomic theory [29]”.

1.1 Historical Background

The photodisintegration of deuteron and its inverse reaction are of interest not only to nuclear physics as it provides a sensitive probe of nuclear force but also to astrophysics, in the neutron energy range of the order 10 to $10^2$ keV in c.m., in the context of Big Bang Nucleosynthesis and stellar evolution [6, 7, 9]. Among the many experimental and theoretical studies which reveal important aspects of nuclear forces, the most significant in the early days have been those centered on the low energy $p - p$ and $n - p$ elastic scattering. The radiative capture of thermal neutrons by protons [30, 31, 32] furnished the first evidence that the singlet $^1S_0$ interaction corresponds to a virtual state, in contrast to the existence of the real bound state of $^2H$ in the $^3S_1$ channel.
Along with the cosmic microwave background radiation[4] and Hubble expansion[5], the Primordial Nucleosynthesis has emerged as one of the corner stones of big bang cosmology[12]. The Big Bang Nucleosynthesis (BBN) plays a key role in forging the connection between cosmology and nuclear and particle physics as it involves the events that occurred at temperatures of order 1 MeV [8, 9]. As the Universe cools from an astounding $10^{32}$ K to temperatures $\approx 10^9$ K, four light nuclei viz., $^2$H, $^3$He, $^4$He and $^7$Li are produced in significant amounts [33, 34], which depend on the baryon density $\Omega_B$. The yield of $^4$He is the largest and is known to a theoretical uncertainty of less than 0.1% [35]. At this accuracy, the uncertainty in the abundance is dominated by the experimental uncertainties in the neutron life time. The recent precision determinations [36] of neutron life time using Penner trap techniques have thus attracted considerable attention, in this context. The first step in the success story of BBN was in fact taken while establishing the primeval abundance of $^4$He [37]. Measurements of $^3$He were also carried out in the solar wind, meteorite and lunar soil [38]. These provide constraints [8] on the deuterium abundance. Based on solar wind and meteoritic measurements [39], Reeves, Audouze, Fowler and Schramm [40] emphasized the cosmological origin of deuterium. Therefore, the detection of deuterium provided an important evidence in favour of BBN.

The Big bang nucleosynthesis or primordial nucleosynthesis is initiated by np fusion reaction ($T \approx 10^9$ K, about 100 keV) and the production of deuterium becomes significant at this temperature. Smith, Kawano and Malaney [10] have compared the various deuterium creating reactions like $p(n, \gamma)d$, $^3He(\gamma, p)d$, $t(\gamma, n)d$, $^6Li(\gamma, \alpha)d$ and find that almost all the deuterium is produce by $n – p$ fusion reaction. The contribution to deuterium production by other processes is comparatively much less [10]. The
deuterium creation and destruction reactions are as shown in the Figures 1.1 and 1.2. Interstellar measurements [41] made by the Copernicus Satellite and the conclusive argument [42] which showed that no realistic astrophysical process could produce significant deuterium led to the realization that primordial deuterium is burnt to $^3$He. On the other hand, determination of deuterium abundance has been notoriously difficult and is plagued by large uncertainties as it is a fragile isotope, which burns at a temperature of $10^6$ K because of its low binding energy. As such it is rapidly destroyed in the stellar interiors. In a comprehensive evaluation of the reaction rates and uncertainties in 1993, Smith et al., [10] have pointed out: “With a binding energy of 2.22 MeV, deuterium is the most fragile of the primordial isotopes: it is rapidly destroyed in stellar interiors.... Given that significant quantities of deuterium can only be produced during primordial nucleosynthesis, detection of deuterium provides important evidence in favor of the big bang model... Given the range of D/H observed in the interstellar medium, it is difficult to directly determine a lower limit... a determination of the upper limit is plagued by uncertainties arising from chemical evolution effects. The ratio of the primordial abundance of deuterium to that observed today could be anywhere between 1 and 50". However astronomical observations of deuterium abundance in High red shift hydrogen clouds [11] and the measurements obtained with NASAs FUSE satellite [43] have improved the scenario on the astronomical side. ‘Understanding how much of deuterium was created in the Big Bang and how much has been destroyed over time are two Holy Grails of modern astrophysics’ [43]. In a re-examination of the estimates of the uncertainties in 1999 to sharpen the predictions of big bang nucleosynthesis (BBN), Burles, Nollett, Truran and Turner [12] have observed: “Our method breaks down for the process $p + n \rightarrow d + \gamma$. This is because of a near-complete lack of data at the energies relevant for BBN. The approach used for this reaction is a constrained theoretical model that is normalized to high precision
Considerable interest centers also on the determination of the primordial deuterium abundance, not only because it facilitates, in turn, the accurate predictions of the abundances of $^3\text{He}$, $^4\text{He}$ and $^7\text{Li}$, but also because it pins down the primordial baryon density, $\Omega_B$ since it varies sharply with the density. It is therefore referred to as the COSMIC BARYOMETER. The predicted abundances of light elements, as a function of the baryon density is shown in Figure 1.3.

‘One of the great successes of the big bang theory is that it predicts the light element abundances in the Universe with reasonable accuracy. However, the exact abundance predictions depend on the cosmic baryon density. The abundance most sensitive to $\Omega_B$ is deuterium, so measuring the primordial deuterium-to-hydrogen ratio has become an important method for constraining $\Omega_B$ in cosmological models’ [44].

Laboratory measurements and decisive developments in astronomical observations go hand in hand to remove crucial ambiguities in nuclear physics input parameters and sharpen theoretical predictions in the astrophysical context. Thus the work of Burles et al., [12] catalyzed the first experimental study [13] on the analyzing power $\Sigma(\theta)$ in deuteron photodisintegration using 100% linearly polarized photons from the High Intensity Gamma-ray source (HIGS) at the Duke Free Electron Laser Laboratory. It was followed by further studies [14, 15, 16, 17, 18, 19]. These measurements have been analyzed, using a theoretical formalism [45] where the isovector $M_{1v}$ and isovector $E_{1v}$ multipole contributions (which are dominant at energies of thermal neutron capture and deuteron photodisintegration respectively) were calculated separately. However it is important to examine whether there are contributions arising out of these two am-
plitudes and also to examine the role of the isoscalar $M_{1s}$ and $E2_s$ amplitudes which are usually assumed to be small. This is particularly relevant to astrophysical energies since the theoretical studies [20, 21, 46] have shown that the $M_{1s}$ amplitude which is dominant at thermal neutron energies comes down sharply with energy while the $E1_s$ amplitude makes a small beginning in this energy region and then increases with energy. It is pertinent to note that the $E1_s$ and $M1_s$ strengths are approximately equal at around c.m. neutron energy of order 500 keV [23] (as shown in Figure 1.4).

1.2 Photodisintegration of $^2H$

The two reactions $d + \gamma \rightarrow n + p$ are related by time reversal and hence the cross sections are related by the principle of detailed balance. The exothermic fusion reaction can take place at energies $E_n$ as low as $10^{-6}$ keV (thermal neutron fusion) whereas the endothermic photodisintegration has a threshold energy determined by the binding energy (2.226 MeV) of the deuteron. The experimental study of these reactions has a rich history going back to the measurements by Chadwick and Goldhaber [47] in 1935 and by Fermi and his group [30, 31] in 1936. It may be noted that the studies on photodisintegration of the deuteron are well documented [48, 49, 50] at lab photon energies $E_L \gamma \geq 2.33$ MeV and a large number of measurements exist for the $n - p$ fusion cross section at thermal neutron energies which correspond to $E_L n = 10^{-5}$ keV [51, 52]. On the other hand, due to the tendency of neutrons to thermalize at low energies, it is only by 1995 that first measurements of the fusion were reported [22] at laboratory neutron kinetic energies $E_L n = 20, 40$ and 64 keV, followed by another measurement [23] at 550 keV. A summary of the data is shown in Tables 1.1 and 1.2. The thermal neutron cross-section [51, 52] of around 334.2 mb for fusion, has traditionally been interpreted as an isovector $M1_v$ transition from the $^1S_0$ state of the $n - p$ system in the continuum.
Introduction

On the other hand the isovector $E_{1v}$ transition has long been known to be primarily responsible for deuteron photodisintegration at photon energies $E_{\gamma} > 2.62$ MeV.

The cross-sections for photodisintegration [48, 49, 50] are of the order of millibarns as seen from Table 1.2. It is worth noting from Table 1.1 that the fusion cross-section in the range of energies of astrophysical interest is small by a factor of $10^{-3}$ to $10^{-4}$ of the thermal neutron cross-section. The earliest estimates of the reaction rates by Fowler, Caughlan and Zimmerman (FCZ) [53] used the theoretical calculations [54] of deuteron photodisintegration normalized to the then available thermal neutron radiative capture cross section measurements [55]. Potential model calculations for thermal neutron fusion [56] and photodisintegration [57, 58, 59] revealed appreciable differences between theory and experiment. The twin facts that the $^1S_0$ scattering length of $(-23.714 \pm 0.013)$ fm is large and the isovector magnetic moment is 5 times larger than the isoscalar magnetic moment, clearly lend support to the dominance of the isovector $M1$ amplitude. The possibility of an isoscalar $M1$ amplitude contributing to the radiative capture from the initial $^3S_1$ state was completely ignored based on the orthogonality arguments in the early years. Breit and Rustgi [60] were the first to propose a polarized target-beam experiment to look for an isoscalar magnetic dipole amplitude denoted as $M1_s$, in view of the then existing 10% discrepancy between theory and experiment in the case of thermal neutron capture by protons. The meson exchange current contributions (MEC) suggested by Riska and Brown [61] explained this discrepancy with surprising accuracy.

Theoretical calculations [20] including MEC, isobar currents and pair currents show that the $M1_v$ strength decreases sharply with energy, while the isovector $E1$ strength increases with energy and becomes comparable to the $M1$ strength at $E_n$ of order 500 keV. This is shown in Figure 1.4. Nagai et al, [23] have pointed out that “the theory
is in good agreement with the cross section measured for neutrons above 14 MeV, but it deviates by about 15% from the measured cross section of the $d(\gamma, n)p$ reaction by using the $\gamma$ ray of between 2.5 and 2.75 MeV [62], corresponding to neutron energies of 550 and 1080 keV”. In several theoretical works [57, 63, 64], it was also predicted that photoneutrons should be polarized due to the interference of the $M1$ amplitude with the $E1$ amplitude, which is normally dominant at higher energies. While the measurements of John and Martin [65] with 2.75 MeV $\gamma$-ray were found to be in good agreement with the calculations of Kramer and Müller [64]. A more precise experimental study [66] at $E_\gamma = 2.75$ MeV (which corresponds to $E_n = 1080$ keV) found that the magnitude of the polarisation was $(12 \pm 7)$% smaller than Kramer’s theoretical calculation using effective range theory.

Measurements of the neutron polarization [67] in photodisintegration for $E_\gamma$ in the energy range 6 to 13 MeV as well as of the analyzing power [68] in fusion with polarized neutrons for $E_n$ in the energy range 6 to 13.43 MeV were found to differ from theoretical estimates which included MEC contributions. In fact, it has also been pointed out by Rustgi, Vyas and Chopra [69] that there is an unambiguous disagreement between theory and experiment when a comparison is made with the data at a photon energy of 2.75 MeV. They pointed out moreover, that the inclusion of the two body effects widens this disagreement.

Using the accumulated data of neutron capture at thermal energies and energies higher than 14 MeV, Hale et al. [70] revised the FCZ [53] estimates while Ohtsubo et al., [71] carried out calculations, taking into account the MEC contributions. These estimates are in agreement with each other but are higher than the FCZ estimates [53] by about 15% between 10 keV to 100 keV and lower at energies above 700 keV.
Introduction

A first measurement of circular polarization $P_\gamma$ of photons [72] to detect their presence was not quite encouraging but a subsequent measurement [73] yielded a value of $P_\gamma = (-2.29 \pm 0.9) \times 10^{-3}$. To explain this large value, a six quark admixture was introduced [74] into the deuteron wave function which however led to a disagreement with the magnetic moment of the deuteron. A recalculation [75] of $P_\gamma$ taking into account the main contribution $P^1_\gamma(M1)$ from the isoscalar $M1$ transition, together with a relativistic correction $P^2_\gamma(M1)$ to the above and a contribution $P_\gamma(E2)$ from the isoscalar $E2$ transition yielded a value of $(-1.1 \times 10^{-3})$ within an accuracy of 25%. This was found to be in reasonable agreement with the latest measured value [76] of $(-1.5 \pm 0.3) \times 10^{-3}$. Photodisintegration experiments have focussed attention on measuring the angular distribution [77] to extract the relative contributions of the $E1$ and $M1$ amplitudes. An experimental study [78] of the disintegration has also been carried out using a polarized beam from Bremsstrahlung source at $\gamma$-ray energies between 5 and 10 MeV. The relative strengths of $M1_v$ and $E1_v$ have also been discussed in several studies using effective field theory [79]. While the role of isoscalar $M1_s$ have been discussed by Chen et al., [25] and Park et al., [80] using different versions of effective field theory. The predictions of these two versions led to an experimental measurement of the $\gamma$ anisotropy by Muller et al., [81]. Although the measured value of $(1.0 \pm 2.5) \times 10^{-4}$ for the $\gamma$ anisotropy $\eta$ was not sufficiently sensitive to distinguish between the two theoretical predictions, we may use Eq. (2) of Müller et al., [81] to estimate the ratio $R$ of the triplet to singlet capture cross sections to be $1.202 \times 10^{-3}$. If we multiply $R$ by the well-known cross section [51], we get an estimate of $401.7 \, \mu b$ for the $^3S_1$ contribution to the cross section at thermal neutron energies. Quite surprisingly, this number is of the same order as the measured cross sections for capture at astrophysical energies of 20, 40 and 64 keV [22]. In fact, it is even larger by a factor of 10 than the measured cross section at 550 keV [23]. Therefore one has to consider
Introduction

carefully, not only the relative contributions of isovector $M1$ and $E1$ contributions but also the contribution of isoscalar $M1$ amplitudes at the energies relevant to BBN. The calculations of $E2_s$ contributions have also been discussed by Chen et al., [25] and Hadjimichael et al., [24]. Although the $E1_v$ transition dominates photodisintegration of deuteron, the $E2_s$ contributions, though small, has been considered to be still significant [82].

More recently, it was shown [83] using a model independent theoretical approach that the photon polarization arising out of the interference of the dominant isovector $M1_v$ amplitude at thermal neutron energies with the small isoscalar $M1_s$ and $E2_s$ amplitudes can be studied with advantage in suitably designed polarized beam and polarized target experiments. Appropriate spin observables have been identified [84] to determine empirically the initial spin triplet and singlet contributions to the differential cross-section of the fusion reaction. When the initial preparation of the neutron and proton polarizations $P(n)$ and $P(p)$ are such that they are either opposite to each other or orthogonal to each other, the interference of the small isoscalar amplitudes with the large isovector amplitude could substantially contribute to the observable photon polarization. Attention has also been focussed on the spin response of the deuteron, i.e., the asymmetry of photoabsorption with respect to parallel and antiparallel spins of photon and deuteron and the Gerasimov-Drell-Hearn (GDH) sum rule [85, 86] by Arenhovel et al. [87], who have also considered other polarization observables in electromagnetic deuteron break-up [88] and compare their formalism with that of Dmitrasinovic and Gross [89]. We might also mention an experimental measurement of recoil proton polarization in electrodisintegration of deuteron by polarized electrons [90].

In view of the above theoretical and ongoing experimental studies, it is felt that a
detailed theoretical study of the spin structure of the amplitudes in photodisintegration of deuterons and their expansion in terms of 'electric' and 'magnetic' amplitudes is needed to analyze measurements of spin observables, which leads to a more incisive understanding of the problem at the range of energies interest to astrophysics and hence for sharpening the predictions of BBN.

1.3 Kinematical Considerations

Let us consider a beam of photons with energy $E^L_\gamma$ incident on a deuteron target which is at rest in the laboratory. We use natural units with $c = 1$ and $\hbar = 1$. The lab momentum $k^L_\gamma$ of the photon is then given by

$$|k^L_\gamma| = E^L_\gamma.$$  \hspace{1cm} (1.1)

Since the deuteron is at rest the total momentum $p^L_T$ and the total energy $E^L_T$ of the two particle system in the laboratory are given by

$$p^L_T = k^L_\gamma; \quad E^L_T = E^L_\gamma + M_d,$$  \hspace{1cm} (1.2)

where $M_d$ denotes the mass of the deuteron.

The invariant mass $W$ associated with the system is given by

$$W = \sqrt{E^L_T^2 - |p^L_T|^2} = \sqrt{M_d^2 + 2E^L_\gamma M_d}.$$  \hspace{1cm} (1.3)

The invariant mass $W$ has a velocity

$$v = \frac{|p^L_T|}{E^L_T},$$  \hspace{1cm} (1.4)
in the laboratory, while it is at rest in the c.m. frame. The total energy $E$ in the c.m. frame, which is usually referred to as the c.m. energy, is then identical with $W$ and is given by

$$E = \sqrt{M_d^2 + 2E_L^2M_d}.$$  \hspace{1cm} (1.5)

The c.m. frame for any reaction is defined as one in which the total momentum $(p_{c.m.}^T) = 0$ and as such the photon and the deuteron will have equal and opposite c.m. momenta $k$ and $-k$. In general, if there are two particles with masses $M_1$ and $M_2$ such that $p_1 + p_2 = 0$; $E_1 + E_2 = W$ in c.m. frame, we can readily determine $E_1$ and $E_2$ as follows. We note that

$$E_1 = (|p_1|^2 + M_1^2)^{1/2}; \quad E_2 = (|p_2|^2 + M_2^2)^{1/2},$$  \hspace{1cm} (1.6)

and express

$$E_2 = (E_1^2 - M_1^2 + M_2^2)^{1/2}.$$  \hspace{1cm} (1.7)

We have the total energy

$$E = E_1 + (E_1^2 - M_1^2 + M_2^2)^{1/2} \quad \text{or} \quad E - E_1 = (E_1^2 - M_1^2 + M_2^2)^{1/2}.$$  \hspace{1cm} (1.8)

Squaring both sides and eliminating $E_1^2$ we have

$$E_1 = \frac{E^2 + M_1^2 - M_2^2}{2E}.$$  \hspace{1cm} (1.9)

Thus the energies $E_\gamma, E_d, E_n$ and $E_p$ of the photon, deuteron, neutron and proton respectively are given by

$$E_\gamma = |k| = \frac{E^2 - M_d^2}{2E}, \quad E_d = \frac{E^2 + M_d^2}{2E},$$  \hspace{1cm} (1.10)
in the initial state and
\[ E_n = \frac{E^2 + M_n^2 - M_p^2}{2E}, \]  
\( (1.11) \)
\[ E_p = \frac{E^2 + M_p^2 - M_n^2}{2E}, \]  
\( (1.12) \)
in the final state of the reaction. The threshold energy for this endothermic reaction corresponds to
\[ E = M_n + M_p. \]  
\( (1.13) \)
The corresponding lab photon threshold energy is then given by
\[ (E_{\gamma}^L)_{th} = \frac{(M_n + M_p)^2 - M_d^2}{2M_d}, \]  
\( (1.14) \)
on using Eqs. (1.5) and (1.13). We may write the numerator in Eq. (1.14) as \((M_n + M_p - M_d)(M_n + M_p + M_d)\) and recognize the first term as the binding energy of the deuteron, which is 2.23 MeV.

Choosing the beam direction to be along z-axis, as usual, the velocity \(v\) of the c.m. frame along the z-axis, any momentum-energy four vector \((p, E)\) transforms from Lab to c.m through the Lorentz transformation given by
\[
\begin{bmatrix}
  p_{x}^{cm} \\
  p_{y}^{cm} \\
  p_{z}^{cm} \\
  E^{cm}
\end{bmatrix}
= 
\begin{bmatrix}
  1 & 0 & 0 & 0 \\
  0 & 1 & 0 & 0 \\
  0 & 0 & \alpha & -\beta \\
  0 & 0 & -\beta & \alpha
\end{bmatrix}
\begin{bmatrix}
  p_{x}^{L} \\
  p_{y}^{L} \\
  p_{z}^{L} \\
  E^{L}
\end{bmatrix}
\]  
\( (1.15) \)
where \(\alpha = \frac{1}{\sqrt{1-v^2}}\) and \(\beta = \frac{v}{\sqrt{1-v^2}}\).

In particular, if we consider the four vector \((\vec{0}, W)\) in c.m., it transforms into total
momentum and energy \((p_L^p, E_L^p)\) given by Eq. (1.2) through the inverse Lorentz transformation and is given by

\[
\begin{bmatrix}
0 \\
0 \\
p_L^p \\
E_L^p + m_d
\end{bmatrix}
= \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & \alpha & \beta \\
0 & 0 & \beta & \alpha
\end{bmatrix}
\begin{bmatrix}
0 \\
0 \\
W
\end{bmatrix}
\] (1.16)

From the above equation, it is clear that

\[
\alpha = \frac{E_L^p + M_d}{W}; \quad \beta = \frac{|p_L^p|}{W} = \frac{|k_L^p|}{W}.
\] (1.17)

Given \(W\) and the angle \(\theta\) between \(p_n\) and \(k\) (see Figure 1.5), the momentum-energy four vectors of the neutron in the lab frame are readily obtained from the corresponding four vectors in the c.m. frame through inverse Lorentz transformation. If \(p_n^L\) has components \((p_n^L \sin \theta_n^L, 0, p_n^L \cos \theta_n^L)\), the inverse Lorentz transformation leads to

\[
\begin{bmatrix}
p_n^L \sin \theta_L \\
0 \\
p_n^L \cos \theta_L \\
E_n^L
\end{bmatrix}
= \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & \alpha & \beta \\
0 & 0 & \beta & \alpha
\end{bmatrix}
\begin{bmatrix}
p \sin \theta \\
0 \\
p \cos \theta \\
E_n
\end{bmatrix}
\] (1.18)

where \(p_n = \sqrt{E_n^2 - M_n^2} = p\).
Thus we have

\[ p_n^L \sin \theta_L = p_n \sin \theta, \]
\[ p_n^L \cos \theta_L = \alpha p_n \cos \theta + \beta E_n, \]
\[ E_n^L = \beta p_n \cos \theta + \alpha E_n. \]  

(1.19)

Similarly for the proton momentum-energy in the lab, if \( p_p^L \) has the components \( (p_p^L \sin \theta_p^L, 0, p_p^L \cos \theta_p^L) \), the inverse Lorentz transformation leads to

\[
\begin{bmatrix}
  p_p^L \sin \theta_p^L \\
  0 \\
  p_p^L \cos \theta_p^L \\
  E_p^L
\end{bmatrix}
= \begin{bmatrix}
  1 & 0 & 0 & 0 \\
  0 & 1 & 0 & 0 \\
  0 & 0 & \alpha & \beta \\
  0 & 0 & \beta & \alpha
\end{bmatrix}
\begin{bmatrix}
  p \sin \theta \\
  0 \\
  -p \cos \theta \\
  E_p
\end{bmatrix}
\]

(1.20)

where \( p_p = \sqrt{E_p^2 - M_p^2} = p \).

The description of the reaction in c.m frame is elegantly carried out in terms of two variables \( E \) and \( \theta \). Our formalism in this thesis is described in c.m. the frame.

The differential cross section for any reaction \( A + B \rightarrow C + D \), in general, is given by Fermi’s Golden Rule

\[
\frac{d\sigma}{d\Omega} = \frac{2\pi D}{v} |\langle f|T|i \rangle|^2;
\]

(1.21)

where \( D \) is the density of final states, \( v \) is the modulus of the relative velocity in the initial state and \( T \) denotes the on-energy-shell transition matrix.

The density of final states is given by

\[
D = \frac{(2\pi)^{-3}E_CE_D|p_C|^3}{|p_C|^2E - (p \cdot p_C)E_C},
\]

(1.22)
where

\[ \mathbf{p}_A + \mathbf{p}_B = \mathbf{p} = \mathbf{p}_C + \mathbf{p}_D, \]  

(1.23)

and the relative velocity in the initial state is

\[ v = |\frac{\mathbf{p}_A}{E_A} - \frac{\mathbf{p}_B}{E_B}|. \]  

(1.24)

In the c.m. frame, the total momentum \( \mathbf{p} = 0 \) and \( \mathbf{p}_C = -\mathbf{p}_D \).

In the problem under consideration, the density of final states in c.m frame is

\[ D = (2\pi)^{-3} \frac{E_n E_p |\mathbf{p}|}{E^3}, \]  

(1.25)

and the magnitude of the relative velocity in the initial state is given by

\[ v = \frac{E}{E_n E_p}. \]  

(1.26)

However, the neutron and the proton in the final state have spin \( \frac{1}{2} \) each, the deuteron in the initial state has spin 1. The photon too is a spin 1 particle with only two states of polarization. Let \( \mu = \pm 1 \) denote the right and left circular states of the photon polarization as defined by Rose [91]. Let \( m_d, m_n \) and \( m_p \) denote the spin projections of the deuteron, neutron and proton respectively.

The unpolarized differential cross section for \( d + \gamma \rightarrow n + p \) in c.m. is then given by

\[ \frac{d\sigma_0}{d\Omega} = \frac{1}{6} \frac{E_n E_p E_d |\mathbf{p}|}{(2\pi E)^2} \sum_{m_n, m_p, m_d, \mu} | \langle \frac{1}{2} m_n, \frac{1}{2} m_p; \mathbf{p} | T | k \mu; 1 m_d \rangle |^2. \]  

(1.27)

after summing over the final spin states and averaging over the initial spin and photon polarization states.
Table 1.1: Measured cross-sections for $p(n, \gamma)d$

<table>
<thead>
<tr>
<th>Energy $E_n^{L}$ keV</th>
<th>Cross-section $\sigma$ mb</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-5}$</td>
<td>334.2 ± 0.5</td>
<td>[51]</td>
</tr>
<tr>
<td>$10^{-5}$</td>
<td>332.6 ± 0.7</td>
<td>[52]</td>
</tr>
<tr>
<td>20</td>
<td>$(318 \pm 2) \times 10^{-3}$</td>
<td>[22]</td>
</tr>
<tr>
<td>40</td>
<td>$(203 \pm 19) \times 10^{-3}$</td>
<td>[22]</td>
</tr>
<tr>
<td>64</td>
<td>$(151 \pm 7) \times 10^{-3}$</td>
<td>[22]</td>
</tr>
<tr>
<td>550</td>
<td>$(35.2 \pm 2.4) \times 10^{-3}$</td>
<td>[23]</td>
</tr>
</tbody>
</table>

Table 1.2: Measured cross-sections for $d(\gamma, n)p$

<table>
<thead>
<tr>
<th>Energy $E_{\gamma}^{L}$ MeV</th>
<th>Cross-section $\sigma$ mb</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.33</td>
<td>$0.683 \pm 0.053 \pm 0.042$</td>
<td>[49]</td>
</tr>
<tr>
<td>2.52</td>
<td>$0.983 \pm 0.039 \pm 0.061$</td>
<td>[49]</td>
</tr>
<tr>
<td>2.62</td>
<td>$1.300 \pm 0.029$</td>
<td>[48]</td>
</tr>
<tr>
<td>2.754</td>
<td>$1.456 \pm 0.045$</td>
<td>[50]</td>
</tr>
<tr>
<td>2.76</td>
<td>$1.474 \pm 0.032$</td>
<td>[48]</td>
</tr>
<tr>
<td>2.79</td>
<td>$1.47 \pm 0.03 \pm 0.09$</td>
<td>[49]</td>
</tr>
<tr>
<td>4.45</td>
<td>$2.430 \pm 0.17$</td>
<td>[48]</td>
</tr>
<tr>
<td>6.14</td>
<td>$2.191 \pm 0.100$</td>
<td>[48]</td>
</tr>
<tr>
<td>7.60</td>
<td>$1.803 \pm 0.016$</td>
<td>[48]</td>
</tr>
<tr>
<td>9.00</td>
<td>$1.570 \pm 0.036$</td>
<td>[48]</td>
</tr>
</tbody>
</table>
Figure 1.1: Processing rates for deuterium creation reactions [10].

Figure 1.2: Processing rates for deuterium destruction reactions [10].
Figure 1.3: The predicted abundances of light elements, as a function of the baryon density.
Figure 1.4: The dependence of the calculated $p(n, \gamma)d$ reaction cross section $\sigma$ times the neutron velocity $v$ on the neutron lab energy [23].
Figure 1.5: The reaction $\gamma + d \rightarrow n + p$ in c.m. frame, choosing the reaction plane to be the $z - x$ plane