INTRODUCTION

Delbrück (D) scattering [2] is the elastic scattering of photons in the static Coulomb field of atomic nuclei via virtual electron-positron pairs. It is one of the four elastic scattering mechanisms of photon-atom interaction. The other three are Rayleigh (R) scattering by the bound atomic electrons, nuclear Thomson (T) scattering by the nuclear charge distribution and nuclear resonance (N) scattering via the giant dipole resonances.

Of these processes, Delbrück scattering has been a subject of continued investigations as one of the fundamental reactions of elastic photon-atom interaction. D scattering is one of the few nonlinear processes of Quantum electrodynamics (*QED*) which can be precisely measured by experiment and therefore it offers a direct access to vacuum polarization [8] in the presence of strong electric fields. This provides a test of the reliability of the perturbative nature of *QED* at higher orders in fine structure constant. Other nonlinear *QED* processes which are a direct consequence of vacuum polarization and hence closely related to the Delbrück scattering are light-light scattering, photon splitting or coalescence of photons. D scattering may also serve as gauge-invariant tests of the *QED* electron propagator since its Feynman diagrams contain closed electron loops.

In nuclear physics, experiments involving elastic scattering of photons by nuclei are performed in which attempts are made to extract the information on nuclear structure and mesonic and nucleon internal degrees of freedom [9]. In such experiments contribution of Delbrück scattering to the elastic scattering considerably modifies the differential cross section. Therefore, precise predictions for Delbrück scattering amplitudes may be required for valid interpretation of data of such experiments.

In recent years some interesting results involving Delbrück scattering are being reported. The possibility of photon emission in collisions of ultra-relativistic heavy nuclei ($Z_1Z_2 \rightarrow Z_1Z_2\gamma$) via the virtual Delbrück scattering sub-process [16, 17] can be investigated experimentally at RHIC or LHC collider. In another work modification of Delbrück scattering by the application of intense laser field has been investigated [12], such a situation is likely to exist in pulsars. Applications of Delbrück scattering in the field of high-energy astrophysics such as the possibility of observing Delbrück-scattered γ-rays from objects like a gamma ray burst or pulsar is being investigated and its preliminary findings have been reported in chapter five of this thesis.

The four different mechanisms of elastic scattering, namely, *R*, *T*, *N* and *D*, cannot be distinguished physically. Experimentally, one can measure the elastic differential scattering cross section which can also be theoretically estimated provided the scattering amplitudes of each of the mechanisms are known accurately. The amplitudes of these competing elastic scattering processes are dependent on incident photon energy (ω), the atomic number of the target atom (Z) and the scattering angle (θ). For example, *R* scattering dominates at photon energies $\omega \leq 1$ MeV, most of the angles and heavy nuclei. Contribution of *R* scattering to the elastic scattering cross section is negligible for energies $\omega \geq 6$ MeV and $\theta \geq 20^0$. The *N* scattering is important at energies in the 4-25 MeV domain. *T* amplitudes take simple forms when the nucleus is treated as a single free particle and are well known. Generally, *R*, *N* and *D* amplitudes are complex, while *T* amplitudes are real. The imaginary part of *D* amplitudes is zero at energies below the electron-positron pair production threshold, while the real part is negligible at ultra-relativistic energies $\omega >> m$, m being the rest mass of electron and we choose $\hbar = c = 1$. *D* scattering becomes important at $\omega > 10$ MeV although its presence can be detected even at low energies (up to 0.9 MeV). The elastic scattering is almost dominated by *D* scattering at $\omega > 100$ MeV. Thus, we see that, in spite of the experimental incapability to isolate these four mechanisms, by properly selecting $\omega, \theta\ and\ Z$, it is possible to minimize one or more effects. For example, R and N scatterings leave a window on the energy scale between about 2 and 4 MeV.

Experimental investigation of Delbrück scattering has been a subject of continued interest since its discovery by Max Delbrück in 1933. Experimentally, D scattering cross sections for various energies and scattering angles have been measured. Results by Jarlskog *et al.* [79] or Schumacher *et al.* [92] are some of the important landmarks in the annals of experimental investigation of Delbrück scattering. But, on the theoretical side, the prediction of Delbrück scattering amplitudes for an arbitrary angle of scattering and photon energy is not yet available. Being a *QED*-problem, a general solution of Delbrück scattering problem, in principle, is obtainable. However, the calculation becomes intractable for an arbitrary angle of scattering and photon energy. Therefore, all the theoretical results have been obtained by making certain approximations and hence the predictions are limited to special regions. The theoretical results of Delbrück scattering for high photon energies ($\omega >> m$) and small scattering angles have been obtained by Cheng and Wu [41, 42] and Milstein *et al.* [32, 33]. The calculations in [41, 42] and [32, 33] are based on two different approaches but they yield similar numerical results. The other important theoretical breakthrough includes the lowest-order Born approximation calculation by Papatzacos and Mork [49], generally valid at low energies (of the order of few MeV) and all scattering angles. Results for high-energy large-angle regime have been obtained by Milstein et al. [45, 46] but their accuracy has not been experimentally established completely. The exact amplitudes for forward scattering due to Rohrlich and Gluckstern [30] are one of the earliest calculations of Delbrück scattering.

The lowest-order Born approximation calculation of Delbrück amplitudes[49] and the S-matrix Rayleigh amplitudes[63-67] have been used to identify the contribution of Delbrück scattering to the experimentally measured elastic scattering cross sections at low photons energies (0.9 to 11 MeV). Investigation at these energies was due to the sustained and coordinated efforts made by theorists and experimentalist.

The agreement between the measurement and the theory was, by and large, good in the low energy range. However, it was noticed that the predictions were somewhat smaller than the experimental values in the whole angular range from 30° to 90° and this difference went up to a factor 1.7 for lead at 2.754 MeV. Similar behavior was observed in the entire few MeV range and for $Z \geq 50$. Additions of the so called Coulomb correction terms (of order ~ $(Z\alpha)^4$) to the lowest order Delbrück amplitudes were found to be remove the disagreement with most of the experimental data in the energy range 2-11 MeV. Exact QED-calculation of Coulomb correction terms being a difficult task, their tentative estimates have been made by analyzing the dependence of measured elastic scattering cross sections on the atomic number, photon-energy and scattering angle. Reliability of such estimate depends on the accuracy with which other elastic scattering amplitudes (namely, the amplitudes of Rayleigh, nuclear Thomson and nuclear resonance scatterings) are known theoretically. Interferences from nuclear resonance scattering at energies between 7 to 20 MeV are known to make the process of disentanglement of Coulomb corrected *D* amplitudes and the nuclear resonance scattering amplitudes from the experimental data difficult.

At energies near pair-production threshold, atomic Rayleigh scattering is the dominant contributor to the elastic scattering. It has been extensively investigated from theoretical, computational and experimental point of view. The main interest behind those systematic investigations of Rayleigh scattering was the experimental observation of the real part of the Delbrück scattering. The S-matrix amplitudes [63-67] are considered as one of the best predictions of Rayleigh scattering made so far. Their validity at these energies is beyond doubt [96]. The S-matrix Rayleigh amplitudes together with the real part of the lowest-order *D* amplitudes have been used to detect the Delbrück scattering up to energies as low as 0.889 MeV.

The adequacy of the lowest-order Born approximation calculation of Delbrück amplitudes at energies near and below the pair production threshold (Photon energy ≤ 1.33 MeV), particularly by high atomic number scatterers, has been a subject of concern for quite some time. Issues related to the question whether the higher-order corrections (Coulomb corrections) are needed to the Born approximation results [49] at these energies are to be addressed. A somewhat similar situation has been observed [137, 140] in the energy dependence of photoeffect cross sections, where the Born approximation energy dependence is corrected, in addition to a Stobbe factor, by further terms (but in the predicted scaling pattern [151] in terms of a modified pattern. In the theoretical side, it has been shown for the first time that the Delbrück scattering phenomenon can be applied to some astrophysical situations where high energy γ-ray photons interact with a dense molecular cloud such as in a gamma-ray burst.

The present thesis consists of *five* chapters and the contents of each chapter are briefly described below.

The ***first*** chapter is a review on the theoretical and experimental developments of Delbrück scattering (*DS*) in particular and those of elastic scattering of γ-ray photon in general. The theoretical aspects are discussed through *Sec.*1.1 to 1.3 and the experimental investigations carried out at different γ-ray energies have been discussed at the later half of this chapter (*Sec.*1.4).

In *Sec.*1.1 the *DS* has been introduced as a non-linear *QED* phenomenon and its importance vis-à-vis other nonlinear effects like light-light scattering, photon splitting and photon coalescence have been highlighted. All the major theoretical results of *DS* have been discussed in *Sec.*1.2. Starting from the classic results of Rohrlich and Gluckstern [30] for forward scattering amplitudes, the approaches and results of other approximate theories have been presented in it. The theories of *DS* for high photon energies and small scattering angles, intermediate energies and moderately large angles and low energies and all angles have been discussed in *Sec.*1.2.1, 1.2.2 and 1.2.3 respectively. The *Sec.*1.2.1 contains the Green function results of Milstein *et al.* [32, 33] and the Feynman-*QED* results of Cheng and Wu [41,42] , which are based on the quasiclassical and impact factor approximation respectively. *Sec.*1.2.2 refers to the high-energy large-angle results of Milstein *et al.* [45, 46]. The lowest-order Born-approximation results of Papatzacos and Mork [49], which are useful for estimating Delbrück amplitudes in the low-energy all-angles regime, have been briefly outlined in *Sec.*1.2.3. This section also mentions some of the other theoretical works, particularly those applicable to the low-energy regime [47, 48, 50-55].

The predictions of other (*R, T* and *N*) elastic scattering processes and the importance of their accuracies in the experimental investigation of *DS* have been explained in *Sec.*1.3. The form factor and S-matrix formalisms of Rayleigh scattering, the most dominant contributor to the elastic scattering at photon energies around 1 MeV, are presented in *Sec.*1.3.1 while nuclear Thomson and nuclear resonance scatterings are briefly mentioned in *Sec.*1.3.2 and 1.3.3 respectively.

The last part of this chapter, i.e., *Sec.*1.4, deals with different aspects of experimental studies of *DS* and the results of some of the important experiments. Information regarding the sources of γ-rays, detectors, targets etc., which have been used in past experiments conducted at different energies and angles are given through *Sec.*1.4.1.1 to 1.4.1.3. The experimental results and their comparisons with the theories are outlined in *Sec.*1.4.2. The high-energy small-angle experiments are discussed in *Sec.* 1.4.2.1 and it includes the results of Jarlskog et al. [79], which is considered as the first clear observation of Delbrück scattering. The low-energy all-angle measurements are discussed in *Sec.* 1.4.2.2. Beginning with the measurements of Schumacher *et al.* [92], in which the first definite observation of the real part of Delbrück scattering was made, most of the other results of this regime are included in this section. The role of S-matrix Rayleigh amplitudes in identifying the *D* component of elastic scattering at very low energies has also been outlined in this section. *Sec.* 1.4.2.2.1 includes the results involving the Coulomb correction effect with respect to the lowest-order Born-approximation Delbrück amplitudes, which were mostly carried out by the Göttingen group [100-103, 106-113]. The experimental results of large-angle intermediate-energy regime have been discussed in *Sec.*1.4.2.3.

A summary of this chapter has been presented in *Sec.*1.5 in which some important facts and figures about the present status of *DS* are discussed.

The ***second*** chapter carries a detail account of the measurements of total photon-atom cross sections (attenuation coefficients) including the procedure followed and the results obtained. The second half of this chapter also includes the results obtained by using the indirect method of finding the experimental values of photoelectric cross sections.

The theoretical predictions of attenuation coefficients in the form of tabulation prepared by Hubbell et al [117] is one of the most widely used data on attenuation and it also provides references to most of the concerned theoretical works. Currently two such tabulations, which are frequently used in recent works relating to attenuation coefficients, XCOM [119-121] and FFAST [122], are available in NIST websites. Although the overall agreement between these predictions and the measurements are good there exists some discrepancy between the XCOM and FFAST predictions for high Z elements [123]. The estimation of elastic scattering cross section from the experimental data is dependent on the value of attenuation coefficient chosen. Thus, an accurate value of attenuation coefficient of the scatterer is needed for the experimental observation of Delbrück scattering. Therefore, the values of attenuation coefficients of the scatterers used in the elastic scattering measurements were precisely measured through a series of narrow beam experiments. Also, experimental data of photoelectric absorption cross sections for few elements near pair production threshold have also been derived from the measured values of total cross sections.

Sec. 2.1 introduces the various processes contributing to the attenuation of photons in matter. After mentioning the basic criteria of a 'good geometry' in *Sec.* 2.2, the different measures taken for the establishment of the experimental arrangement have been summarized through *Sec.*2.3.1 to 2.3.5. The experimental method and the measurements are outlined in *Sec.*2.4. Evaluation of errors is presented in *Sec.*2.5. The procedure and the estimation of photoelectric cross sections have been discussed in *Sec.*2.6. Discussions on the result have been made in *Sec.*2.7.

The ***third*** chapter deals with the experimental observation of *DS* at 1.115 MeV using the high purity germanium (HPGe) detector. Differential cross sections of elastic scattering from 99.9995 % pure materials (lead and tungsten) at scattering angles ranging from 30° to 135° have been measured. The experimental results are compared with the theoretical predictions including Delbrück amplitudes calculated with the lowest-order Born approximation, the S-matrix Rayleigh amplitudes and the nuclear Thomson scattering amplitudes. The measurements are also compared with the form factor predictions of elastic scattering.

The chapter begins with an introduction in *Sec.*3.1. The fundamental requirements in the design of the experimental set up are enumerated in *Sec.* 3.2.The various steps taken to minimize the sources of errors and the precautions taken for checking any deviation from 'good geometry' are discussed through *Sec.* 3.3.1 to 3.3.4.

The experimental method and the measurements are presented in *Sec.*3.4. The procedure of acquiring scattered and background spectrum and the method of data reduction have been enumerated in *Sec.* 3.4.1. The major sources of errors and uncertainties and their possible corrections and estimations have been highlighted in *Sec.*3.4.2. The procedure of obtaining the theoretical results in different formalisms has been explained in *Sec.*3.5. Experimental results are described in *Sec.*3.6 and a discussion on the subject has been made in *Sec.*3.7.

In the ***fourth*** chapter of the thesis the scaling behavior of the Delbrück scattering cross sections has been discussed. The Delbrück scattering amplitudes have been predicted to scale in the form $\omega^{-1}f(\theta)$ for fixed scattering angle θ when $\omega >> m$ and $\Delta >> m$, where $\Delta\,(=2\omega\sin(\theta/2))$ is the momentum transfer [143]. Such scaling behavior of *DS* was predicted by Cheng, Tsai and Zhu in the paper [143] in which they were actually attempting exact calculation of the lowest-order Delbrück amplitude without approximations.

In the present work it has been shown that the available experimental data in the energy range between 140 MeV to 7.11 GeV do not exhibit scaling behavior. At relatively lower energies scaling is, however, noticed to a certain extent but in a slightly modified manner than what Cheng *et al.* [143] had originally prescribed.

The subject has been introduced in *Sec.* 4.1. The theoretical aspects related to the predicted scaling law have been described in *Sec.* 4.2. Analysis of the experimental data in the energy range between 140 MeV to 7.11 GeV have been carried out in *Sec.* 4.3. Since the high-energy (≥100 MeV) elastic scattering of photons are mostly dominated by Delbrück scattering the experimental values of differential cross sections can be directly used in testing the proposed formula. The data were not found to obey the predicted law in a strict sense. In *Sec.* 4.3.1 an attempt has been made to remove the deviations by using a modified formula. Finally, in *Sec.*4.4 a discussion on the results of the analysis has been presented. The probable reasons for such non-observation of scaling feature are also explored in this section.

The ***fifth*** chapter deals with the astrophysical applications of Delbrück scattering. Examples of astrophysical scenarios where high energy γ-rays interact with an environment containing atomic or molecular dust are plenty in nature. For example, the gamma rays emitted by a *GRB* are bound to undergo scatterings in the regions having dense gaseous clouds of their host galaxies [149]. Similar situation may prevail in a pulsar too. The elastic scattering of high energy gamma rays by the atomic nuclei present in the dense cloud is solely determined by the Delbrück amplitudes at energies $\geq$100 MeV. In this chapter the elastic scattering of energetic γ-rays from the dust of a *GRB* is investigated and it has been shown for the ultra-relativistic γ-rays that the flux corresponding to the Delbrück scattering is many times more than that due to the Compton scattering in the regions of small angle of scattering. Those γ-rays, which are scattered in the almost forward directions, correspond to the delay time of few milliseconds to few seconds of the *GRB*.

After introducing the subject in *Sec.* 5.1 the relevance of elastic and hence Delbrück scattering of high energy gamma radiation with the concerned environment of an astrophysical object has been explained. In *Sec.*5.2 the Delbrück scattering has been compared with Compton scattering in the context of a *GRB* dust. In *Sec.* 5.3, expressions for γ-ray flux of dust scattered radiation from *GRB* have been enumerated. Issues related to their detectability have been given in *Sec.* 5.4.