PREFACE

Investigations, both theoretical and experimental, on electromagnetic interaction processes of leptons have been carried out for many years. The importance of such investigations is due not only from the point of determination of interaction in these electromagnetic processes between fast leptons and matter but also to the possibility of testing quantum electrodynamics(QED) at very high energies. New experimental facilities are now available to increase the possibilities of experimenting with high energy electrons and positrons. For example, colliding electron-electron and electron-positron beam experiments are being carried out to verify the high energy predictions of QED. Experiments, using high energy muons to study electromagnetic interaction processes and to prove QED at small distances have been carried out in the past. Although there has been considerable progress in this experimental domain but still there are some difficulties and problems that have remained unsolved. We are concerned more with high energy electromagnetic muon interactions with matter and the test of electrodynamics with muons. The important high energy interaction processes are:direct muon-electron knock on collision process, bremsstrahlung process of muon in the coulomb field of atomic nuclei and direct production of pair of electron-positron (DPP) by muons in the coulomb field of atomic nuclei and electrons. The muon DPP process is the main subject of investigation in this thesis. The present status of the theory of DPP process appears to be higher than that of the experiments so far reported for this process. In the latest theoretical developments, derivations of cross section expressions have been made with high mathematical rigour. Bhabha's (1935) theory of DPP process and other similar treatments were done more than 35 years ago. Bhabha's theory and also theory of Racah(1937) have been used extensively in the past. Except in one case of theoretical review with experimental investigation by Wright (1933,1975), the recent exact calculations (Kel'ner, Kel'ner-Kotov, Kokoulin Petrukhin (KP)) have not been used in previous experiments. It appears desirable to make a critical evaluation of old and new DPP calculations in order to understand the degree of improvement attained at present and to know inter-relation among various treatments.Probably there is also a need for a critical reanalysis of past experiments on DPP process in view of new theoretical results and more precise data on muon spectra both at sea level and underground. Such a reanalysis of the existing experimental data may help evaluate the reliablity of available theoretical cross sections.

At the University of North Bengal (1962 –), we made a new start in 1970 in organising some research activity in the field of high energy muon interactions. It was not possible to think in terms of such large equipment installations as are in use in a number of projects abroad. We started a project in collaboration with Prof. M. S. Sinha (Investigator-in-Charge, Department of Atomic Energy Project, Durgapur) by taking on loan some DAE equipments from his project. The equipment is a medium size (85 cm x 85 cm x 50 cm) multiplate cloud chamber with its accessories. In a previous underground investigation under the DAE project, the same multiplate cloud chamber was used to study the electromagnetic interactions of muons at a mean energy of about 35 GeV (Chaudhuri 1970). The equipment was transfered to N.B.U. early in 1971 and then suitably housed and set up after a continuous struggle for nearly 2 years. A large area scintillation counter control system was constructed during 1970–1971 for measurements of directional intensities of cosmic ray muons. This system was then combined with the multiplate cloud chamber apparatus for investigations of interactions in different target materials of high energy cosmic ray muons from greatly inclined directions. The main consideration in undertaking this project was that interaction study at increasing primary muon energies could be made by operating the multiplate cloud chamber at ground level in several zenith angles. As already mentioned, our interest in the present investigation is on the DPP process of high energy muons in different target elements. A summary of work done in the project and described in the four chapters in the thesis is included here.

CHAPTER 1

In order to bring uptodate old and new theoretical work on DPP process and to evaluate the status of the theory of DPP process, a critical analysis has been made of important DPP cross section formulae. The most familier and extensively used treatment of Bhabha among the earlier treatments was included for evaluation of the cross section results. The inclusion of Bhabha's treatment has been made with a view to understanding the degree of improvement in the subsequent calculations. The first QED calculation by Feynman-Dyson (FD) method (Murota, Ueda, Tanaka(MUT) (1956)) which has been used for comparison in experimental measurements after 1957 has been discussed with reference to the important cross section results only. More exact cross section formulae according to very recent calculations (Ternovskii 1960, Kel'ner 1967, Kel'ner-Kotov 1968, Kokoulin-Petrukhin 1971) have been evaluated.

Approximate cross section formulae (Kobayakawa 1967, Wright 1973) have also been included for examination. Numerical evaluation of cross sections according to various calculations has been made for the purpose of checking over a wide range of energy transfers in low, medium and high Z atoms. The contribution to the cross sections from orbital electrons under complete screening has been included. Such contribution in case of low Z atoms is about 20%. The examination of the computed data shows among other features the following:

(1) Bhabha cross section in the lower energy transfer range is not worse than QED calculation of MUT(1956) considering closer agreement of Bhabha results with the exact results from latest treatments.

(2) Ternovskii (1960) cross section agrees closely with MUT ($\alpha = 1$) cross section over an energy transfer range which widens with increasing primary energy starting from an energy transfer of about 80 MeV.

(3) There is agreement among predicted cross sections according to calculations of Kel'ner (1967), Kelner-Kotov (1968) and Kokoulin Petrukhin (1971) upto an energy transfer value half the primary energy.

(4) The approximate cross section formulae give cross sections higher than the values predicted by the calculations on which these formulae are based.

A representative selection of numerical cross section data in tables and graphs has been included.

CHAPTER 2

A reassessment of the past investigations on DPP process has been made through a reanalysis of individual experiments. It is found that some experiments are conflicting and only a few help check the theoretical cross sections. The reexamination of the data of these experiments has been made by taking latest theoretical cross section results (KP) and the incident muon spectra from latest measurements. In the experiments in which a distinction was not possible between direct muon-electron knock on events and DPP events, the combined theoretical cross sections of these processes were taken into account for interpretation of the available experimental data. Our re-examination of two such experiments (Allkofer (1971) and Binns (1972)) has shown that the data of Allkofer(1971) are in excellent agreement with the theoretical expectations from KP theory for DPP process, Bhabha theory for KO process and Christy Kuraka (1941) theory for bremsstrahlung process. The picture in case of experiment of Binns Kearney(1972) is different showing a systematic discrepancy between the observed and expected number of events almost over the whole range of energy transfer investigated. It is unlikely that this discrepancy arises from the failure of the theories of the interaction processes. In a few experiments (Das and Sinha (1967), Chaudhuri and Sinha (1965) , Kearney and Hasen (1965)) the multiplate clcud chamber measurement data were analysed after seperating out events of direct muon-electron knock on collision. The reanalysis of the first two experiments shows an overall agreement or agreement within statistical error bars with the KP theory of DPP process taking also bremsstrahlung contribution into account. The recent experiment (Jain 1974) with 15.8 GeV/c accelerator muons in emulsion ($Z = 21$) gives a cross section of 89 mb/nucleus which is smaller by more than a factor 2 than cross section expected according to various theories of the DPP process. This result is in total disagreement with the data in the similar energy transfer range for copper ($Z = 29$) in the experiment of Das and Sinha (1967) and the results of the present experiment (Chapter 3). The reanalysed data are also given in tables.

CHAPTER 3

The present experimental study of the DPP process of high energy muons is described. A multiplate cloud chamber with control arrangement of a narrow angle plastic scintillation counter telescope was designed to observe interactions of muons from large zenith angles. In a previous investigation (Chaudhuri and Goswami 1970) the same cloud chamber was operated underground for the study of high energy muon interactions. The sea level observation was made first at the vertical direction and then at two zenith angle ranges (40°–50°, 70°–80°) under the coincidence selection system for single particles. The basic data on DPP events produced in thin (1.5 mm) aluminium, copper and lead targets (table 3.1) have been analysed, for energy transfer interval and interaction cross sections. With thin targets the difficulty in definite identification of direct electron pairs was absent and errors arising from finite target thickness were thus eliminated. Thin target bremsstrahlung may also appear as direct pairs, but the correction for this effect is negligible at energy transfer and the target thickness considered. The energy of the direct pairs was estimated using newly published accurate energy loss data of electrons and positrons (Berger and Seltzer 1967). The total number of direct pairs observed is 109 with energy in the interval 3 MeV-30 MeV.

Two sets of underground (148 mwe) data which were not analysed before were included in the present study. One set of data is for 12.6 gm/cm^2 iron targets and another for 70.9 gm/cm^2 lead target. The total number of events (pairs and showers) in iron target is 114 and total number of showers observed in lead target is 123.

For the purpose of estimation of energy of events, a critical examination was first made of the available relationship between shower-maximum and shower energy according to conventional shower theory under approximation B, new shower theory of Thielheim Zollner (1972) shower treatment according to Monte Carlo method (Crawford and Messel 1965) and shower theory of Buja (1963). It is shown that shower energy estimated by Monte Carlo method is above the results from other analytic methods by a factor of about 2. It is also shown that results under approximation B of conventional theory are within 30% of the results from the theory of Thielheim and Zollner (1972) who used exact interaction cross sections instead of asymptotic values used in conventional shower theories. For shower development in iron and copper we have used the relationship between shower maximum and shower energy from the conventional shower theory under approximation B. The experimental cross section data derived from all sets of observations have been presented and, for evaluation, expectations according to the theories of the various processes involved have also been included. These data have been used to study (1) the dependence of the DPP interaction cross section on energy transfer in a range from 3 MeV to 16 GeV, (2) dependence of interaction cross section on primary muon energy (3) the dependence of interaction cross section on the ratio Z(Z+a)/A. The energy transfer dependence of DPP interaction cross section at very low energy transfer is found to be reasonably interpreted by the latest theories and also by the original theory of Bhabha. In this energy transfer region MUT(α=2) cross sections are above the experimental values (experimental error bars touching them in some cases). At medium and higher energy transfer, there is no discrepancy between the data and expectation considering contributions from all the three processes involved. The trend of behavior of the data is same for both low, medium and high Z elements. The observed behavior concerning dependence on primary energy and on target material is in accordence with theoretical predictions. An account of systematic errors and corrections considered in the analysis is included.

CHAPTER 4

The absolute intensity of the hard component (muon) of cosmic rays at sea level is a datum used as a standard in cosmic ray work. The standard value that was used extensively before 1970 had been derived(Rossi 1948) from measurements made more than 30 years ago (Greisen 1942). Very recently, new measurements have been made by using sophisticated equipment by several workers(Allkofer et al 1970, 1971,Ashton 1972, Crooks 1971,1972;Karmakar 1973, De 1972, Ng 1974, Ayre 1971, 1972). The first of the recent measurements by Allkofer et al indicated a discrepancy of about 25% between standard integral value and their measured values of intensities at 1 GeV. Subsequent measurement by other groups have been made in an effort to check the results of Allkofer et al.

An account of the measurement of vertical cosmic ray muon intensity made at NBU campus during (1972) is given. A very narrow angle scintillation counter telescope with arrangement for exclusion of incident showers was used to measure absolute integral intensity in the minimum momentum range (0.352-2.7) GeV/c. In the evaluation of absolute intensity, the effect of multiple scattering in the absorber material within the geometry (fig.(4.1)) and other corrections for instrumental errors were taken into account. The basic data and the final absolute intensities after various corrections have been given. A comparison of the present results is given with the earlier measurements and separately with the recent measurements taking into account the effect of 11 years cycle of solar activity and latitude effect. Almost all the earlier measurements disagree when corrected for latitude effect. The recent measurements corrected for latitude effect except two or three (Bhattacharjee 1970, Flint 1973, Crookes 1969) show close agreement confirming the reliability of recent measurements at different geomagnetic latitudes. This comparison thus confirms that original standard absolute intensity at 0.33 GeV/c and 1 GeV/c are at least 10% and 20% respectively smaller than the intensities now determined.

In the earlier and more recent works, both experimental and theoretical review, there were gaps and difficulties. In the present work, an evaluation of important theoretical treatments is further extended covering existing limitations. A reanalysis of the existing measurements has been made more critically than was ever done before. The present measurements give new results augmenting and filling up the gaps and clearing to a considerable extent the confusion that persisted so long.