PREFACE

There has been considerable advancement in experimental research in the field of high energy lepton-nucleon interaction processes. The great advances in the experimental technique have led to several experimental cosmic ray lepton-nucleon investigation programmes which are either in progress now or near in completion. Several such inelastic lepton-nucleon experiments have been completed using either cosmic ray muons or accelerator produced lepton, both electrons and muons, with energy upto 18 GeV. At higher energies unattainable at present by accelerator, very high energy cosmic ray muon experiments have been undertaken by several experimental groups using large complex installation of sophisticated equipments.

At the new university of North Bengal a new start was made in 1970 in organising some research activity by engaging interest in the area of high energy cosmic ray muon interactions. It was not possible to think of any sophisticated equipments for research and efforts were naturally centered around simple and small apparatus based on multiplate cloud chamber in combination with scintillation counters. A proposal for research in collaboration with Prof. M.S. Sinha (Investigator in charge, D.A.E. Project, Regional Engineering College, Durgapur) on "Studies on interaction of nearly horizontal muon in a multiplate cloud chamber at N.B.U." was made to the Department of Atomic Energy, Government of India. The D.A.E. approved the project and issued the multiplate cloud chamber apparatus on loan to N.B.U. This apparatus was built in a previous D.A.E. Project under Prof. M.S. Sinha at Bose Institute, Calcutta. The cloud chamber equipment from Prof. M.S. Sinha's D.A.E. laboratory, Durgapur was transfered to N.B.U. in 1971. After a continous struggle for obtaining the minimum facilities the equipment was housed and set up early in 1973 for the proposed investigation on interactions of high energy muons from greatly inclined directions,

The main consideration in undertaking the work was that the interaction study at gradually increasing mean muon energies could be made by operating the apparatus at ground level in several angles to the vertical direction. The aim was primarily on muon-nuclear interactions and direct production of electron pairs in different target materials.

The work described in this thesis is concerned with muon nuclear interactions only.

There are several interesting theoretical proposals concerning inelastic lepton-nucleon interaction processes. These are 'scale invariance', 'vector meson dominance', 'Regge-Pole theory', There are also other theoretical formulations. The trends of the behaviour of various theoretical proposals are in need of a critical study. In most of the past investigations, one or other earlier theoretical proposals were taken for the interpretation of the experimental data. The previous published works contain only fragmentary information on the relative status of the various theoretical proposals and their correlations. The state of the theory of the inelastic lepton-nucleon collision process has to be evaluated by using the observed data for a clear understanding of the process.

The work described in this thesis includes:

(1) A critical evaluation of a number of theoretical formulations on inelastic lepton-nucleon collision (Chapter 1)

(2) A reanalysis of the important past experiments on inelastic muon-nucleon interaction processes (Chapter 2).

(3) Description of an experimental investigation using cosmic ray muons from three zenith angular directions and analysis

of the recorded data on nuclear interactions, air showers containing penetrating particles and parallel multiple muons (Chapter 3)

(4) Description of absolute measurements on directional intensities of muons at zenith angles up to 89° (Chapter 4)

It is relevant to present here a summary of the work done and included in the thesis.

Chapter 1.

The initial William-Weisäcker semi-classical formulation on the concept of 'virtual photon exchange' in the high energy lepton-nucleon inelastic process has been derived for understanding of the underlined physical processes. The limitations of the method to calculate the differential cross section for muon-nuclear interaction have been pointed out. The quantum electrodynamical treatment, using 'single photon exchange' have been briefly mentioned for evaluation of the corresponding differential cross section formulae. Only the cross section formulae are given excluding the details of calculation. The theoretical treatments used two 'structure functions' related to transverse and longitudional virtual photon-nucleon cross sections. The analytic forms of this cross sections have not been obtained in these treatments and approximations about these cross sections have been made. These approximations bring in the differential lepton-nucleon cross section formulae, the 'squared nucleon electromagnetic form factor'. The 'scale invariance conjecture' of J.D. Bjorken in the behaviour of structure function (also called inelastic form factor) of Drell and Walaca is discussed. The virtual photon-nucleon interactions via vector meson is discussed. The use of this model in the Drell and Walaca formulation under approximation for transverse and scaler virtual photon cross section leads to a differential cross section formula containing the square of ρ-meson propagator.(The contribution of other vector mesons ω and φ are not included in the formulation). Sakurai's ρ-meson dominance calculations of transverse and scaler photon cross sections have been used to obtain differential lepton-nucleon cross section formula containing ρ-meson propagator in the first power. The region of applicability of the vector meson dominance model is discussed. The extensive numerical computations have been made of the differential and integral cross sections for the muon-nucleon inelastic cross sections according to (i) Kessler formulation (Eq. 1.46) with the form factor under factorization approximation of total virtual photon cross section. (ii) Kobayakawa proposal (Eq. 1.52) for the DKMN formulations (Eq. 1.50 & 1.51), (iii) Sakurai's ρ-meson dominance model (Eq. 1.79). A representative selection of numerical data are given in tables (1.1 – 1.21) and graphs (1.5 – 1.32). These show corelation among the different theoretical proposals.

Chapter 2.

Most of the past experiments of multi-pion productions in high energy muon-nucleon collision are reanalysed using our computed values of theoretical cross sections included in chapter 1. In the early experiments Williams-Weisacker approximation formula was used for the data interpretation. In some of more recent experiments either the initial formula (Eq. 1.4?) of Kessler & Kessler or DKMN form factor approximation formulae (Eq. 1.50 & 1.51) were used and both the formulae were used in two or three experiments. In the underground cosmic ray experiments the assumed differential muon spectrum had uncertainties about the exponent and the mean energy loss rate in the penetration depth of muon in the rock. In the present work the underground muon spectrum in each of the past experiments considered was derived from recently measured vertical ground level spectrum and the new results (Kobayakawa, 1973) for muon energy loss rate in the rock. Our reanalysed cosmic ray data explained (i) the status of previous measurements (ii) consistency or inconsistency of the data with each of several theoretical proposals under consideration. Some recent accelerator data have been reanalysed. The vector meson dominance model was not applied in the work of Kirk et al 1969. To analyse their 10.5 GeV muon data they used the formulation of Hand & Wilson (as quoted in paper of Kirk et al 1969) and analysed the data with two extreme limits of scaler virtual photon cross sections; the scaler virtual total photon cross section was set equal to transeverse virtual total photon cross section and transeverse virtual total photon cross section was set equal to zero. Jain et al (1970) in their final experiment with 10.1 GeV and 14.6 GeV muon found results in conflict with earlier results of Dieterle et al (1969) at the same muon energy. We have shown that the data of Kirk et al (1969) are in general agreement with the predictions of vector meson dominance. The 14.6 GeV data of Jain et al (1970) lie between the predictions of v m d model and those of Kessler under the factorisation hypothesis of total virtual photon cross section. We have pointed out that the measurement of very small (<< square of the mass of muon) squared four momentum transfer in the nuclear emulsion is the subject to uncertainty and the behaviour observed in Jain et al (1970) below 0.02 GeV^2 may be due to some error.

Chapter 3.

A multiplate cloud chamber with control arrangement of plastic scintillator counter telescope was designed to study at sea level at large zenith angles the air showers incident on the apparatus, parallel muon groups and interactions of muons in different solid target materials placed within the apparatus. The observation was made first for muons from the vertical direction and then for two x zenith angle ranges $40^\circ - 50^\circ$ and $70^\circ - 80^\circ$ respectively. The cloud chamber operation was carried out under three fold coincidence selection system set for singly incident particles. At $70^\circ - 80^\circ$ zenith angle range, the apparatus was in operation about 1229 hours (sensitive time). The basic data of observations at three directions are summarised and an analysis of nuclear interactions, incident air showers and parallel multiple particles is given.

The observed frequency of nuclear interaction as a function of zenith angles indicate that the observed interaction events at $70^{\circ}- 80^{\circ}$ zenith angular range should be due to incident muons only. By applying considerations for protons and pions contributions the observed nuclear events at the vertical and $40^{\circ}- 50^{\circ}$ zenith angular observations, muon induced nuclear interactions were found to be negligible in number. Taking the nuclear interactions at the $70^{\circ}- 80^{\circ}$ operation as due to muons the integral cross sections have been evaluated for iron, lead and concrete ($Z \approx 11$) and integral energy transfer spectrum for iron and lead have been presented along with the predicted spectra according to v m d model. Our experimental data seemed to be consistent with the idea of vector meson dominance.

The showers from the atmosphere containing penetrating particles (penetration of 25 radiation length at the vertical and $40^{\circ}- 50^{\circ}$ operations and 65 radiation length during $70^{\circ}- 80^{\circ}$ operation required of the incident particles) and parallel muon multiples have been analysed separately for the variation of their frequency with zenith angle. Both the phenomena show the same trend of behaviour and are examined together for an interpretation in terms of nuclear interaction alone and then nuclear interaction and muon bremsstrahlung processes. It is shown that the observed frequency is too high to be explained solely by muon-nucleon inelastic process for a muon spectrum extended upto 10 TeV. If muon bremsstrahlung process is included, the observed frequency at 70^{o}- 80^{o} zenith angular range is found to be closed to intensities calculated for range of effective thickness of the atmosphere for producing showers, the size range is 10^{2}- 10^{8}.

Air showers from nearly horizontal directions (called HAS) and parallel muon groups have been the current topics of investigation. The observed features of HAS in the current studies by the Tokyo group (Matano et al 1965, Hara et al 1970) and the Keil group (Bohm et al 1970, Nagano et al 1971) have led to several interesting proposals (Chapter 3, Sec. 3.9) concerning the production process of HAS and their parent particle. One of the proposals is muon-nucleon inelastic interaction process taking place at high energy with increasing cross section is responsible for HAS events. The events "parallel muon groups" have been observed by several workers underground (Rogers and Wright 1973) and by Rogers et al(1969) at several zenith angles at sea level. The underground data on this event have been analysed by Barton & Stokel 1968 and Rogers and Wright 1973 using semiemphirical expression of Greisen (1960) for muon in air showers.

By treating the observed muon groups as remnants of air showers and combining them with air showers, the present analysis of these events gives an independent explanation. This explanation is in support of that of the Durham group (Alexander et al 1970, Kiraly et al 1971) and of Bohm and Nagano (1973)

Chapter 4

The current interest in the absolute measurement of directional cosmic ray muon intensities is discussed. A set of independent absolute measurements of muon directional intensities at lower geomagnetic latitude (16°N) has been carried out by using a simple instrument. The method adopted takes into account a number of important factors including (1) the effect of incident showers on the apparatus, (2) effect of multiple scattering of low energy muons in the absorber material within the apparatus (fig. 4.1 & 4.2). Absolute measurements have been carried out for several directions of muon incidence from vertical to the direction to 89° zenith angle. The large intensity data are considered something new in this field. The status of the early measurements in relation to more recent measurements has been examined. A reassessment of all the current vertical intensity measurements have also been made taking into account latitude effect, the effect of 11 year cycle of solar activity to find that there is a good agreement of vertical intensity data among the higher latitude experiments of Ng et al 1974 at 57.5° N, Allkofer et al 53°N, Aston et al 57.5°N and the present work at the latitude of 16° N.

The previous measurements at large zenith angles are compared with the present measurements and also with theoretical predictions according to expected intensities, according to (1) recent rigorous calculation of K. Maeda (1973) on conventional pion to muon decay model and (2) calculation of Aston et al (1966). All the experimental data over the range of zenith angle upto 90° suggest all muon production in the atmosphere from pion decay and support the assumption of energy-dependent inelastic cross section for cosmic ray hadron-nucleon interactions and other assumptions made in the models of calculations.