ON THE HIGH ENERGY PROTON SPECTRUM MEASUREMENTS

R. W. ELLSWORTH, A. ITO,* J. MACFALL,** F. SIOHAN,†
R. E. STREITMATTER, S. C. TONWAR,†† P. R. VISHWANATH,
and G. B. YODH‡

Department of Physics and Astronomy, University of Maryland, College Park, Md., U.S.A.

and

V. K. BALASUBRAHMANYAN

Goddard Space Flight Center, Laboratory for High Energy Astrophysics, Greenbelt, Md., U.S.A.

(Received 8 June, 1977)

Abstract. The steepening of the proton spectrum beyond 1000 GeV and the rise in inelastic cross sections between 20 and 600 GeV observed by the PROTON 1–2–3 satellite experiments may be explained by systematic effects of energy dependent albedo (back-scatter) from the calorimeter.

Résumé. L'accroissement avec l'énergie de l'albedo dû au calorimètre peut expliquer l'augmentation de la pente du spectre primaire de protons au-delà de 1000 GeV et la croissance des sections efficaces inélastiques entre 20 et 600 GeV observés lors des expériences en satellite PROTON 1, 2 et 3.

1. Introduction

Cosmic ray particles constitute the only sample of matter from outside the solar system available to us for direct studies. Study of the composition and energy spectra of cosmic ray particles provide important data with which one may test theories of astrophysical processes such as stellar evolution, nucleo-synthesis (Schramm and Arnett, 1973), interstellar processes (Shapiro and Silberberg, 1970), as well as theories of acceleration and propagation of cosmic rays (Scott and Chevalier, 1975; Rasmussen and Peters, 1975).

The most abundant component of cosmic rays up to 2000 GeV is protons (Akimov *et al.*, 1969a, b; Grigorov *et al.*, 1971; Ryan *et al.*, 1972; and Schmidt *et al.*, 1969). The question of the origin of these protons has been a perplexing one: Do they arise in acceleration processes of supernova ejecta mixed with interstellar hydrogen at the interface of supernova remnants and interstellar medium (Scott and Chevalier, 1975), or do high energy protons arise as secondary products in nuclear collisions of heavier

* Now at State University of New York at Stony Brook, Long Island, N.Y.
** Now at Pfizer Corp., Columbia, Md.
† NAS/NRC Resident Research Associate at Goddard Space Flight Center, Greenbelt, Md.
†† Now at Tata Institute of Fundamental Research, Bombay, India.
‡ On sabbatical leave at Goddard Space Flight Center, Greenbelt, Md.

Astrophysics and Space Science **52** (1977) 415–427.

nuclei in interstellar medium in a Galaxy closed to escape of particles (Rasmussen and Peters, 1975; or Peters and Westergaard, 1976)? To understand these problems, a knowledge of the proton spectrum beyond 2000 GeV is of importance.

The only measurement of the proton energy spectrum above 2000 GeV comes from the ionization calorimeter experiments done on the PROTON 1, 2 and 3 satellites (Akimov *et al.*, 1969a, b). These measurements gave two unexpected results: (1) a steepening of the proton spectrum at $\sim$1000 GeV with an apparent change of slope by 0.7 unit and (2) a 20% increase in inelastic cross sections of protons on carbon and polyethylene nuclei between 20 and 600 GeV.

The observation of a steepening of the proton spectrum at so low an energy has given rise to many speculations about the interpretation of extensive air shower measurements (Gaisser *et al.*, 1973; McCusker, 1975; Wdowczyk and Wolfendale, 1973). The increase of 20% in cross sections has led to speculation about the possible existence of deuterons in cosmic rays (Grigorov and Mamontova, 1975). Therefore, it is important to examine the experimental technique for possible energy dependent systematic effects.

Back-scattered particles from interactions in the calorimeter could give rise to an energy dependent bias which can cause steepening of the observed proton spectrum. The PROTON experimenters did consider back-scatter, but came to the conclusion that it was not significant. Recent experiments done by the University of Maryland group at Sacramento Ridge Cosmic Ray Laboratory (SRCRL), Sunspot, New Mexico (elevation 2900 m) (Ellsworth *et al.*, 1975a; MacFall, 1976; Siohan, 1976), have shown that the magnitude of the back-scatter, which is indeed quite large, has a logarithmic variation with the energy of the incident hadron. Using this information from the Maryland calorimeter, we have made attempts to correct the proton spectrum for systematic bias. We show that effects of energy dependent albedo can give rise to steepening of the proton spectrum at high energies.

In Section 2 we describe the experimental apparatus used in the PROTON experiments. In Section 3 we describe the University of Maryland experimental setup to study the albedo from the calorimeter and experimental results obtained on the magnitude and energy variation of albedo. The effects this albedo could have on the proton spectrum and cross section measurements of the PROTON experiments is estimated in Section 4. Finally, a summary discussion of these results is given in Section 5.

2. Experimental Apparatus of the PROTON Series

The calorimeter in the PROTON experiments (Grigorov, *et al.*, 1967a; Akimov *et al.*, 1969a, b) (Figure 1) had a depth of three interaction lengths. A scintillator N was placed above the calorimeter with 2.5 cm of lead immediately above. A block of carbon (about 34 g cm^{-2} thick) separated this scintillator from a stack of two proportional chambers, called Z_1. The trigger required a minimum energy deposition

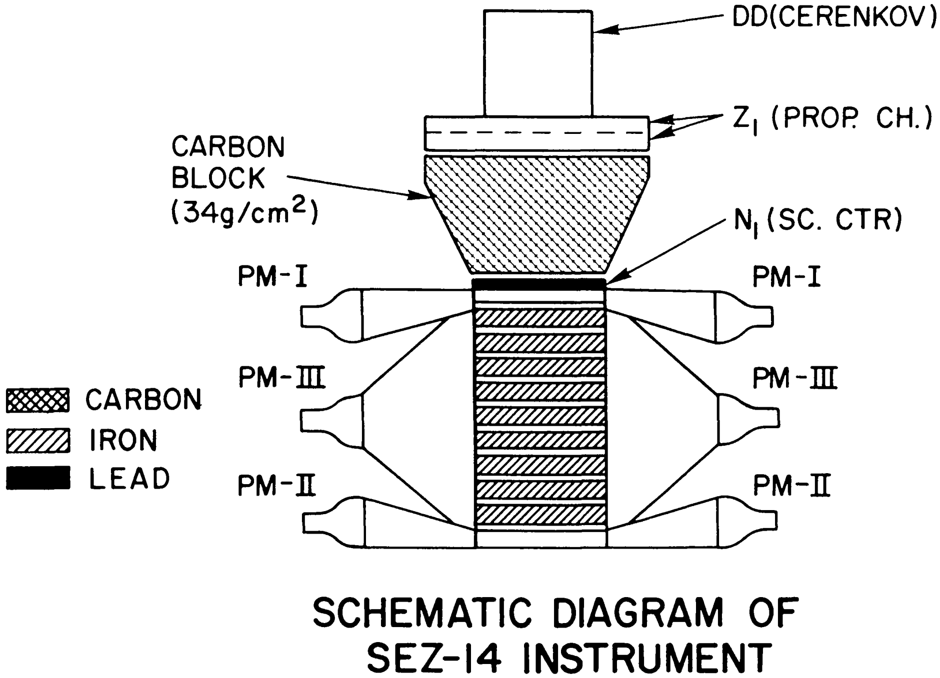

Fig. 1. SEZ-14 instrument flown in PROTON 1–2–3 experiments.

in the calorimeter, E_{ci}, a pulse in the proportional chambers Z_1, and a pulse in scintillator N.* To select protons, the pulse heights of both proportional chambers Z_1 were required to be less than $2.7V_{mp}$, where V_{mp} is the most probable pulse height for sea-level muons. In order to decrease the probability of albedo particles from the calorimeter affecting Z_1 pulse heights, the carbon block was in place for most of the experiment. The proton spectrum data were taken in this configuration in which all events interacting either in the carbon block or in the calorimeter were included. It was argued that this configuration eliminates back-scatter problems (Grigorov *et al.*, 1971).

3. Study of Albedo from Calorimeters

3.1. Apparatus of University of Maryland Experiment

The SRCRL calorimeter (Ellsworth *et al.*, 1975b; MacFall, 1976; Siohan, 1976) had a total depth of eight interaction lengths of iron and an area of about 4 m^2. The hadronic cascade is sampled by seven layers of liquid scintillators. The experimental array had the following components (see Figure 2).

(a) A scintillator T1, of thickness 1.25 g cm^{-2} and area 3.3 m^2 placed just above the calorimeter.

* The first published spectra from the PROTON experiments (Grigorov *et al.*, 1967b) were taken with a trigger $Z_1N_1E_{ci}$, where N_1 is the requirement that the pulse height in scintillator N be in a window 0.4 to 1.7 times the most probable sea-level muon pulse height. Later publications (Akimov *et al.*, 1969a) present the combined spectra $Z_1N_1E_c + Z_1N_2E_{ci}$, where N_2 is the requirement that the pulse height in N be $\geqslant 1.7$ times the most probable muon pulse height.

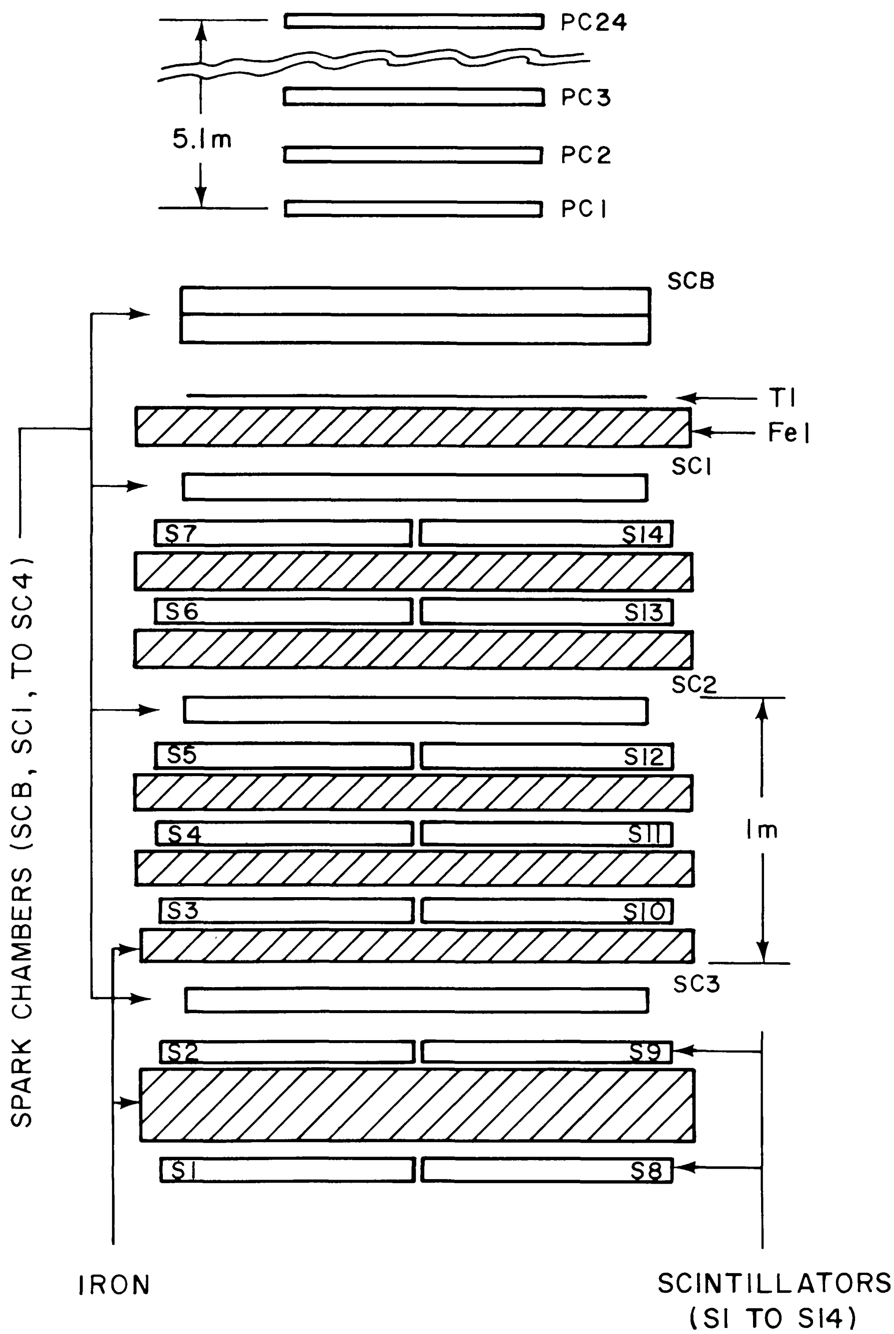

Fig. 2. A vertical cross-section of the University of Maryland cosmic ray calorimeter showing the locations of proportional chambers and counter T1 which were used in studying back-scatter.

(b) A transition radiation detector (TRD) consisting of a stack of 24 proportional chambers placed above the beam spark chamber described below. (The proportional chambers (PC), which were used to differentiate between protons and pions, had an area of 1 m^2, an active depth of 5 cm, and were filled with argon–methane mixture (90% Ar and 10% CH_4) at a pressure of 0.73 atm.)

(c) A set of four wide gap chambers: a beam chamber, SCB, placed above the counter T1 and underneath the TRD; three chambers, SC1, SC2 and SC3 placed below 1λ, 3λ and 6λ of iron in the calorimeter.

Special features which made this instrument suitable for the study of back-scattered albedo were: (1) the trigger was on the total detected signal from the calorimeter and did not depend on the pulse height of detectors placed directly above the calorimeter iron (T1 and PCs); (2) the spark chambers embedded in the calorimeter made it possible to select single hadronic jets; (3) these jets could be correlated by reconstruction with the incident track in the beam spark chamber; (4) for each event the pulse heights of T1 and the PCs were recorded; and (5) these detectors were completely enclosed in aluminium boxes which shielded them from spark chamber noise. Therefore, it was possible to study the pulse height distribution of these detectors as a function of energy of the hadron and of the depth of the point of first interaction.

The response of the T1 counter was measured in terms of pulse height deposited by a muon with energy greater than 800 MeV. For the same muons, V_{mp}, the most probable pulse height from the PCs in the TRD, was determined to be 5.6 keV.

The exposure factor at 2900 m altitude enabled us to cover an energy range of 100 to 2000 GeV for the study of back-scatter.

3.2. Results on albedo from the SRCRL experiment

While the main purpose of the experiment was a study of cosmic ray fluxes at mountain altitude, the magnitude and energy dependence of the back-scatter albedo from the calorimeter was also measured. The events which interacted in the first λ (interaction length) and beyond the first λ were labelled as 'Fe1' and 'Fe2' events, respectively. The proportional chambers used for this study were the lowest (1–3) and the middle (8–13) chambers in the TRD stack. Table I shows the average signals as a function of energy and depth for the scintillator T1. The table also lists signals of PC1 (0.66 m above the calorimeter iron) and the average of PCs 8–13 (approximately 2.75 m above the calorimeter iron). The individual hadrons for which the averages have been presented in Table 1 were required to have traversed the detector being

TABLE I

Average signals of detectors

Energy (GeV)	T1		PC1	Av. PCs 8–13
	Fe1	Fe2	Fe1	Fe1
130	3.89 ± 0.42	1.34 ± 0.05	1.34 ± 0.14	1.09 ± 0.09
500	5.27 ± 0.12	1.81 ± 0.10	1.84 ± 0.10	1.47 ± 0.07
700	5.98 ± 0.17	1.95 ± 0.10	1.87 ± 0.11	1.51 ± 0.09
1300	7.10 ± 0.10	1.92 ± 0.07	2.23 ± 0.16	1.67 ± 0.12

studied – i.e., they were 'hits'. A similar study, not presented here, was done for 'misses' also.

The most important point to note is the increase of the average signals in T1 and PC1 for events which interacted in the first λ. In these 'Fel' events, signals show a logarithmic increase with energy. Figures 3 and 4 also show the pulse height distributions in T1 and PC1 at energies of 130 GeV and 1300 GeV. It can be seen that the pulse height tail increases with energy in both the scintillator and the proportional chamber.

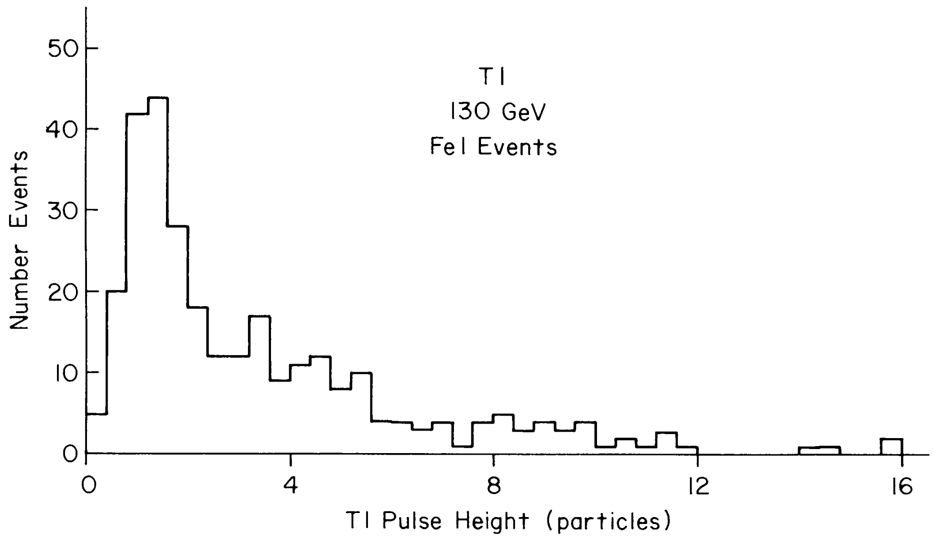

Fig. 3a.

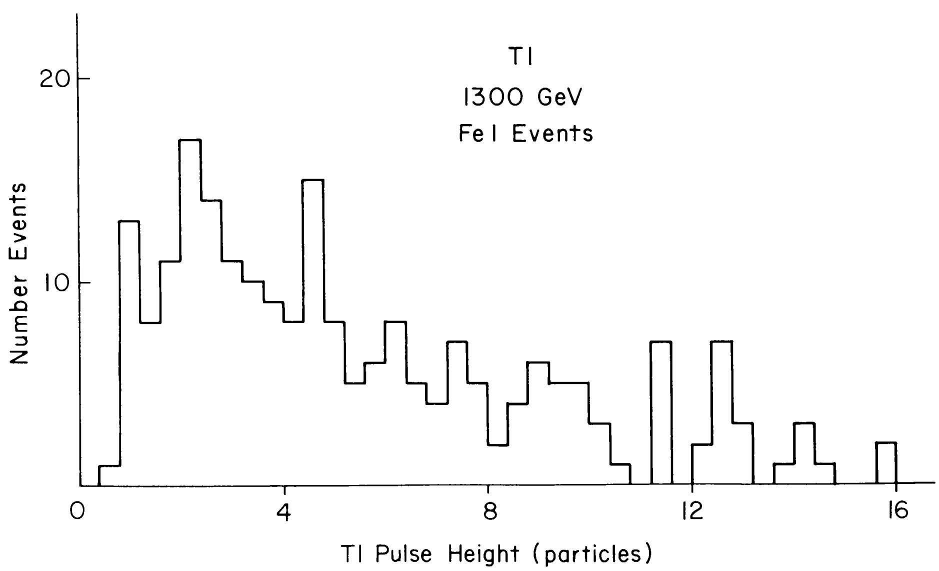

Fig. 3b.

Fig. 3. Pulse height distributions of counter T1 for single unaccompanied hadrons of average energy (a) 130 GeV and (b) 1300 GeV, interacting in the first 120 g cm^{-2} of iron. The abcissae are in terms of minimum particles.

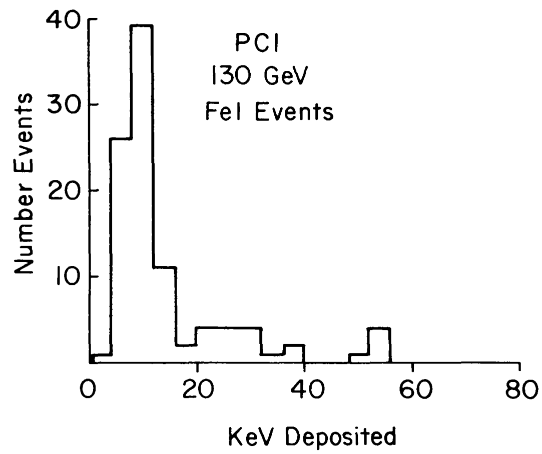

Fig. 4a.

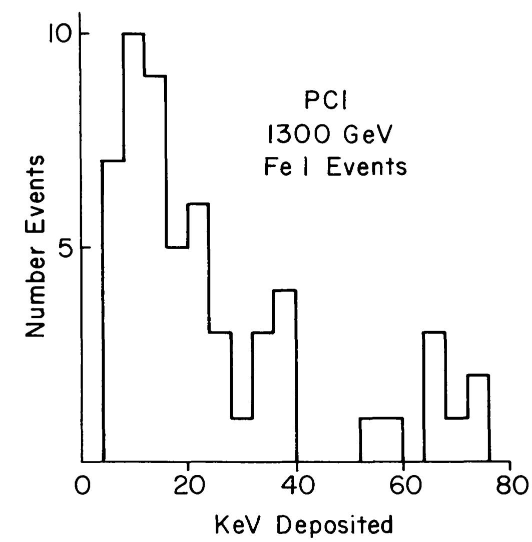

Fig. 4b.

Fig. 4. Pulse height distributions of proportional chamber 1 (PC1) for single unaccompanied hadrons of average energy (a) 130 GeV and (b) 1300 GeV. The abcissae are in KeV deposited.

The magnitude and energy dependence of this back-scatter becomes smaller with an increase in the distance and the amount of matter between the point of first interaction and the detector, as illustrated by the following points. (1) When the interaction takes place deeper in the calorimeter (Fe2 events), the average signal in T1 is much smaller than when the interaction is in the highest layer of the calorimeter. (2) When the depth of interaction in the calorimeter is fixed (Fe1), Table I indicates that the average signal in PC1 (near the calorimeter) is larger and increases more rapidly with incident hadron energy than that of the high PCs 8–13. These two results can be understood as due to the ranging out and geometrical divergence of the back-scatter particles.

The albedo from a calorimeter will, in general, be made up of (i) heavy charged particles, (ii) neutrons, (iii) photons and (iv) electrons. In the proportional chambers of the TRD, an additional energy dependent contribution due to transition radiation will exist for those incident particles whose Lorentz factor is above the TR threshold.

Scintillation counter T1 and proportional chamber PC1 will both record charged back-scatter with high efficiency. Neutrons contribute to the T1 pulse height with greater efficiency, while photons contribute to the PC pulse height with greater efficiency.

3.3. Effect of albedo on the measured proton spectrum

The magnitude of the albedo observed in the SRCRL experiment implies that the pulse heights in the proportional chambers, Z_1, of the PROTON experiments were significantly increased by albedo from interactions in both the carbon block and the calorimeter. Since the fraction of events with pulse heights greater than $2.7V_{mp}$ also increases with energy, the percentage of events rejected as nonproton events increases with energy.

To estimate the effects of albedo on an apparatus similar to that of the PROTON experiments, we examined the signal distributions for a subset of data; i.e., for those hadrons which passed through both PC1 and its projection downward on the horizontal plane at the depth of spark chamber SC1. Any difference between these data and those of PROTON experiments are due only to the following differences in the apparatus: (a) there is 7 g cm^{-2} of absorber between PC1 and the top of the SRCRL calorimeter due to which some albedo may range out; (b) PC1 is located 0.66 m above the calorimeter and hence has a smaller geometrical acceptance than proportional chambers Z_1 in the PROTON experiments; (c) the upper calorimeter layer is iron and not carbon. While the presence of carbon may decrease the albedo effect, the total number of interactions which increase with energy and contribute to an increasing albedo is not expected to be very different from the number in a pure iron calorimeter.

Geometrical divergence of the albedo permits subtraction of the TR contribution in PC1 by using pulses from higher chambers which subtend a small angle to the point of cascade origin. Let $f(E)$ be the fraction of events with signals in a particular counter greater than $2.7V_{mp}$. By a study of pulse height distributions at several energies, the magnitude and variation of this fraction with energy was obtained for T_1 and the lower and the middle proportional chambers. Both Fe1 and Fe2 events were used for this analysis. The increase due to transition radiation, as given by the middle chambers (PCs 8–10), was subtracted from the observed fractions for PC1. The resulting fractions reflect the increase of back-scatter alone with energy. The values of f for T1 and PC1* have been listed in Table II and plotted in Figure 5.

* Being 0.66 m above the Fe1 layer, PC1 itself will give f values which are an *underestimate* of those from the PROTON experiment counter Z_1. While a downward extrapolation could be made to hypothetical chambers on the calorimeter, a lack of knowledge about the energy and angular distribution of the back-scatter makes interpretations of such extrapolations difficult.

TABLE II

Variation of f with energy

Energy (GeV)	f(T1)	f(PC1)
130	0.29 ± 0.04	0.16 ± 0.04
500	0.49 ± 0.02	0.23 ± 0.04
700	0.52 ± 0.03	0.24 ± 0.04
1300	0.56 ± 0.04	0.27 ± 0.05

When $f(E)$ is the fraction of protons rejected at energy E, the true differential flux J_t at that energy is related to the observed differential flux J_o as $J_t = J_o/(1 - f(E))$. We have taken J_o from the fitted PROTON 1–2–3 integral spectrum reported by Akimov *et al.* (1969b). Using the fractions $f(E)$ for T1 and PC1, corrected integral spectra were obtained and are plotted in Figure 6 along with the PROTON 1–2–3 spectrum.

The important point to note is that the steepening in the corrected spectra is less than in the observed spectrum. Since the PROTON experiments had *two* proportional chambers immediately above the calorimeter to veto larger signals, the corrected spectra are approximations to the true spectrum. The correction derived from the response of the scintillator T1 has the limitation that neutron back-scatter will count more efficiently in the scintillator than in the proportional chamber Z_1. Since PC1 was located farther above the calorimeter than Z_1 in the PROTON experiments, the flux corrected from the response of PC1 will be smaller than the true flux.

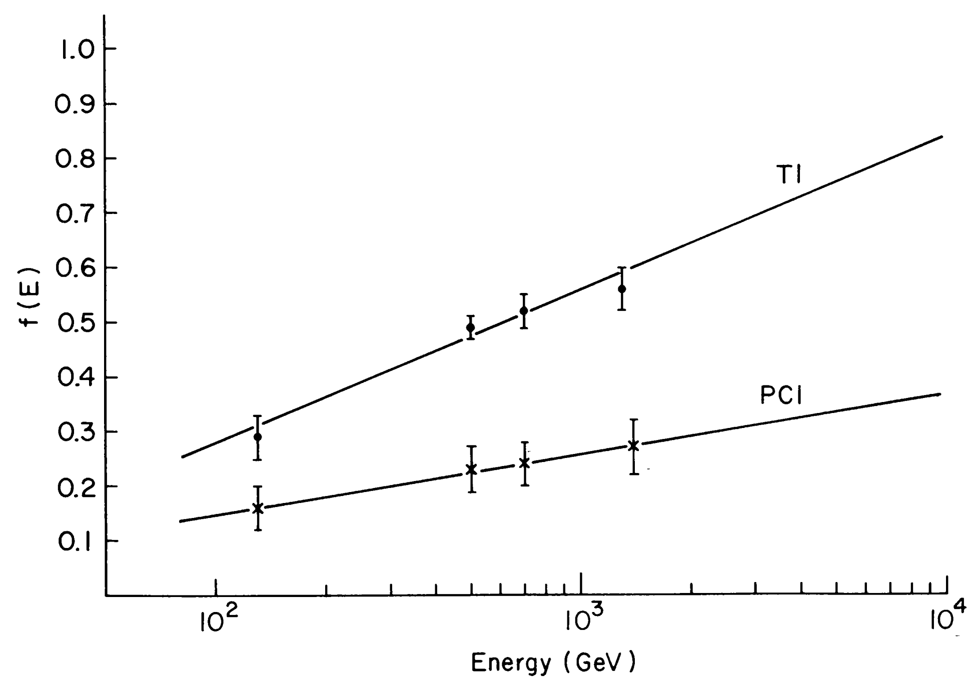

Fig. 5. $f(E)$ versus incident hadron energy.

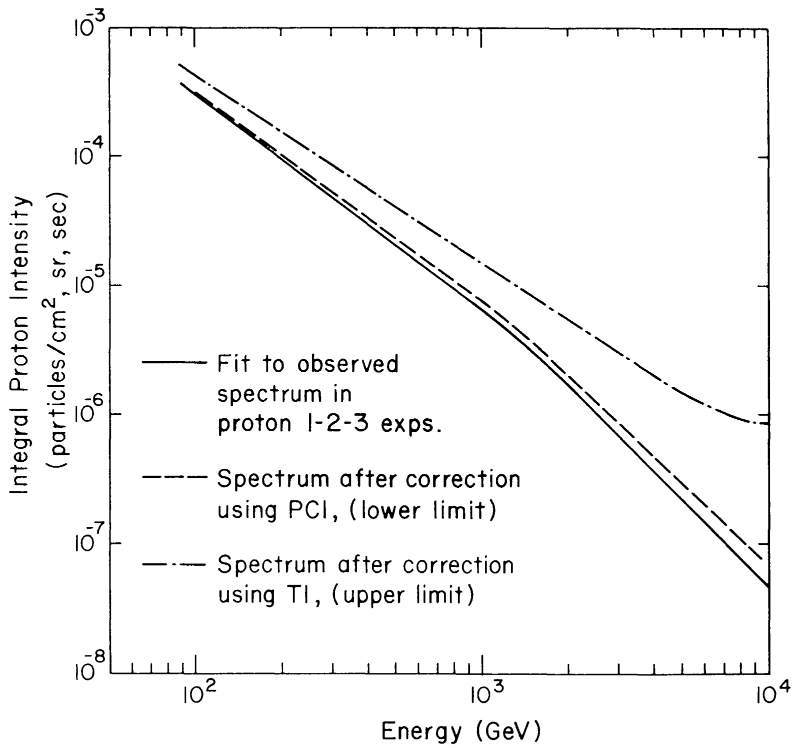

Fig. 6. Integral energy spectrum of protons with and without correction for back-scatter.

5. Effect of Albedo on Cross Sections

In the same series of experiments, inelastic cross sections of protons on carbon were measured using a transmission technique. A trigger $Z_1N_1E_c$ was used to measure J_o, the flux of protons without the absorber and J_x with the absorber between the scintillator and the proportional chamber. The pulse heights in Z_1 and N_1 were required to be less than $2.7V_{mp}$ and $1.7V_{mp}$, respectively. The inelastic cross section was calculated using $\sigma = k^{-1} \ln J_o/J_x$, where k is a constant dependent on the absorber thickness and properties. An increase of 20% in cross section was seen in the energy range 20 to 600 GeV. While this rise has not been seen in accelerator measurements with different projectiles (protons, pions and neutrons) on nuclear targets (Busza, 1975; Murthy, 1975; Baker, 1975), this apparent increase can also be attributed to albedo related effects.

This increase ($\sim$20%) in the cross section arises from a small ($\sim$10%) increase in the ratio J_o/J_x. In the SRCRL data, the fraction of events which give a signal in PC1 for hadrons whose trajectories *missed* PC1 increases from about 9% at 100 GeV to about 25% at 1300 GeV. Similarly, in the PROTON experiments back-scatter from hadrons whose trajectories miss Z_1 and N but deposit enough energy in the calorimeter, can give rise to $Z_1N_1E_c$ triggers and contribute to a spurious increase in J_o. This effect on J_x is much smaller since the absorber attenuates the back-scatter, giving less than minimum signals in Z_1. Thus, this systematic effect due to albedo also explains the apparent increase in the cross sections. With limited statistics, data taken with direction detector DD in the trigger show no statistically significant increase in cross section (Grigorov *et al.*, 1970). The Čerenkov counter DD does not detect slow moving back-scatter.

5.1. Discussion

We have seen that both unexpected observations from the PROTON experiments – steepening of the proton spectrum and increase of cross sections – can arise as consequences of energy dependent albedo from the calorimeter. While we have given estimates of corrections to the observed proton spectrum, we note that it is difficult to obtain the true spectrum due to the differences between the two experimental setups. There exists, however, a clear need for extending the proton spectrum measurements beyond 2000 GeV with experiments not susceptible to back-scatter.

One may further ask if the albedo effects would have interfered with the measurements of the He spectrum reported in the same series of experiments. Back-scatter effects can modify the He spectrum. However, the magnitude of the effect might be smaller than that for protons, because of the large window allowed for Z_1 pulse height in the α-mode ($2.7V_{mp} < V_{Z1} < 8V_{mp}$). As far as one can understand the triggering for the α-mode, it appears that the Čerenkov counter signal was required to be in coincidence with those of Z_1 and the calorimeter. The Čerenkov detector is insensitive to low velocity back-scatter and therefore a pulse height requirement on it would not remove the high energy α particles. Thus the α-spectrum may be an undistorted result. The exposure factor for the α-spectrum is not high enough to reach energies of overlap with the bend region for the proton spectrum.

One additional observation is in order regarding the all-particle spectrum. The albedo effects discussed in this paper should have no effect on the flux or the slope of the all-particle spectrum. Indeed, the measurements of the satellite experiment (Akimov *et al.*, 1969a) and those of GSFC experiment (Ryan *et al.*, 1972) are in agreement where they overlap.

Since the rise in cross sections can be attributed to albedo effects, it is not necessary to invoke a large fraction of deuterons in the primary cosmic ray beam to account for this increase, as discussed recently (Ganguli *et al.*, 1974; Grigorov and Mamontova, 1975). A small fraction of deuterons is not ruled out (Apparao, 1973).

Finally, we make a few remarks as to the origin and nature of albedo particles. While we have established the magnitude and energy dependence of the albedo, a more difficult task is to determine the nature of these particles. Their logarithmic dependence on energy suggests that they arise from interactions of secondary and tertiary hadrons in the cascade. Since the number of these secondaries increases logarithmically with energy, the number of their interactions also has the same dependence on energy. Every one of these interactions, apart from producing fast particles, gives rise to a small number of slow particles, both protons and neutrons. The charged slow particles, known as heavy prongs in emulsion techniques, are isotropic in the lab system. While the number of these heavy prongs per interaction itself is independent of energy, their total number increases with incident hadron energy. While the slowest (the 'black' tracks) of the slow particles get absorbed soon, the faster ones (the 'gray' tracks), with a typical energy of 160 MeV, are likely to reach the top of the calorimeter. An analytical calculation (Siohan, 1977) was done assuming an isotropic production of these particles. It was found that the number of these particles reaching the top of the calorimeter did indeed increase with energy. Apart from these charged particles and neutrons, the back-scatter also contains photons from the electromagnetic cascade. A proportional chamber placed immediately on top of the calorimeter can be studied to obtain a better estimate of the photon flux.

Acknowledgements

We would like to thank Dr J. F. Ormes for useful discussion and Dr W. V. Jones for Monte Carlo simulation. The work was supported in part by National Science Foundation No. Phy. 76-14853 and by the University of Maryland Computer Science Center. G. B. Yodh would like to thank Dr F. B. McDonald of Laboratory for High Energy Astrophysics for his hospitality.

References

Akimov, V. V., Grigorov, N. L., Mamontova, N. A., Nesterov, V. E., Prokhin, V. L., Rapoport, I. D. and Savenko, I. A.: 1969b, *Proc. Int. Cosmic Ray Conf., Budapest, Acta Phys. Hung., Suppl.* **29**, Vol. 2, 211.

Akimov, V. V., Grigorov, N. L., Nesterov, V. E., Rapoport, I. D., Savenko, I. A., Skuriden, G. A. and Tirenkov, A. F.: 1969a, *Proc. Int. Cosmic Ray Conf., Budapest, Acta Phys. Hung., Suppl.* **29**, Vol. 1, 517.

Apparao, M. V. K.: 1973, *Proc. 13th Int. Cosmic Ray Conf., Denver* **1**, 126.

Baker, W.: 1975, private communication. 'Preliminary Results on Pion-Nucleus and Proton-Nucleus Inelastic Cross Sections'.

Busza, 1975, *Phys. Rev. Letters* **34**, 836.

Ellsworth, R. W., Goodman, J., Ito, A., MacFall, J., Siohan, F., Streitmatter, R. E., Tonwar, S. C. and Yodh, G. B.: 1975a, *Proc. Calorimeter Workshop, Fermi National Acc. Lab.*, p. 201.

Ellsworth, R. W., Goodman, J. A., Ito, A. S., MacFall, J. R., Siohan, F., Streitmatter, R. E., Tonwar, S. C. and Yodh, G. B.: 1975b, *Proc. 14th Int. Cosmic Ray Conf., Munich* **7**, 2528.

Gaisser, T. K., Maurer, R. H. and Noble, C. J.: 1973, *Proc. 13th Int. Cosmic Ray Conf., Denver* **4**, 2652.

Ganguli, S. N., Raghavan, R. and Subramanian, A.: 1974, *Pramana* **2**, No. 6, p. 341.

Grigorov, N. L., Kakhidze, G. P., Nesterov, V. E., Rapoport, I. D., Savenko, I. A., Smirnov, A. V., Titenkov, A. F. and Shishkov, P. P.: 1967a, *Kosmich. Issled.* **5**, 383.

Grigorov, N. L., Nesterov, V. E., Rapoport, I. D., Savenko, I. A., Skuridin, G. A. and Titenkov, A. F.: 1967b, *Kosmich. Issled.* **5**, 395.

Grigorov, N. L., Nesterov, V. E., Rapoport, I. D., Savenko, I. A. and Skuridin, G. A.: 1970, *Soviet J. Nucl. Phys.* **11**, 455.

Grigorov, N. L., Mamontova, N. A., Rapoport, I. D., Savenko, I. A., Akimov, V. V. and Nesterov, V. E.: 1971, *Proc. 12th Int. Cosmic Ray Conf.* **1**, 1752.

Grigorov, N. L., Gubin, Tu. V., Rapoport, I. D., Savenko, I. A. and Yakovlev, B. M.: 1971, *Proc. 12th Int. Cosmic Ray Conf.* **5**, 1746.

Grigorov, N. L. and Mamontova, N. A.: 1975, *Proc. 14th Int. Cosmic Ray Conf., Munich* **7**, 2303.

MacFall, J. R.: 1976, Ph.D. thesis, University of Maryland, Report No. PP76232 (unpublished).
McCusker, C. B.: 1975, Physics reports.
Murthy, P. V. R.: 1975, *Nucl. Phys.* **B92**, 209.
Peters, B. and Westergaard, N. J.: 1976, *Danish Space Res. Inst.* (preprint).
Rasmussen, I. L., Peters, B.: 1975, *Nature* **258**, 412.
Ryan, M. J., Ormes, J. F. and Balasubrahmanyan, V. K.: 1972, *Phys. Rev. Letters* **L8**, 985.
Scott, J. S. and Chevalier, R. A.: 1975, *Ap. J. Letters* **197**, L5.
Schmidt, W. K. H., Pinkau, K., Pollvogt, U. and Huggett, R. W.: 1969, *Phys. Rev.* **184**, 1279.
Schramm, D. N. and Arnett, W. D.: 1973, *Explosive Nucleosynthesis*, University of Texas, Austin.
Shapiro, M. M. and Silberberg, R.: 1970, *Ann. Rev. Nucl. Sci.* **20**, 323.
Siohan, F.: 1976, Ph.D. Thesis, University of Maryland, Report No. PP77611 (unpublished).
Siohan, F.: 1977, unpublished.
Wdowczyk, J. and Wolfendale, A. W.: 1973, *Proc. 13th Int. Cosmic Ray Conf., Denver* **3**, 2336.