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EVIDENCE FOR THE EXISTENCE OF NEW PROCESSES AT ENERGIES ABOVE 2×10^{11}eV

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ABSTRACT

Cosmic ray flux measurements in the energy region 10^{10}-10^{14}eV obtained by calorimeters on the Satellites Proton I and II have shown results that are at variance with previous data.

While a single power law provides an approximate fit to the all-particle spectrum, the primary proton flux falls sharply at energies above $\sim 5 \times 10^{11}$eV, indicating that at high energies protons become progressively scarcer in the primary flux. The cross section for particle production of protons on carbon is found to rise by 20% in the interval between 2×10^{10} and 10^{12}eV.

Assuming that, in the energy region of interest:

1) the real proton flux is given by a single-power law,

2) the nuclear composition remains constant,

we show that the satellite flux measurements can be explained by an energy loss mechanism in the calorimeter, with the loss being a function of the energy per nucleon, rather than total energy. Furthermore, this "X" process has a cross section of the right magnitude to account for the p-carbon cross section measurements. The X process could be described in terms of particle production or dissociation of the primary protons.

We discuss the relation of our results to other cosmic ray data, and possible experiments to verify the nature of the process are proposed.

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I. Introduction

Measurements of the primary cosmic ray flux and the p-carbon cross sections at high energies performed by the Artificial Earth Satellites of the Proton Series(1-3) have yielded results at variance with other data and with currently held beliefs.

The detector used by the Soviet workers consisted of pairs of ionization calorimeters(1), each three nuclear mean free paths long, together with suitable triggering and particle counting hardware. Carbon and polyethylene targets could be inserted in the path of the incident primary particles. These instruments were flown in Protons I, II and III, and on November of 1968, a fourth satellite, Proton IV, carrying more advanced instrumentation, was launched.(4)

The results of the measurements on the cosmic ray flux in the energy range $10^{10} - 2 \times 10^{14}$eV show(2) an integral spectrum for the total particle flux that was fit by $F(\geq E) = AE^{-\gamma}$, where $A = 7.2 \times 10^{-4} \text{cm}^{-2}\text{sec}^{-1}\text{sr}^{-1}$, $\gamma = 1.74 \pm .06$, and E is measured in units of 10^{11}eV.

The proton flux is found to behave in a surprising way. While its behavior is similar to that of the all-particle flux at low energies, above 10^{12}eV it can be best described by a power law with an exponent $\gamma \stackrel{\sim}{\sim} 2.30$. This shows a drop in the proton flux that is larger than that measured by ground based techniques.(5) This satellite data implies that nuclei other than protons become the dominant component of the primary flux above 10^{13}eV. This is at variance with other measurements.(6,7)

The results of the p-carbon cross section measurements were just as surprising, showing a 20% increase in the cross section for "pionization"(8) (σ_π), a term used to describe particle production: $\sigma_\pi = \sigma(\text{total}) - (\sigma(\text{elastic}) + \sigma(\text{quasi-elastic}))$.

The results of Proton I and II are available(1-3), and they seem to have been confirmed by Proton III(9). We are not aware of any published data on the measurements of Proton IV. This information might change our analysis.

II. Interpretation of the Results

The experimental results obtained by the Proton satellites can be interpreted in one of the following ways:

(1) We can accept the measured data as accurately reflecting the primary cosmic ray flux and p-carbon pionization

cross section, assuming that the previous results reflect inadequate data or measuring techniques.

(2) One may assume that the Soviet satellite measurements were not carried out properly, either due to instrumental malfunction or imperfect calibration of the calorimeter.

We tend to discard the idea of instrumental malfunction because of the consistency of the data obtained during different flights. Also, Proton I was returned to Earth and checked after its flight(10), and any malfunctions should have become apparent at that time.

It can be argued that three nuclear mean free paths of absorber are insufficient for accurate energy determination, and that the strange results reflect poor calibration of the instrument. By calibration we mean the prediction of the behaviour of the calorimeter in terms of its behaviour at accelerator energies. This is a question still to be settled, but one must point to the large body of experience with calorimeters accumulated in the Soviet Union,(11,12) some of them having as many as eight nuclear mean free paths of absorber. We therefore assume that the behavior of the smaller calorimeter was well correlated with that of the larger ones. A careful analysis of possible sources of systematic error in the space experiment was carried out in Ref. 2, and it was concluded that none was large enough to account for the observed results. It is worth noting that Proton III was designed(9) to eliminate what was considered the largest source of error.(2)

(3) Finally, we are tempted to speculate on new processes that may become possible at energies of over 100GeV. Any process that creates particles with interaction lengths substantially longer than the pion's will alter the percentage of incident particle energy deposited in the calorimeter and may cause an apparent dimunition in the number of very high energy particles.

In this work we investigate the consequences of assuming that the last interpretation is correct. It will be seen that an energy loss mechanism dependent on particle energy per nucleon can account for the drop in the proton spectrum and the shape of the all-particle spectrum; that most of the observed increase in p-carbon cross section can also be explained; and finally, that this mechanism has some of the characteristics of a particle production process.

III. Phenomenological Analysis of the Proton Spectrum

It is found that at energies below 10^{11}eV the integral proton spectrum can be described by $F_1(\geq E) = AE^{-\gamma}$, with $A = 7.2 \times 10^{-4} cm^{-2} sec^{-1} sr^{-1}$, and $\gamma = 1.45$. This form is obtained by fitting the proton data in the energy interval 10^{10}-10^{11}eV. In the energy region above 10^{12}eV one finds that the spectrum can be described by the function $14.3 \times 10^{-4}E^{-2.30}$ $cm^{-2}sec^{-1}sr^{-1}$. (See Fig. 1).

The differential proton spectra used in this work are $N_1(E) = -\frac{dF_1(\geq E)}{dE} = \gamma A E^{-(\gamma+1)}$, below $E = 2.24 \times 10^{11}$eV,

and $N_2(E) = -\frac{dF_2(\geq E)}{dE} = (2.3 \times 14.3) \times 10^{-4}E^{-3.30} - 27.6 \times 10^{-4}$ $\exp(1-2E)$ above 2.24×10^{11}eV, where, as previously, the energy is measured in units of 10^{11}eV, and the fluxes in units of $cm^{-2}sec^{-1}sr^{-1}$. This particular form of $N_2(E)$ is chosen so that it has the right form at energies above 10^{12}eV, fits the spectrum in the 10^{11}-10^{12}eV region, and $N_1(E_{th}) = N_2(E_{th})$ for $E_{th} = 2.24 \times 10^{11}$eV, corresponding to a total center of mass energy of 20.5GeV. In this sense E_{th} can be considered the reaction threshold for the onset of a postulated "X" process. This threshold could have been chosen anywhere between $\sim 1.5 \times 10^{11}$ and $\sim 5 \times 10^{11}$eV, corresponding to center of mass energies of 17GeV and 31GeV respectively.

We can now write

$N_1(E) = N_R(E)+N_A(E)$ for $E < E_{th}$, Eq. 1

and $N_2(E) = N_R(E)-N_L(E)+N_A(E)$ for $E > E_{th}$ Eq. 2

where $N_R(E)$ is the real primary proton spectrum between 10^{10} and 10^{14}eV, and $N_L(E)$ and $N_A(E)$ are the number of particles lost from and added to an energy "bin" at energy E, due to the action of the X process in the calorimeter.

We notice that the total number of particles added below E_{th} is very small. This number can not be larger than the value of the integral spectrum above 2.24×10^{11}eV, which is approximately 10^{-4}cm^{-2}sec^{-1}sr^{-1}. Thus the spectrum below 10^{11}eV is not appreciably changed by what happens above 10^{12}eV, and we can set $N_A(E) << N_1(E)$ and $N_1(E) \stackrel{\sim}{-} N_R(E)$ for $E < E_{th}$.

In general, we can write the number of particles lost as $N_L(E) = N_R(E)\ P(E)$, where P(E) is the probability of occurrence of the X process. In the case of $N_A(E)$ we approximate the contribution from all higher energies by calling $E+\Delta$ the average energy that contributes particles to the energy "bin" at energy E due to the working of the X process, and we write $N_A(E) = N_R(E+\Delta)\ P(E+\Delta)$.

If we assume that the real proton spectrum obeys a simple power law at all energies under consideration, $N_R(E) = N_1(E)$ and equation 2 becomes

$$N_2(E) = N_1(E) - N_1(E)P(E) + N_1(E+\Delta)P(E+\Delta) \qquad \text{Eq. 3}$$

Let us consider equation 3 in two ways:

1. We assume all protons undergo the X interaction: then $P(E) \equiv P(E+\Delta) \equiv 1$. This would be the case if the anomaly in the spectrum arises from a defect in the calorimeter. Then we obtain

$$N_2(E) = N_1(E+\Delta) \qquad \text{Eq. 4}$$

where now Δ is the average energy lost by all protons of primary energy $E+\Delta$. Since the forms of N_1 and N_2 are known, it is easy to obtain

$$E+\Delta = \left(\frac{\gamma A}{N_2(E)}\right)^{\frac{1}{\gamma+1}}$$

Figure 2 shows the average energy measured for a proton of energy $E+\Delta$. Figure 3 shows the average fraction of the energy lost by all protons. It can be seen that this fraction reaches a value as high as 88% of the total energy at 2×10^{14}eV.

The Soviet group has estimated that 50% of the primary energy of a cosmic ray particle is deposited in the calorimeters they used, and all the data presented herein has been corrected for this. However, it is clear from the analysis above that explaining the drop in the proton spectrum necessitates the inclusion of a total 90% systematic energy loss at high energies. This is a large error in view of what is presently known about calorimeters.

2. Another way to use equation 3 is to assume that the energy loss for protons that undergo the X interaction is total. Then, $N_A(E) \tilde{\sim} 0$, because the protons that interact effectively disappear from the beam. Then, equation 3 becomes

$$N_2(E) = N_1(E)\ (1-P(E)),$$

and $P(E) = 1-N_2(E)/N_1(E)$ Eq. 5

If the X process is one of heavy particle creation, we calculate from kinematic considerations that the primary proton will, on the average, lose ∿50% of its energy through this process. A paper by Adair and Price presents essentially the same conclusion(13). Of course, protons with energies substantially above threshold can undergo multiple interactions if the calorimeter is "thick" enough, thus losing most of their energy.

To see how P(E) varies when we go from a 100% energy loss per interaction to 50%, we let $E+\Delta = 2E$, and assume that P(E) is varying slowly enough so that $P(E) \sim P(2E)$ (this is a drastic approximation, but $N_1(2E) = .18N_1(E)$, and the results are not too sensitive to the change in P(2E)).

Under these conditions

$P(E) = 1.22(1-N_2(E)/N_1(E))$ Eq. 6

We previously defined P(E) as the probability for losing a primary proton through the X interaction. Then for almost total energy loss, or for a "thin" calorimeter $P(E) = 1-e^{-\sigma_x \cdot \mu}$, from which we obtain

$\sigma_x(E) = -\mu^{-1}\ln(1-P(E))$ Eq. 7

where σ_x (E) is the total cross section for the X process, and μ is the nucleon density of the calorimeter. This density is given by $\mu = \frac{X_{Fe} N_o}{M_{Fe}} M_{Fe}{}^{2/3} + \frac{X_{pl} N_o}{M_{pl}} M_{pl}{}^{2/3} = 6.5 \times 10^{25}$ nucleons/cm^2, where $X_{Fe}=376\text{g/cm}^2$ and $X_{pl}=19.5\text{g/cm}^2$ are the amount of iron and plastic scintillator in the calorimeter respectively, N_o is Avogadro's number, M is the nucleon number and the $M^{2/3}$ factor takes into account the shadowing of nuclei in the nucleus (14,15).

If the energy loss is less than total, and if the mean free path for the X interaction is less than the calorimeter thickness, a proton can undergo more than one X interaction, and the value for the X cross section obtained from equation 7 becomes an upper bound on σ_X. For comparison purposes we estimated the energy dependence of the cross section for heavy particle production by assuming that the process is $p+p \rightarrow p+p+X$, with $M_X = 18.6\text{GeV}$, and that below $4E_{th}$ the energy dependence is given by phase space only. Above $4E_{th}$ we have arbitrarily assumed that the cross section has the behaviour suggested by Adair and Price, (13)

$$\sigma_X = \sigma_o \left(\frac{E}{4E_{th}} \right)^{1/4} \qquad \text{Eq. 8}$$

In Figure 4, we show the values obtained from equation 7 for the case of total energy loss, and the approximate upper bounds on the cross section obtained for the case of 50%

energy loss of the proton. The shape of $\sigma_X(E)$ is not strongly dependent of the particular form chosen for $N_2(E)$. The results from the phase space calculation and equation 8, normalized arbitrarily so that σ_o = 24mb, are also shown.

We speculate that the X process is a particle creation process wherein one or more particles with a total mass 15-29GeV, depending on the choice of E_{th}, are produced.

IV. The All-Particle Spectrum

A consistency test on our analysis involves the all-particle spectrum obtained by Grigorov, et al. (Fig. 5).

Both experimental data$^{(6,7)}$ and transport theory$^{(16)}$ considerations indicate that the nuclear composition of the primary cosmic ray spectrum remains constant in the energy range from 10^{10} to 10^{14}eV. This is equivalent to stating that the form of the all-particle spectrum should differ from the proton spectrum only by a multiplicative constant. This differs sharply from the satellite data, wherein the single exponential fit to the all-particle integral spectrum of the form $E^{-1.74}$, (chosen by Grigorov because it provided a best "straight-line" approximation to the measurements), cannot be fit to the proton spectrum.

Starting with the assumption of the constancy of nuclear composition, that is, γ(all-particle) = γ(proton) = 1.45, we fit the all-particle spectrum below 10^{11}eV by $F_{all}(\geq E) = 8.3 \times 10^{-4} E^{-1.45} cm^{-2} sec^{-1} sr^{-1}$.

Then, if the differences between the single power law and the measured all-particle spectra are due to the workings of the X process in collisions of the primary nucleus with nucleons, these differences will be a function of the energy per nucleon, rather than the total energy. Thus, the average energy loss per primary nucleus can be written, in a first order approximation, as

$$\mathcal{L}(E) = M\Delta(E/M) \qquad \text{Eq. 9}$$

where $\mathcal{L}(E)$ is the average energy loss of an incoming nucleus of mass M, and $\Delta(E/M)$ is the average energy loss of a single nucleon with energy E/M. Then, from Eq. 4, applied to the all-particle spectrum,

$$\mathcal{N}_2(E) = \mathcal{N}_1(E+M\Delta(E/M)) \qquad \text{Eq. 10}$$

where $\mathcal{N}_1(E) = -dF_{all}(\geq E)/dE = 1.45 \times 8.3 \times 10^{-4} E^{-2.45} cm^{-2} sec^{-1} sr^{-1}$.

In an attempt to approximately include the effects of shadowing in the incoming nucleus, we express Equation 9 as $\mathcal{L}(E) = M^{2/3}\Delta(E/M)$, where $M^{2/3}$ is the "effective" nucleon number of that nucleus.

In Figure 5 we show the integral spectra obtained by integrating equation 10 for particles of masses 2, 3, 4 and 5 times the nucleon mass. Present estimates of the average mass of the cosmic ray flux range from about 2 to less than 5. This analysis shows that instrument error is an unlikely explanation for the satellite data, since if such an error existed, it would probably be a function of the total energy and would distort the all-particle spectrum in the same way as the proton spectrum.

V. The p-Carbon Cross Section

The interaction cross section of primary protons on carbon was measured by exposing a graphite block of 30.6g/cm^2 thickness over the calorimeter for fixed amounts of time and comparing the number of protons that reached the calorimeter with and without the target in place.(3)

Since the energy was measured only for a singly charged particle reaching the calorimeter (presumably a proton), the results of cross section measurements were independent of detector parameters, as well as variations of the fraction of the primary energy measured by the calorimeter. The latter would lead only to a displacement of the cross section values to an apparently lower energy. Thus, if the energy loss is an instrumental error, the measured cross sections should yield the "pionization" value, but if the energy loss mechanism is due to an X interaction, the measured cross section (σ_m) will have two contributions: one from the regular hadronic "pionization" (σ_π) and the other from the X process (σ_x), thus $\sigma_\pi = \sigma_m - \sigma_x$. This will be the case whether the X process loses energy into charged or neutral channels. In the former case an interaction will be detected since the proton will be accompanied by the X; and in the latter case, the protons will have lost energy and will not register in the energy "bin" of interest.

We calculate the contribution from the X process to the p-carbon cross section by noting that in the interval between 4 and 6 x 10^{11}eV, $\sigma_x \sim 5$mb/nucleon (see Fig. 4). Assuming that carbon has $12^{2/3}$ nucleons one obtains $\sigma_x^C \simeq 26$mb and $\sigma_\pi^C \simeq 244$mb instead of 270mb. Figure 6 shows the data obtained by Grigorov, et al., the corrected point at $\sim 5 \times 10^{11}$eV, and the accelerator value of the cross section obtained by Bellettini, et al.(14) with the quasielastic contribution subtracted(3). The p-carbon inelastic cross section at 21.5GeV is also shown in Figure 6. It can be seen that the cross section for the X process in the calorimeter is of the right magnitude to account for the p-carbon cross section increase.

VI. Other Experimental Data

We now summarize some inadequately explained (and often unconfirmed) effects observed in very high energy interactions which may have some bearing on the present work.

An extensive review of these phenomena is provided by Yu. A. Smorodin(17), covering a wide range of inconsistencies in cosmic ray data above 10^{11}eV. These are:

1. The mean free path of nuclear active particles is apparently larger in water than in air.

2. Fluxes measured by "thick" filters (several nuclear ranges) are consistently lower than those measured by "thin" filters (where only one interaction is probable).
3. The inelasticity coefficient K (for interactions between nucleons and light nuclei) measured by calorimeters is greater than that measured by cloud chambers.
4. Showers are present where most of the energy seems to be transferred to the electromagnetic component.
5. Anomalies exist in the spectrum of extensive air showers.
6. Peculiarities are found in the underground flux of charged particles, such as broad angular distributions, showers produced by particle groups, and showers at large zenith angles.

Smorodin concludes that these contradictions can be eliminated by assuming that, at energies above 10^{11}eV, the nucleon may be transformed into a passive baryon state in which the interaction cross section is much smaller than normal.

After $\sim 10^{-10}$sec this passive baryon decays back into a regular nucleon. While these passive particles have been searched for with negative results(18,19), Smorodin's analysis is significant in that it points toward the type of effects to be expected from a possible change in the characteristics of interactions above 10^{11}eV.

Another effect that may relate to the present work is the observation(20) of an underground muon spectrum that is almost flat as a function of zenith angle, in contradiction with the $\sec\theta$ dependence expected if these muons were the result of pion and kaon decay. Analysis of muon-poor air showers(21) seem to confirm the "Utah-type" mechanism for generating both the "Utah"-muons and these showers. This work(21), as well as an analysis of present experimental data carried out by S. I. Nikolskii(22), indicates that primary gamma rays cannot account for the frequency of observed electromagnetic showers, thus implying that a highly effective mechanism for transfer of energy to the electron-photon component must be at work at high energies. This could involve heavy particles that would decay into muons or electrons with a significant branching ratio. In this connection there is evidence for components with large transverse momentum among the secondaries of ultra-high-energy interactions(7,23), which is suggestive that a massive secondary particle was formed.

Finally, we mention the experimental data on the behaviour of ionization calorimeters:

1. In general, while calorimeters yield energies of the electron-photon components of air showers that are in agreement with that obtained by other methods, they are consistently low in estimating the energies of nuclear-active particles.(24)

2. It has been found that at high energies the rate of energy deposition in these devices is slower than that to be expected from estimates using the known characteristics of nuclear cascade shower developments.(25) Other workers,(26) using an 8 interaction-length (Lint) calorimeter, have found that the rate of energy deposition in iron decreases as a function of energy. The behaviour is such that as the energy changes from 2×10^{11}eV to 5×10^{11}eV, the absorption coefficient of the energy flux changes from 1/Lint to 1/3Lint. Later measurements verify this behaviour.(27)

3. It is reported(28) that when measuring the spectrum of hadrons with the first 2.5 interaction lengths of a 6 Lint calorimeter, a sharp knee appears at about 6×10^{11}eV if the primary's point of interaction in the calorimeter is not known. (This effect is not seen for measurements using the whole calorimeter.) It is then apparent that under these conditions the energy of the primary is underestimated.

Since for a fixed length calorimeter the fraction of the primary energy that is deposited is practically independent of energy, and since the proton interaction cross section stays almost constant, (or increases slowly), one should not expect a sharp knee in the spectrum, but rather a shift in the scale factor. The reported measurement shows that at ∿6 x 10^{11}eV the effects that derive from a lack of knowledge of the primary interaction point in the "thin" calorimeter become suddenly important. We are then led to believe this occurs because at this energy particles that have interaction lengths longer than the proton's are starting to be produced in anomalous amounts.

Thus, evidence has accumulated that tends to indicate that our knowledge of the nuclear interaction at low energies cannot account for effects observed above 10^{11}eV.

VII. The Nature of the X Particle

It is tempting to ascribe the effects considered previously to a particle creation mechanism. The available data does not yield an unambiguous answer on this possibility, but it allows us to speculate on the properties that an X particle might have. The X particle might result from X $\bar{X}$ production or proton dissociation.

1. X production. J.D. Bjorken, et al.,(29) in an analysis of the Utah deep mine experiment(20) have extensively

discussed production. Bjorken adopts the interpretation that in pp collisions at sufficiently high energies, a new class of hadrons is produced in pairs, stable under strong and electromagnetic interactions, decaying into states containing at least one muon with a high branching ratio, and having a summed mass between 6 and 55GeV. The lifetime of these hadrons can be as short as that of semi-weak decays, or as long as $\sim 10^{-7}-10^{-8}$sec, and the production cross section is estimated to be $\sim$9mb in air, for a highly efficient mechanism for energy transfer to the muons. Otherwise, the production cross section would be larger.

From our previous analysis it can be seen that the satellite data lead to results of the same type as those found by Bjorken. We expect a total mass between 15 and 29GeV, and a production cross section in air of $\sim$55mb. This is six times larger than the minimum cross section found by Bjorken, but a lower efficiency in the energy transfer mechanism to muons, non muonic decay modes, and uncertainties in the analysis, can all contribute to this difference.

The lifetime is hard to determine from our work: if the X is as strongly interacting as the proton, then we would expect it to decay before interacting in the calorimeter ($\tau < 10^{-9}$sec). This necessitates decay modes where most of the energy is transferred to a muon, which can then leave the calorimeter.

On the other hand, if the nuclear mean free path of the X is appreciably longer than the proton nuclear mean free path, it can then leave a thin calorimeter with a high probability. In this case if the decay mode is mostly into hadrons, or most of the energy goes into hadrons, we expect the X to live long enough so that it decays outside the calorimeter ($\tau > 10^{-9}$cm). However, if the decay of the X particle transfers most of its energy to muons, no lower bounds can be put on the lifetime, but from the Utah results one can set an upper limit on the X lifetime of 10^{-7}-10^{-8}sec(29). This can account for the decrease in the rate of energy deposition in calorimeters. Even though we have referred to hadrons, it cannot be ruled out that the X is a boson. A particle with the properties mentioned above would have to be created strongly: a work by E.P. Shabalin(30) shows that on the basis of the Kummer-Segre model(31) one can expect strong production of a zero spin boson with about the right properties. Another candidate for the X is the neutral vector boson(32), which has the right properties, and couples strongly to $\mu\mu$ and perhaps ee pairs. The problem with particles that are strongly coupled to muons is that if they are produced strongly, the μ's should scatter strongly on protons (which is not observed). Thus, in explaining the data one would be forced to give up crossing symmetry(33).

The main problem with production mechanisms in general is that of the large cross sections necessary to match the experiments.

2. <u>The X as the Product of Proton Dissociation</u>. It was suggested by J. Dooher(34) that the dissociation of a proton into triplets could account for an inefficiency of energy measurement of a short calorimeter. Dooher points out that since one expects $\sigma_{Tp}^{tot} = 1/3\ \sigma_{pp}^{tot}$, most of the triplets would escape the three nuclear mean free path calorimeter used by Grigorov, without interacting. Given the large mass of the X, one expects that the inelasticity in Tp collisions will be less than the proton inelasticity, and the energy deposition consequently smaller. This idea is provocative in that it suggests that the effects of the X process become less important for thicker calorimeters, as is the case.(28) Dooher suggests that in analogy with nuclear breakup upon collision, the proton could undergo a similar breakup if the energy is high enough. Thus, he considers the process to be $p+p\rightarrow 3T+p+n\pi$ (soft). On the other hand, if a bound system of the triplets has a low mass (say, two triplets make up a meson), then one can treat baryons as a bound system of a di-triplet and a triplet.(35) It is then possible to have $p+p\rightarrow p+T+\text{meson}+n\pi$ (soft). This reaction will occur at a lower energy threshold, and probably with higher probability. It is interesting to note that such an event could easily be confused with fast isobar production.

At this time we lack estimates on the expected values of the cross section. As in Bjorken's analysis, the cross section needed to match experiment is very large, but we note that the measured increase in the p-carbon cross section is of about the right value to be accounted for by the X process, thus lending some credibility to this analysis. In connection with this, we wish to mention some recent experiments which claim to have found new particles(36,37) in cosmic rays. Of course, at this time, one must await further confirmation of these phenomena in the light of negative searches by others.(38,39) Nevertheless, we wish to stress that our mechanism of proton dissociation does not require the existence of fractionally charged triplets. For example, in a theory due to T. D. Lee(40) there are four quarks, an SU_3 triplet and a singlet. The proton is composed of two neutral and one charged particles. Upon total dissociation 2/3 of the incoming energy will go into heavy neutral particles. Dooher points out that the neutrals would be hard to detect unambiguously in cosmic ray experiments. Since the charged quark could decay into a neutral, its detection would also be difficult. The same holds for detection of the quark in the case of partial dissociation.

VIII. Concluding Remarks

Assuming that, in the energy region 10^{10}-10^{14}eV,

(1) the cosmic ray flux can be described by a single power law,

(2) the nuclear composition remains constant;

it is not unreasonable to quantitatively describe the measurements obtained from the Artificial Earth Satellites of the Proton series in terms of an X process, perhaps associated with heavy particles with masses of the order of ∿19GeV. It is also shown that this X process has qualitative characteristics that match other peculiar cosmic ray and particle interactions data at energies above 10^{11}eV.

The experimental verification of the postulated energy loss mechanism is conceptually simple. This would involve conducting mountaintop experiments using a large magnet for momentum measurements and a large calorimeter or TANC(41) crystals to measure energy deposition parameters. Another possibility involves the use of a magnetic spectrometer-hydrogen target combination to measure the cosmic ray flux in a dual mode: 1) by direct determination of the momentum of the primary as it bends through the magnet; and 2) by adding the momenta of the secondaries of a cosmic ray proton interaction in the target(42). If the X is charged it should be identifiable from kinematic and dynamic considerations. If it is neutral we would find an anomalous low primary flux when measured in the latter mode. Within the next few years the CERN storage rings will also afford a further opportunity to detect the possible existence of the X process.

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Attachments
  References
  Figures

REFERENCES

1. N. L. Grigorov, et al., Kosmicheskie Issledovaniya 5, 383 (1967).
2. N. L. Grigorov, et al., Ibid, page 395.
3. N. L. Grigorov, et al., Ibid, page 420.
4. Space Daily, November 21, 1968, page 88.
5. Yu. N. Vavilov, et al., Proceedings of the P. N. Lebedev Physics Institute 26, 75 (1965).
6. P. K. Malhotra, et al., Nature 209, 567 (February 1966).
7. C. B. A. McCusker, L. S. Peak, and M. H. Rathgeber, Phys. Rev. 177, 1902 (1969).
8. N. L. Grigorov and V. Ya. Shestoperov, Bull. Acad. Sci. USSR, Phys. Ser. 28, 1668 (1964).
9. N. L. Grigorov, et al., "Study of Particles of High Energy Cosmic Rays on the Artificial Earth Satellites in the 'Proton' Series", Presented at Eighteenth International Astronautical Congress, Belgrade, September 1967.
10. L. C. Yuan, Private Communication, Brookhaven National Laboratory, L. I., N. Y. (June 1967).
11. V. V. Guseva, et al., Bull. Acad. Sci. USSR, Phys. Ser. 30, 1642 (1966).
12. E. L. Andronikashvili, et al., Bull. Acad. Sci. USSR, Phys. Ser. 31, 1493 (1967).
13. R. K. Adair and N. J. Price, Phys. Rev. 142, 844 (1966).
14. G. Bellettini, G. Cocconi, et al., Nucl. Phys. 79, 609 (1966).
15. D. T. Vardumyan, G. A. Marikyan, and K. A. Matevosyan, Bull. Acad. Sci. USSR, Phys. Ser. 31, 1497 (1967).

References (Continued)

16. G. Gloeckler and J. R. Jokipii, Phys. Rev. Lett. 22, 1448 (1969).

17. Yu. A. Smorodin, Sov. Phys. JETP 24, 290 (1967).

18. A. D. Erlykin and A. K. Kulichenko, Bull. Acad. Sci. USSR, Phys. Ser. 32, 409 (1968).

19. A. D. Erlykin, et al., Ibid, page 412.

20. H. E. Bergeson, J. W. Keuffel, et al., Phys. Rev. Lett. 19, 1487 (1967).

21. R. Maze, T. Wdowczyk, A. W. Wolfendale and A. Zawadzki, Phys. Rev. Lett. 22, 899 (1969).

22. S. I. Nikol'skii, Soviet Physics JETP 24, 535 (1967) and Bull. Acad. Sci. USSR, Phys. Ser. 31, 1542 (1967).

23. J. C. Earnshaw, G. C. Maslin, and K. E. Turver, Can. J. Phys. 46, S115 (1968).

24. Kh. P.Babayan, et al., Bull. Acad. Sci. USSR, Phys. Ser. 32, 37 (1968).

25. I. N. Erofeeva, et al., Bull. Acad. Sci., USSR, Phys. Ser. 30, 1698 (1966).

26. E. V. Denisov, et al., Bull. Acad. Sci. USSR, Phys. Ser. 31, 1505 (1967).

27. N. L. Grigorov, et al., Bull. Acad. Sci. USSR, Phys. Ser. 32, 371 (1968).

28. A. S. Baigubekov, Yu. T. Lukin, and Zh. S. Takibaev, Ibid, page 385.

29. J. D. Bjorken, S. Pakvasa, W. Simmons, and S. F. Tuan, SLAC-PUB-473 (February 1969) to be published in Phys. Rev.

30. E. P. Shabalin, JETP Letters 8, 395 (1968).

References (Continued)

31. W. Kummer, and G. Segre, Nuclear Physics 64, 585 (1965).

32. M. M. Nieto, Phys. Rev. Lett., 21, 488 (1968).

33. Nieto points out that, experimentally, crossing symmetry has been precisely verified only for low energy pp and πp systems. Private Communication, Niels Bohr Inst., Copenhagen, Denmark (June 1969).

34. J. Dooher, Private Communication, Grumman Aircraft Engineering Corp., Bethpage, L. I., N. Y. (July 1969).

35. D. B. Lichtenberg, and L. J. Tassie, Phys. Rev. 155, 1601 (1967).

36. M. Dardo, P. Penengo, and K. Sitte, Nuovo Cimento 58A, 59 (1968).

37. C. B. A. McCusker, Communication to the Tenth International Conference on Cosmic Rays, Bucarest, Hungary, September 1969.

38. H. Kasha, and R. J. Stefanski, Phys. Rev. 172, 1297 (1968).

39. E. P. Krider, T. Bowen, and R. M. Kalbach, University of Arizona Preprint (August 8, 1969).

40. T. D. Lee, Nuovo Cimento 35, 933 (1965).

41. R. Hofstadter, Science 164, 1471 (1969).

42. L. Kaufman, "Cosmic Ray and High Energy Physics Studies in Space", Bellcomm, Inc. TR-69-103-1 (April 1969).

FIGURES

Figure 1. Integral proton spectrum measured by the Artificial Earth Satellites Proton I and II. Curve 1) fits the data in the low energy region and is given by the equation $F_1(\geq E) = AE^{-\gamma}$ where $A = 7.2 \times 10^{-4}$ and $\gamma = 1.45$. Curve 2) is a fit to the data in the high energy region given by $F_2(\geq E) = \alpha E^{-\gamma} - \beta \exp(1-2E)$ where $\alpha = 14.3 \times 10^{-4}$, $\beta = 13.8 \times 10^{-4}$, and $\gamma = 2.30$.

Figure 2. Average energy measured for all primary protons as a function of their energy.

Figure 3. Average fraction of undetected energy for all primary protons as a function of their energy.

Figure 4. Total X cross section per "effective" nucleon in iron, shown for 100% and 50% average energy loss per interaction. At $4E_{th}$, X production amounts to $\sim$14% of the total cross section at 2×10^{10}eV. The shape of the cross section for energies below $4E_{th}$, obtained from phase space considerations, is also shown.

Figure 5. All-particle spectra. The experimental points are as given by Grigorov, et al. The dark line shows the spectrum described by a single power law in this energy range. The fine lines show the spectra for

Figures (Continued)

different nuclei obtained by assuming that the energy loss through the X process is a function of the energy per nucleon. The dashed lines show spectra in the same way as above, but taking into account the shadowing of nucleons in the primary nucleus. The cosmic ray flux has an average mass $2 \sim M < 5$.

Figure 6. p-Carbon cross sections. We show the values measured by Grigorov, et al., the point at 5×10^{11} eV from which the X contribution has been subtracted, and accelerator values of the absorption and "pionization" cross sections at 2×10^{10} eV.

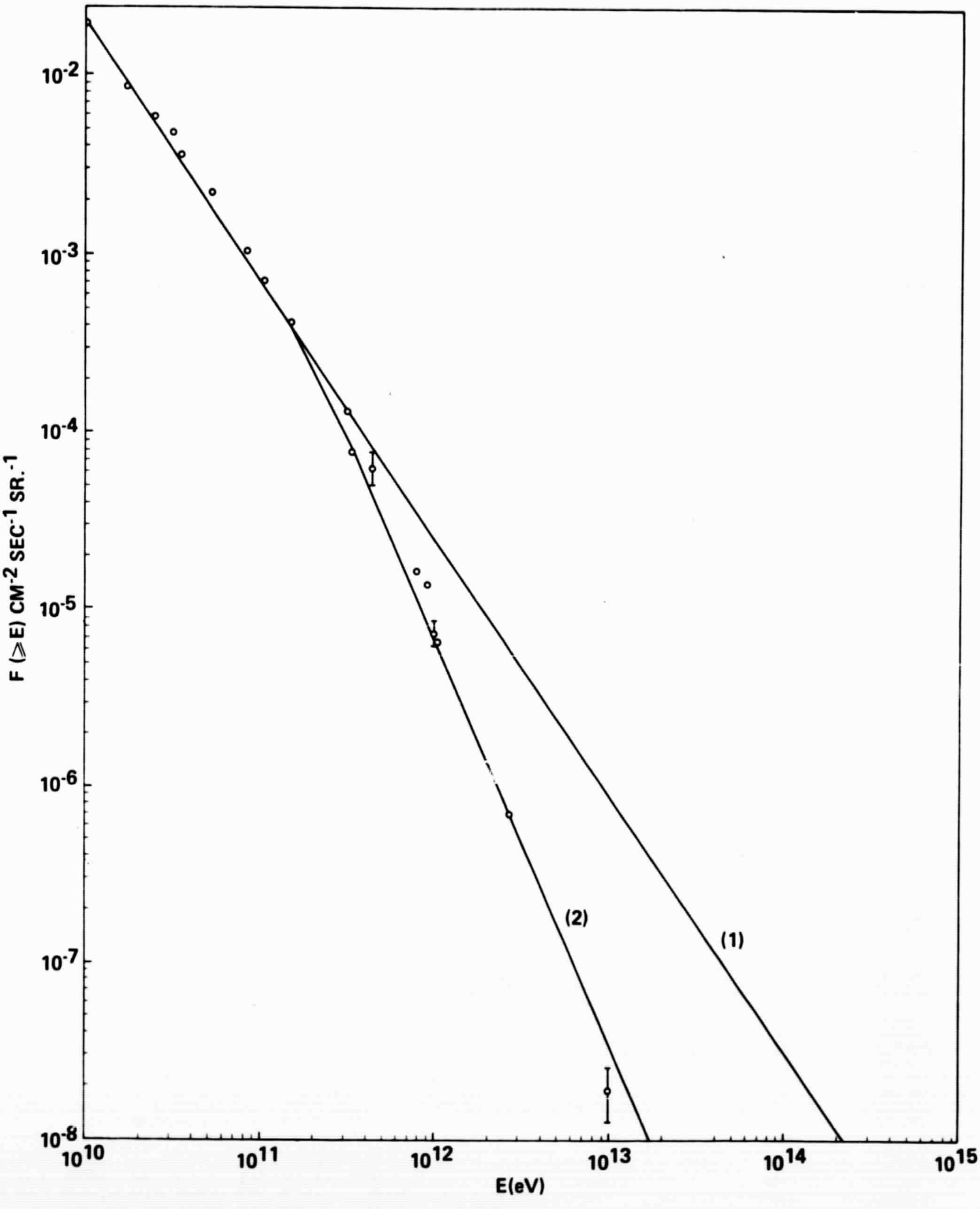

F (≥E) CM-2 SEC-1 SR.-1
10-2
10-3
10-4
10-5
10-6
10-7
10-8
10¹⁰
10¹¹
10¹²
10¹³
10¹⁴
10¹⁵
E(eV)
(1)
(2)

FIGURE 1

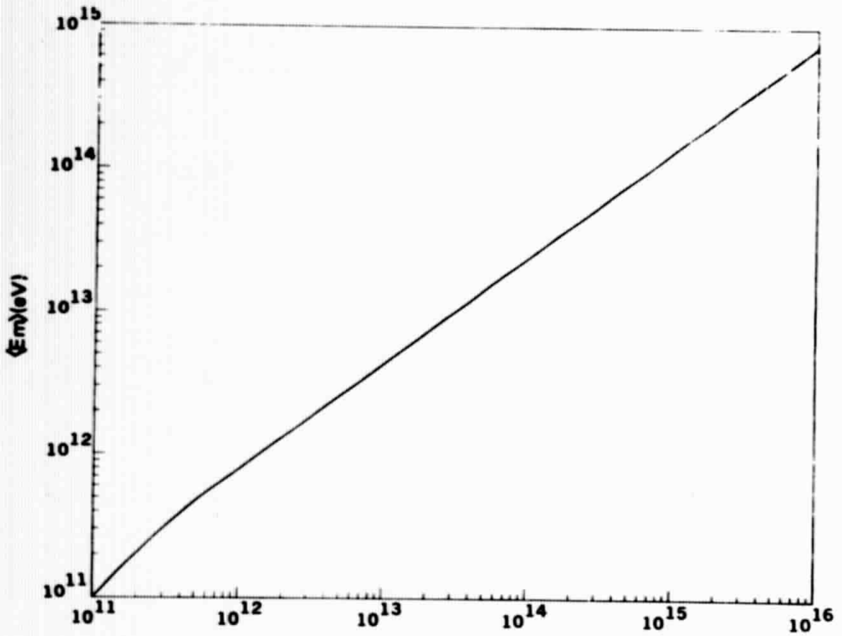


FIGURE 2

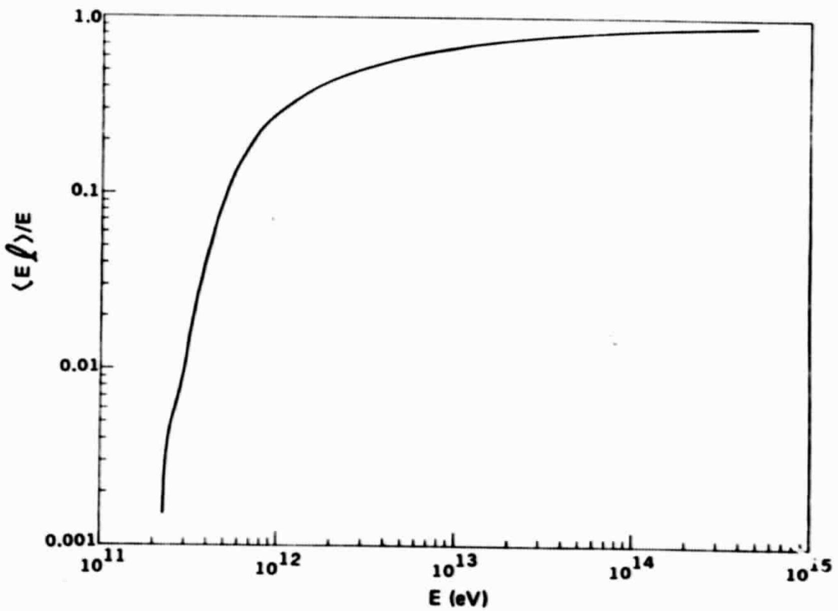


FIGURE 3

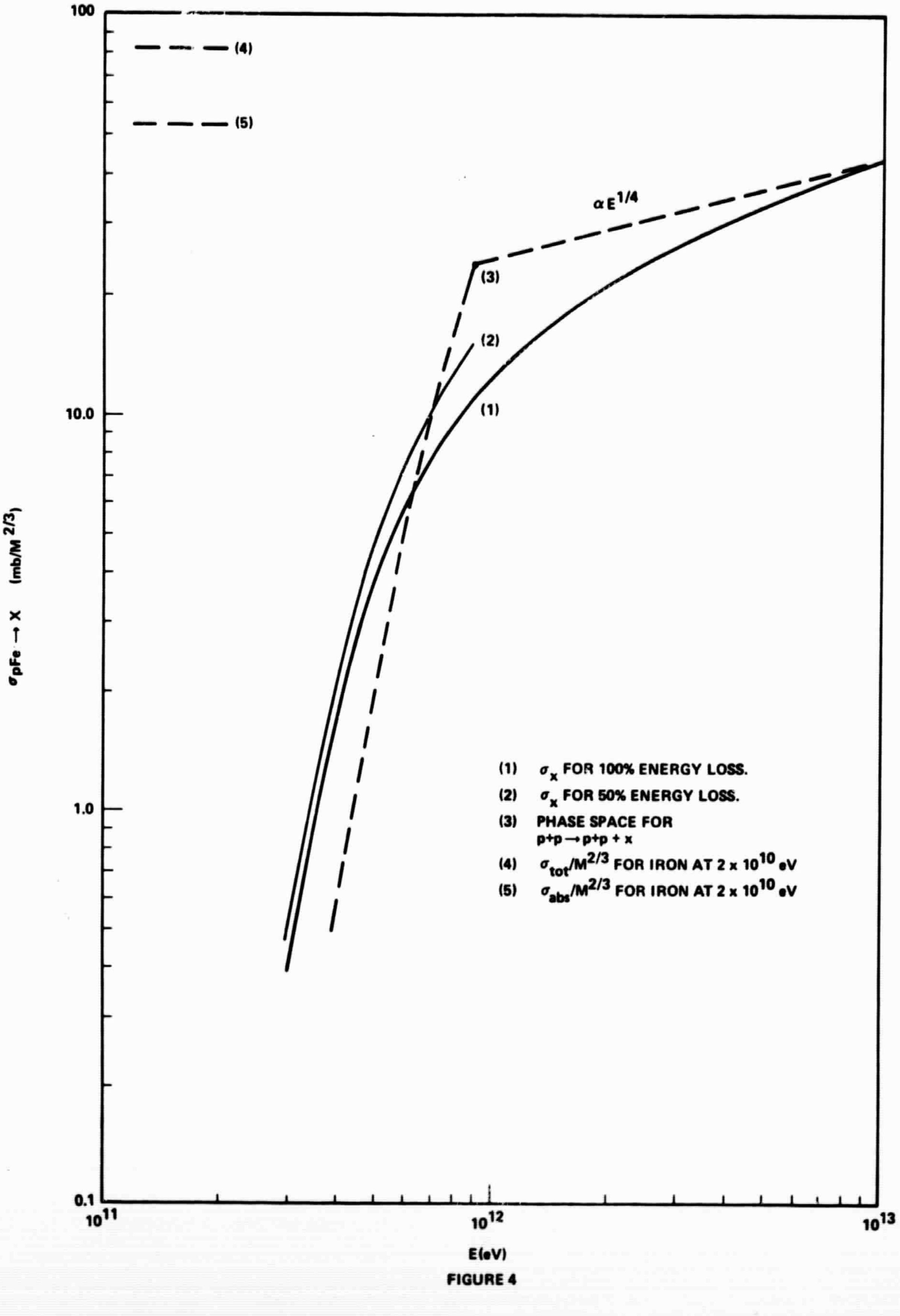
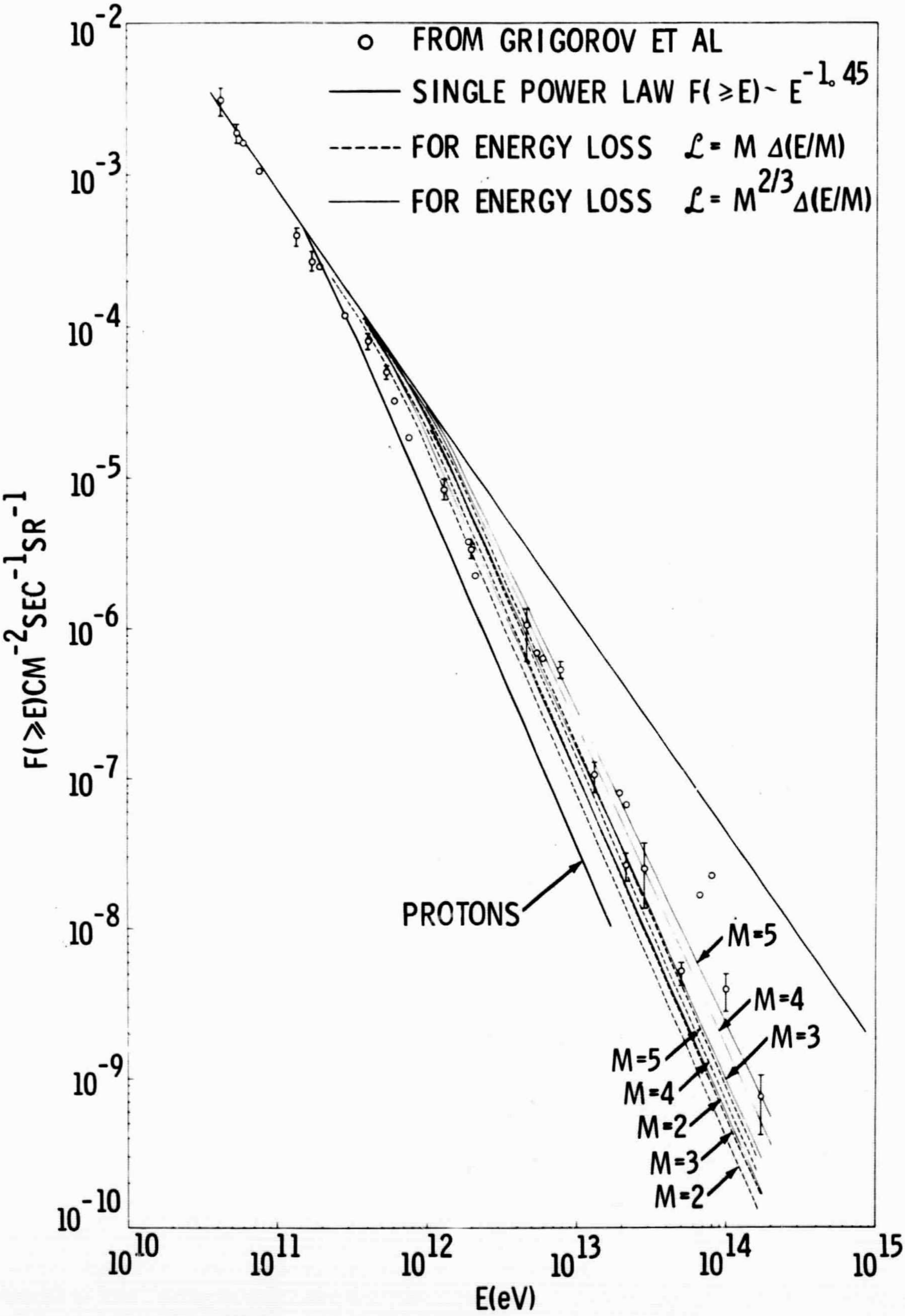

100
10.0
1.0
0.1
10^{11}
10^{12}
10^{13}
E(eV)
$\sigma_{pFe \to X}$ (mb/M $^{2/3}$)
(4)
(5)
$\alpha E^{1/4}$
(3)
(2)
(1)
(1) σ_x FOR 100% ENERGY LOSS.
(2) σ_x FOR 50% ENERGY LOSS.
(3) PHASE SPACE FOR $p+p \to p+p+x$
(4) $\sigma_{tot}/M^{2/3}$ FOR IRON AT 2×10^{10} eV
(5) $\sigma_{abs}/M^{2/3}$ FOR IRON AT 2×10^{10} eV

FIGURE 4



o FROM GRIGOROV ET AL
SINGLE POWER LAW F(≥E) ~ E^-1.45
FOR ENERGY LOSS ℒ = M Δ(E/M)
FOR ENERGY LOSS ℒ = M^2/3 Δ(E/M)
PROTONS
M=5
M=4
M=3
M=5
M=4
M=2
M=3
M=2
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^10
10^11
10^12
10^13
10^14
10^15
F(≥E)CM^-2SEC^-1SR^-1
E(eV)

FIGURE 5

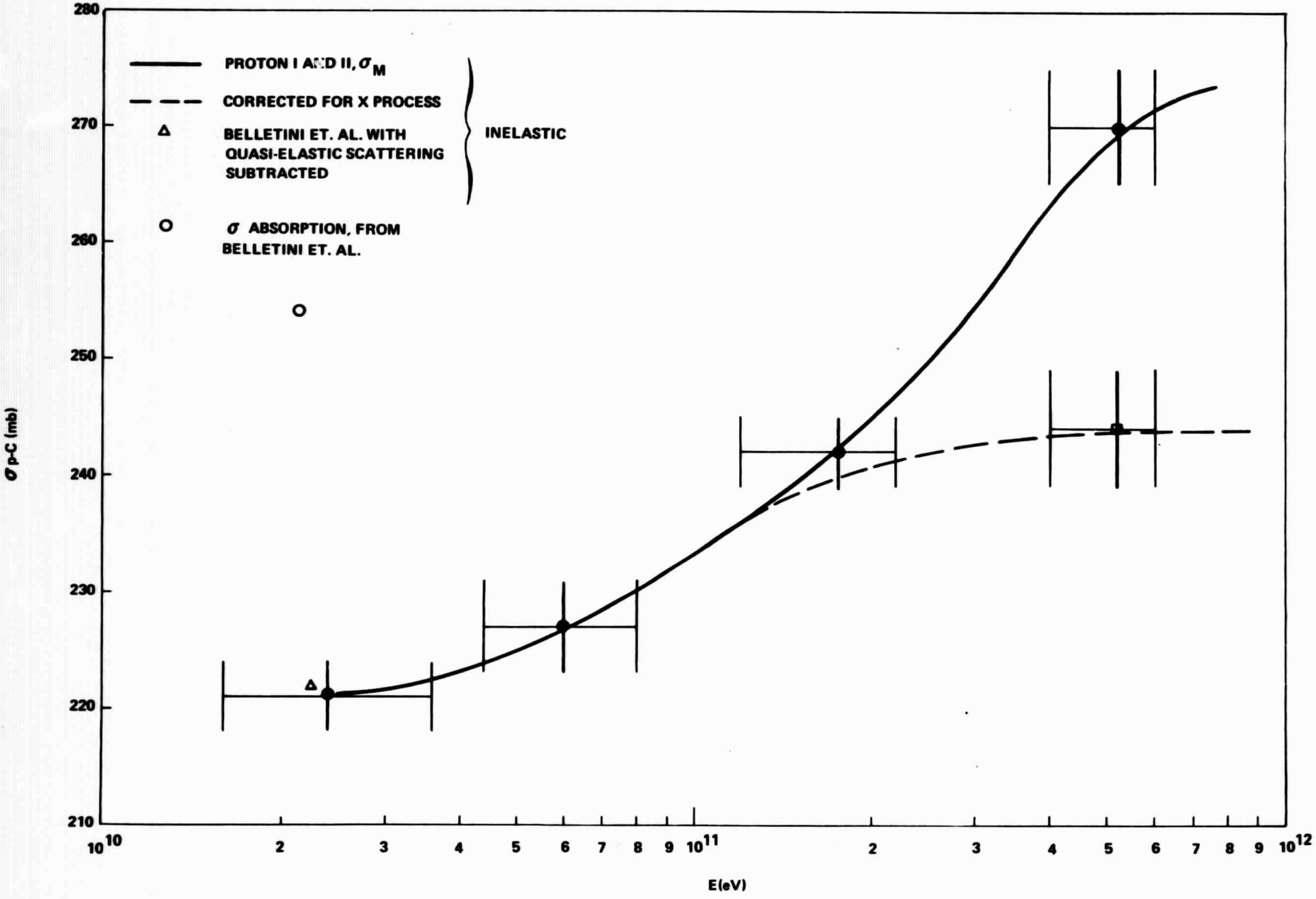

280
270
260
250
240
230
220
210
σ p-C (mb)
10^{10}
2
3
4
5
6
7
8
9
10^{11}
2
3
4
5
6
7
8
9
10^{12}
E(eV)
PROTON I AND II, σ_M
CORRECTED FOR X PROCESS
BELLETINI ET. AL. WITH
QUASI-ELASTIC SCATTERING
SUBTRACTED
INELASTIC
σ ABSORPTION, FROM
BELLETINI ET. AL.

FIGURE 6