operators. A physical particle, however, is found to be limited to states lying on a specified mass shell. Thus only a very limited part of the Hilbert space is available for particle states. This raises the question of why states that are superpositions of different mass eigenkets are not found in nature. The formalism presented here sheds no light on this question.

It is a straightforward matter to extend this formalism to include states of nonzero spin. This extension will be presented in another paper.

The above Hilbert space has been used to derive the Schrödinger equation for a *single* particle. It is, in a sense, a subspace of a Hilbert space containing vectors belonging to an arbitrary number of events. A discussion of multiple event states will be left to another paper. It is clear, however, that the Green's functions for the Schrödinger equations derived for one-particle states can be used to join points of interaction between particles at Feynman vertices.[6] If a field-operator approach is preferred, these operators can be found according to the procedure described in Sec. XII.

It is clear that the eigenvalues of the space-time position operators will determine the location of Feynman vertices, the points where different kinds of particles interact. This does not seem surprising since a space-time position measurement will involve the interaction at a vertex of some probing particle and the particle being observed.

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Evidence for Heavy-Particle Production Processes at Energies above 2×10^{11} eV

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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 $\sim5\times10^{11}$ eV, indicating that at high energies protons become progressively scarcer in the primary flux. The cross section for particle production by 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, and (2) the nuclear composition remains constant, we show that the satellite flux measurements can be explained by an energy-loss mechanism in the calorimeter, the loss being a function of the energy per nucleon rather than the 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.

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 Grigorov *et al.* 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 in 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}–2×10^{14} eV show[2] an integral spectrum for the total particle flux that the experimenters fitted by a single power law with exponent $\gamma=1.74\pm0.06$.

The proton flux is found to behave in a surprising way. While its behavior is similar to that of the all-

[1] N. L. Grigorov *et al.*, Kosmich. Issled. Akad. Nauk SSSR **5**, 383 (1967).
[2] N. L. Grigorov *et al.*, Kosmich. Issled. Akad. Nauk SSSR **5**, 395 (1967).
[3] N. L. Grigorov *et al.*, Kosmich. Issled. Akad. Nauk SSSR **5**, 420 (1967).
[4] *Space Daily*, Nov. 21, 1968, p. 88.

particle flux at low energies, above 10^{12} eV it can be best described by a power law with an exponent $\gamma\approx2.30$. This shows a drop on the proton flux that is larger than that measured by ground based techniques.[5] These satellite data imply 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: $\sigma_\pi=\sigma(\text{total})-[\sigma(\text{elastic})+\sigma(\text{quasielastic})]$.

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 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 satellite measurements of Grigorov *et al.* were not carried out properly, because of either 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 behavior of the calorimeter in terms of its behavior at accelerator energies. This is a question still to be settled, but one must point to the large body of experience with calorimeters accumulated by Guseva *et al.*[11] and Andronikashvili *et al.*,[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 100 GeV. Any process that creates particles with interaction lengths substantially longer than that of the pion will alter the percentage of incident particle energy deposited in the calorimeter and may cause an apparent diminution 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 apparent 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 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 $A=7.2\times10^{-4}$ 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 $14.3\times10^{-4}E^{-2.30}$ cm^{-2} sec^{-1} sr^{-1} (see Fig. 1.) E is measured in units of 10^{11} eV.

The differential proton spectra used in this work are

$$N_1(E)=-dF_1(\geq E)/dE=\gamma AE^{-(\gamma+1)}$$

below $E=2.24\times10^{11}$ eV, and

$$N_2(E)=-dF_2(\geq E)/dE=(2.3\times14.3)\times10^{-4}E^{-3.30}-27.6\times10^{-4}e^{1-2E}$$

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 $N_1(E_{\text{th}})=N_2(E_{\text{th}})$ for $E_{\text{th}}=2.24\times10^{11}$ eV, corresponding to a total center-of-mass energy of 20.5 GeV. 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 $\sim1.5\times10^{11}$ and $\sim5\times10^{11}$ eV, corresponding to center-of-mass energies of 17 and 31 GeV, respectively.

[5] Yu. N. Vavilov *et al.*, Proc. P. N. Lebedev Phys. Inst. **26**, 75 (1965).
[6] P. K. Malhotra *et al.*, Nature **209**, 567 (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.*, paper presented at the Eighteenth International Astronautical Congress, Belgrade, 1967 (unpublished).
[10] L. C. Yuan (private communication).
[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).

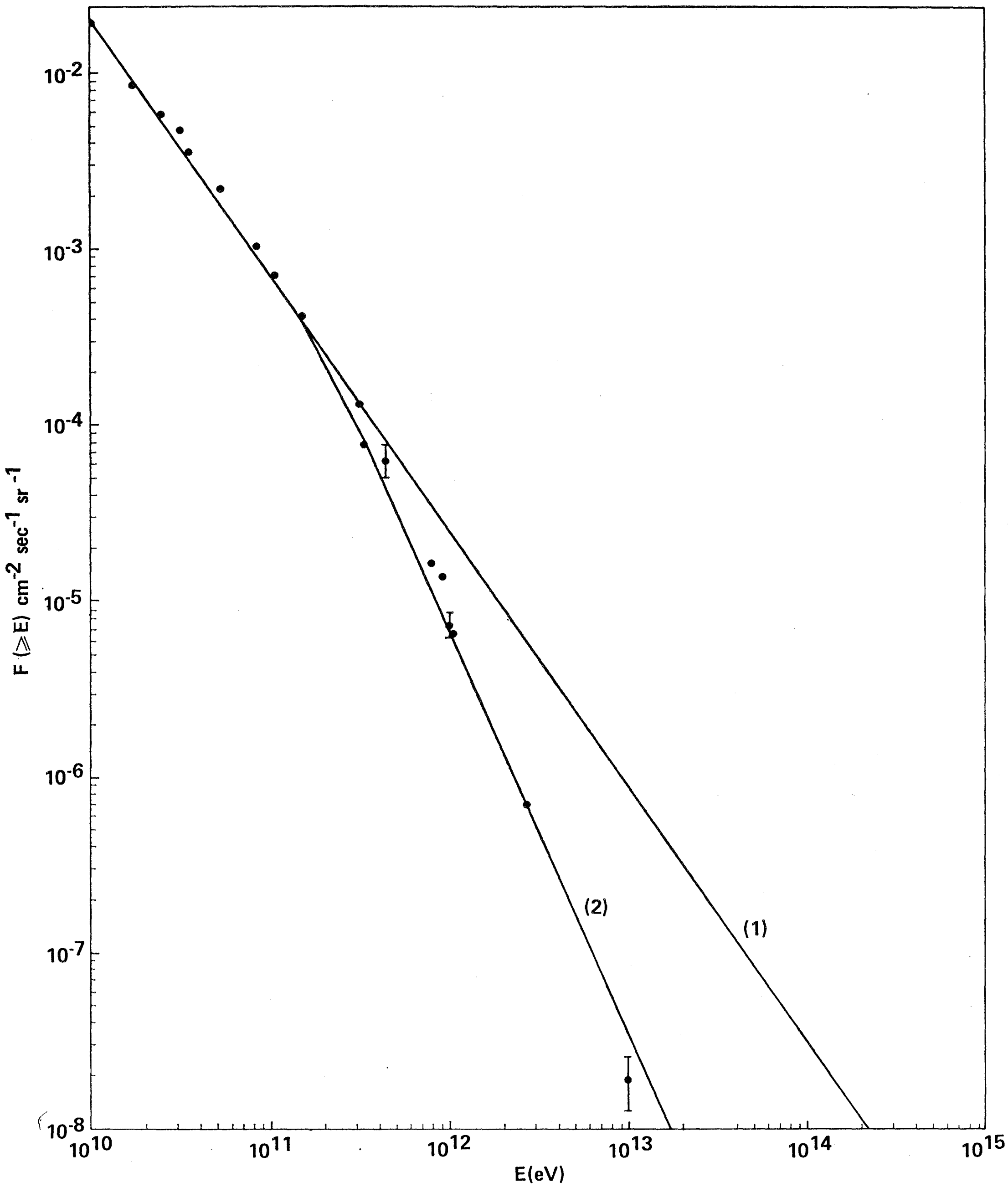

FIG. 1. Integral proton spectrum measured by the artificial earth satellites Proton I and II. Curve (1) fits the data in the low-energy region and is given by the equation $F_1(\geq E)=AE^{-\gamma}$, where $A=7.2\times 10^{-4}$ and $\gamma=1.45$. Curve (2) is a fit to the data in the high-energy region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

We can now write

$$N_1(E)=N_R(E)+N_A(E) \quad \text{for} \quad E<E_{\text{th}} \qquad (1)$$

and

$$N_2(E)=N_R(E)-N_L(E)+N_A(E) \quad \text{for} \quad E>E_{\text{th}}, \qquad (2)$$

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 cannot 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

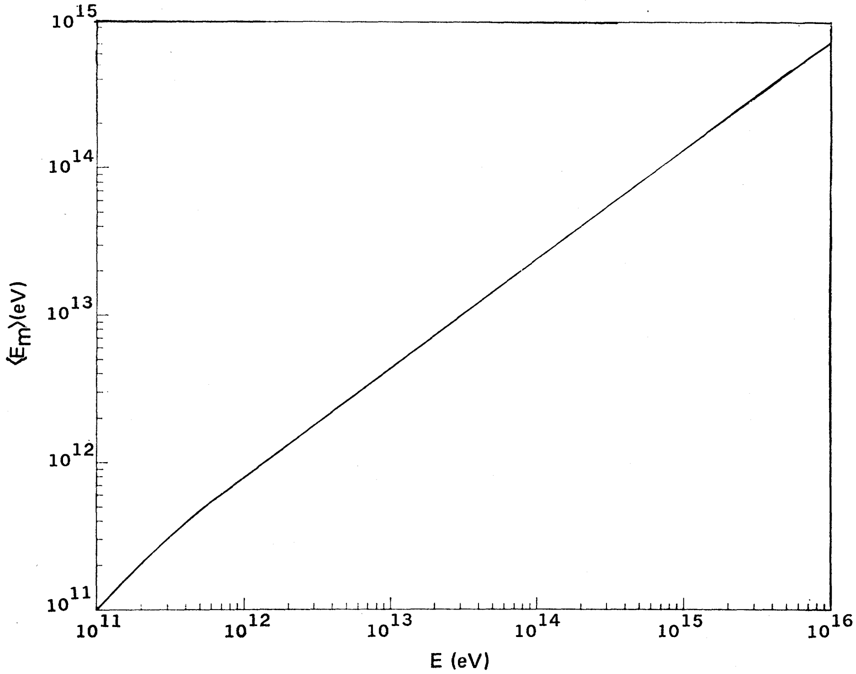

FIG. 2. Average energy measured for all primary protons as a function of their energy.

by what happens above 10^{12} eV, and we can set $N_A(E) \ll N_1(E)$ and $N_1(E) \approx N_R(E)$ for $E < E_{\mathrm{th}}$.

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 Eq. (2) becomes

$$N_2(E) = N_1(E) - N_1(E)P(E) + N_1(E+\Delta)P(E+\Delta). \quad (3)$$

We consider Eq. (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

$$N_2(E) = N_1(E+\Delta), \quad (4)$$

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

$$E+\Delta = [\gamma A / N_2(E)]^{1/(\gamma+1)}.$$

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.

Grigorov *et al.* have estimated that 50% of the primary energy of a cosmic-ray particle is deposited in the calorimaters 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 Eq. (3) is to assume that the energy loss for protons that undergo the X interaction is total. Then we obtain $N_A(E) \approx 0$, because the protons that interact effectively disappear from the beam. Then Eq. (3) becomes

$$N_2(E) = N_1(E)[1 - P(E)],$$

and

$$P(E) = 1 - N_2(E)/N_1(E). \quad (5)$$

If the X process is one of heavy-particle creation, we calculate from kinematic considerations that the primary proton will, on the average, lose $\sim$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 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

[13] R. K. Adair and N. J. Price, Phys. Rev. **142**, 844 (1966).

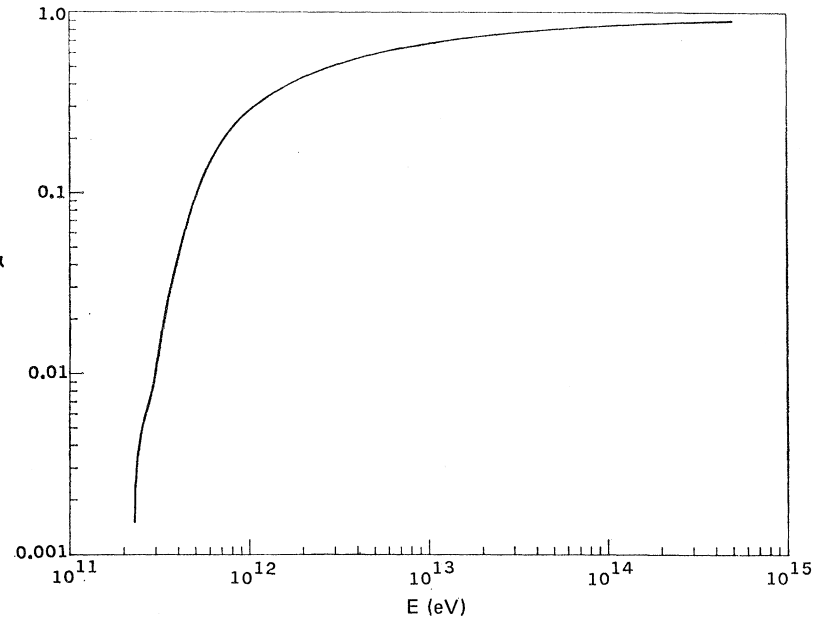

FIG. 3. Average fraction of undetected energy for all primary protons as a function of their energy.

$N_1(2E)=0.18N_1(E)$, and the results are not too sensitive to the change in $P(2E)$].

Under these conditions,

$$P(E)=1.22[1-N_2(E)/N_1(E)]. \quad (6)$$

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, we have $P(E)=1-e^{-\sigma_X\mu}$, from which we obtain

$$\sigma_X(E)=-\mu^{-1}\ln[1-P(E)], \quad (7)$$

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

$$\mu=\frac{X_{\rm Fe}N_0}{M_{\rm Fe}}M_{\rm Fe}{}^{2/3}+\frac{X_{\rm pl}N_0}{M_{\rm pl}}M_{\rm pl}{}^{2/3}$$

$$=6.5\times10^{25}\text{ nucleons/cm}^2,$$

where $X_{\rm Fe}=376$ g/cm^2 and $X_{\rm pl}=19.5$ g/cm^2 are the amount of iron and plastic scintillator in the calorimeter respectively, N_0 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 Eq. (7) becomes an upper bound on σ_X. For comparison purposes we estimate the energy dependence of the cross section for heavy-particle production by assuming that the process is $p+p\rightarrow p+p+X$, with $M_X=18.6$ GeV, and that below $4E_{\rm th}$ the energy dependence is given by phase space only. Above $4E_{\rm th}$ we have arbitrarily assumed that the cross section has the behavior suggested by Adair and Price[13]:

$$\sigma_X=\sigma_0(E/4E_{\rm th})^{1/4}. \quad (8)$$

In Fig. 4, we show the values obtained from Eq. (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 on the particular form chosen for $N_2(E)$. The results from the phase-space calculation and Eq. (8), normalized arbitrarily so that $\sigma_0=24$ mb, are also shown.

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

IV. 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 10^{10}–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

[14] G. Bellettini *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).
[16] G. Gloeckler and J. R. Jokipii, Phys. Rev. Letters **22**, 1448 (1969).

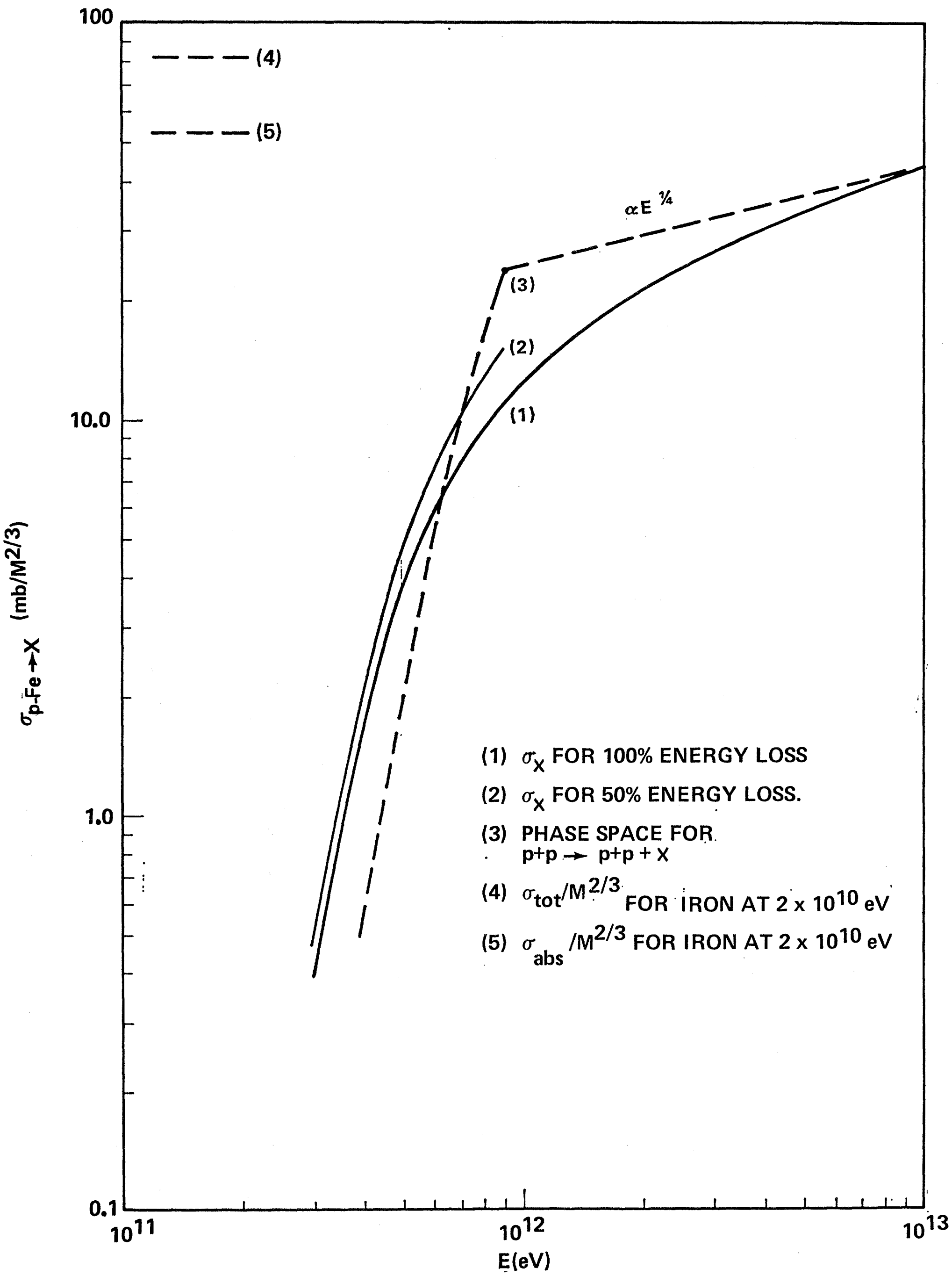

FIG. 4. Total X cross section per "effective" nucleon in iron, shown for 100 and 50% average energy loss per interaction. At $4E_{th}$, X production amounts to ~14% of the total cross section at 2×10^{10} eV. The shape of the cross section for energies below $4E_{th}$, obtained from phase-space considerations,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

spectrum of the form $E^{-1.74}$(chosen by Grigorov *et al.* because it provided a best "straight-line" approximation to the measurements), cannot be fitted to the proton spectrum.

Starting with the assumption of the constancy of nuclear composition, that is, γ(all-particle)$=\gamma$(proton)$=1.45$, we fit the all-particle spectrum below 10^{11} eV by $F_{all}(\geq E)=8.3\times10^{-4}E^{-1.45}$ cm^{-2} sec^{-1} sr^{-1}.

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

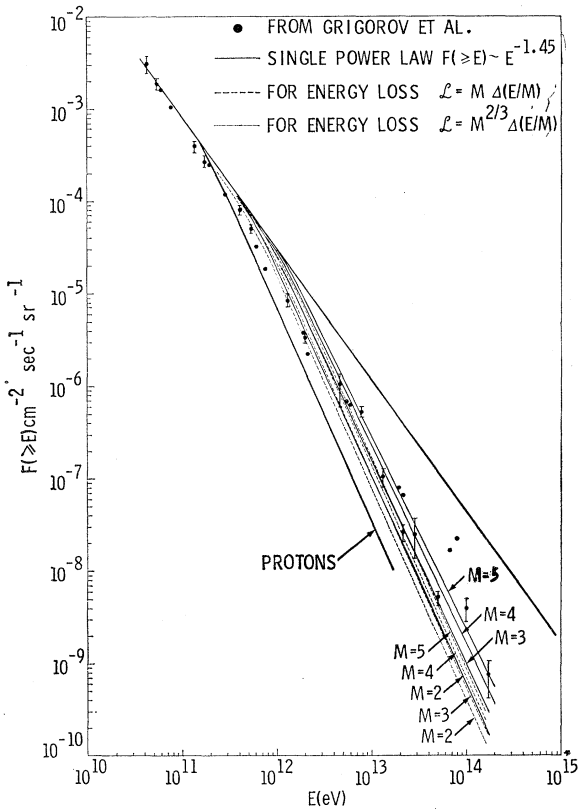

FIG. 5. All-particle spectra. The experimental points are as given by Grigorov *et al.* The dark line shows the spectrum described by a single power law in this energy range. The fine lines show the spectra for different nuclei obtained by assuming that the energy loss through the X process is a function 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 $2\sim M<5$.

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

$$\mathcal{L}(E)=M\Delta(E/M), \tag{9}$$

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,

$$\mathfrak{N}_2(E)=\mathfrak{N}_1(E+M\Delta(E/M)), \tag{10}$$

where

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

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

In Fig. 5 we show the integral spectra obtained by integrating Eq. (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. Our assumption of an energy-loss mechanism that depends on the energy per nucleon, rather than on total energy, can be seen to yield results that are consistent with the measured spectra.

V. p-CARBON CROSS SECTION

The interaction cross section of primary protons on carbon was measured by exposing a graphite block of 30.6 g/cm² thickness over the calorimeter for fixed amounts of time and comparing the number of single 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; 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 6×10^{11} eV, $\sigma_X\sim 5$ mb/nucleon (see Fig. 4). Assuming that carbon has $12^{2/3}$ nucleons, one obtains $\sigma_X{}^{\text{C}}\simeq 26$ mb and $\sigma_\pi{}^{\text{C}}\simeq 244$ mb instead of 270 mb. Figure 6 shows the data obtained by Grigorov *et al.*, with 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 quasi-elastic contribution subtracted.[3] The p-carbon ineleastic cross section at 21.5 GeV is also shown in Fig. 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 Smorodin,[17] covering a wide range of inconsistencies

[17] Yu. A. Smorodin. Zh. Eksperim. i Teor. Fiz. **51**, 431 (1966) [English transl.: Soviet Phys.—JETP **24**, 290 (1967)].

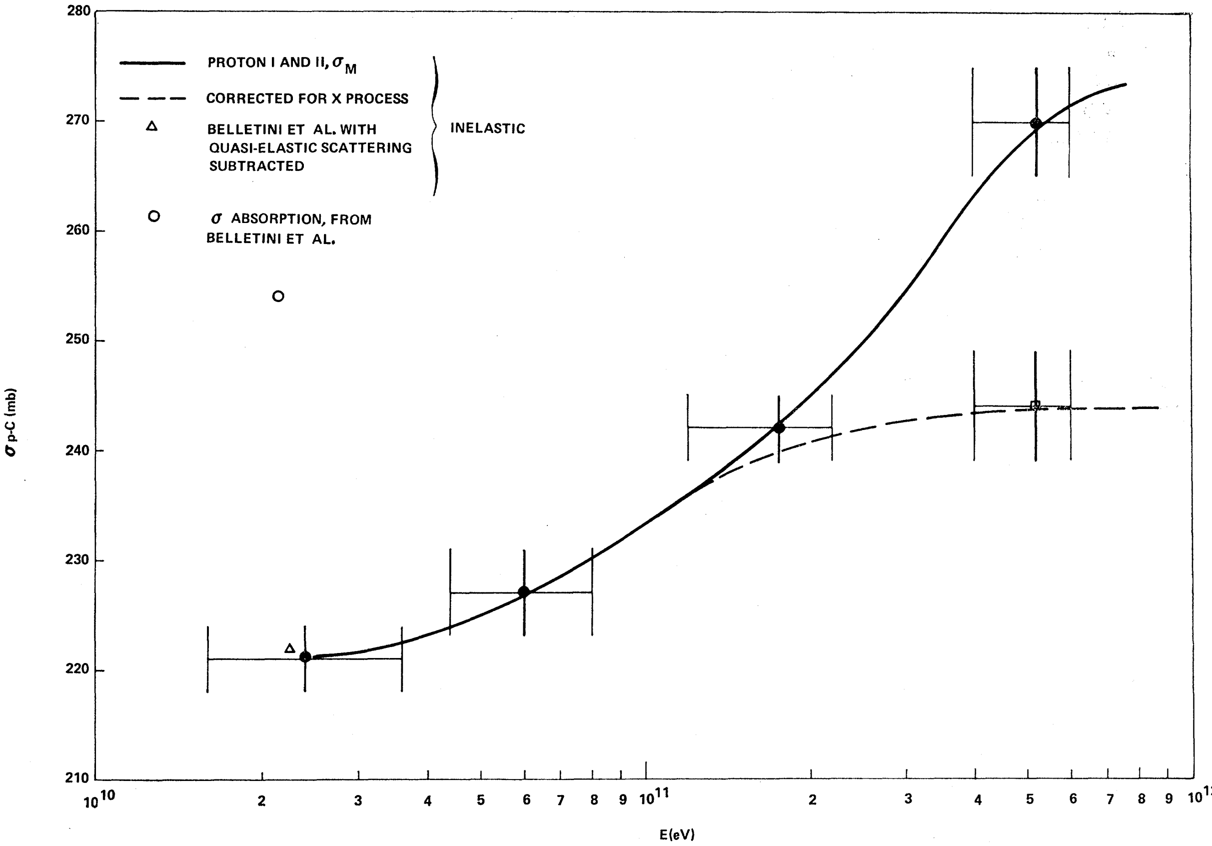

FIG. 6. p-carbon cross sections. We show the values measured by Grigorov *et al.*, the point at 5×10^{11} eV from which the X contribution has been subtracted, and accelerator values of the absorption and "pionization" cross sections at 2×10^{10} eV.

in cosmic-ray data above 10^{11} eV. These are as follows:

(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.[5]

(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 $\sim10^{-10}$ 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 Nikol'skii,[22] indicates that primary γ rays cannot account for the frequency of observed electromagnetic

[18] A. D. Erlykin and A. K. Kulichenko, Bull. Acad. Sci. USSR, Phys. Ser. **32**, 409 (1968).
[19] A. D. Erlykin *et al.*, Bull. Acad. Sci. USSR, Phys. Ser. **32**, 412 (1968).
[20] H. E. Bergeson *et al.*, Phys. Rev. Letters **19**, 1487 (1967).
[21] R. Maze, T. Wdowczyk, A. W. Wolfendale, and A. Zawadzki, Phys. Rev. Letters **22**, 899 (1969).
[22] S. I. Nikol'skii, Zh. Eksperim. i Teor. Fiz. **51**, 804 (1966) [English transl.: Soviet Phys.—JETP **24**, 535 (1967)]; Bull. Acad. Sci. USSR, Phys. Ser. **31**, 1542 (1967).

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 ultrahigh-energy interactions,[7,23] which is suggestive that a massive secondary particle was formed.

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

(1) In general, while calorimeters yield energies of the electron-photon components of air showers that are in agreement with those 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 eight-interaction-length ($8\text{-}L_{\text{int}}$) calorimeter, have found that the rate of energy deposition in iron decreases as a function of energy. The behavior is such that as the energy changes from 2×10^{11} to 5×10^{11} eV, the absorption coefficient of the energy flux changes from $1/L_{\text{int}}$ to $1/3L_{\text{int}}$. Later measurements verify this behavior.[27]

(3) It is reported[28] that when measuring the spectrum of hadrons with the first 2.5 interaction lengths of a $6\text{-}L_{\text{int}}$ 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.

The mechanism for the X process that is described in Sec. VII 2 should exaggerate any energy losses occurring at high energies in shallow calorimeters. The reported measurement shows that at $\sim6\times10^{11}$ 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 that 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. NATURE OF *X* PARTICLE

It is tempting to ascribe the effects considered previously to a particle creation mechanism. The available data do not yield an unambiguous answer on this possibility, but they allow 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 *et al.* adopt the interpretation that in pp collisions at sufficiently high energies, a new class of hadrons is produced in pairs, stable under strong and electro-magnetic interactions, decaying into states containing at least one muon with a high branching ratio and having a summed mass between 6 and 55 GeV. The lifetime of these hadrons can be as short as that of semiweak decays, or as long as $\sim10^{-7}$–10^{-8} sec, and the production cross section is estimated to be ~9 mb 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 *et al.* We expect a total mass between 15 and 29 GeV, and a production cross section in air of ~55 mb. This is six times larger than the minimum cross section found by Bjorken *et al.*, but a lower efficiency in the energy-transfer mechanism to muons, nonmuonic 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 ($\tau>10^{-9}$ sec). 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 weakly interacting boson. A particle with the properties mentioned above

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[28] A. S. Baigubekov, Yu. T. Lukin, and Zh. S. Takibaev, Bull. Acad. Sci. USSR, Phys. Ser. **32**, 385 (1968).
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would have to be created strongly: A work by Shabalin[30] shows that on the basis of the Kummer-Segrè 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. X as the product of proton dissociation. It was suggested by Dooher[34] that the dissociation of a proton into triplets (T) could account for an inefficiency of energy measurement of a short calorimeter. Dooher points out that since one expects $\sigma_{Tp}{}^{\text{tot}}=\frac{1}{3}\sigma_{pp}{}^{\text{tot}}$, most of the triplets would escape the three-nuclear-mean-free-path calorimeter used by Grigorov *et al.*, 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 diffraction dissociation 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).

Dooher estimates the breakup cross section to be of the order a few millibarns per nucleon. As in the analysis of Bjorken *et al.*, 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[35,36] in cosmic rays. At this time, of course, one must await further confirmation of these phenomena in the light of negative searches by others.[37,38] 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 Lee[39] there are four quarks, an SU_3 triplet and a singlet. The proton is composed of two neutral and one charged particles. Upon dissociation, $\frac{2}{3}$ 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.

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, and (2) the nuclear composition remains constant, it is not unreasonable to describe quantitatively the measurements obtained from the artificial earth satellites of the Proton series in terms of an X process, perhaps associated with heavy particles with summed masses of the order of $\sim$19 GeV. It has also been shown that this X process has qualitative characteristics that match other peculiar cosmic-ray and particle interaction 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[40] 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.[41] 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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