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Evidence for long-lived heavy particles with fractional charge

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Three cosmic-ray events have been detected which can be interpreted in terms of long-lived ($\gg 10^{-8}$ sec) particles with charges ($\pm 10\%$) of ± 0.70, ± 0.68, and ± 0.42 respectively, and masses greater than $4.4m_p$, $4.8m_p$, and $20m_p$ at the 90% confidence level, respectively. The probability for explaining the events in terms of previously known particles is estimated and found to be low.

I. INTRODUCTION

A particle telescope has been used to measure masses and charges of slow, heavy cosmic-ray particles using techniques similar to those followed previously.[1] The telescope, which is shown in Fig. 1, was located at sea level under a roof of a few g/cm^2 thickness, and was operational for 4000 hours.

Speeds of particles were calculated from time-of-flight measurements accurate to 0.5 nsec over a 2-m path length. Ionizations were measured via pulse heights in the six scintillator planes shown in Fig. 1. The first three pulse heights (i.e., those in the scintillators above the main absorber), together with the speed measurements, served to determine charges of particles via the equation

$$dE/dx = q^2 f(\beta) . \quad (1)$$

Here, dE/dx denotes the average energy loss in the top three scintillators, β denotes the speed above the main absorber, and q denotes charge. The function f has been tabulated by Janni.[2] The pulse heights in the bottom three scintillators determine masses, with heavier particles producing smaller pulses. We have

$$(dE/dx)' = q^2 f(\beta') , \quad (2)$$

where $(dE/dx)'$ and β' denote the average energy loss and speed in the bottom three scintillators. Equation (2) may be used to determine β', from which a particle's mass m may be deduced from the easily derived equation

$$\frac{m}{m_p} = \frac{q^2 T}{R(\beta) - R(\beta')} . \quad (3)$$

Here, m_p denotes the proton mass, T the thickness of the main absorber (corrected for the finite thicknesses of the scintillators), and $R(\beta)$ the range in iron of a proton with speed β. R has been tabulated by Janni.[2] Equation (3) is valid provided no nuclear interactions occur in the main absorber; if interactions do occur there then it underestimates m.

II. CALIBRATION OF THE TELESCOPE

The timing and pulse-height measurements were performed by displaying and photographing the outputs of the six scintillators on single sweeps at about 10 nsec/div on a Hewlett Packard 183 oscilloscope. Typical photographs are shown in Ref. 1. The timebase of the oscilloscope was calibrated precisely and at frequent intervals by photographing single sweeps of a 50-MHz crystal controlled oscillator. Drifts in the timebase were found to be small and were neglected. All timing

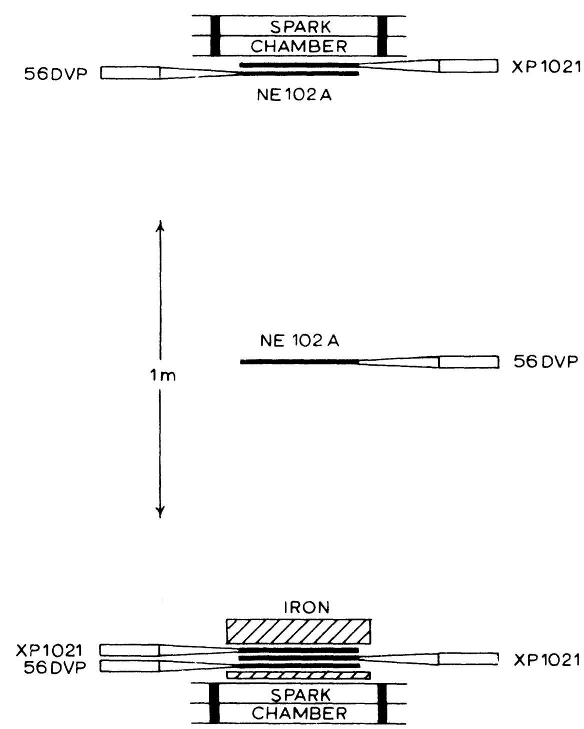

FIG. 1. The telescope. All scintillators are NE102A (40.6 cm ×40.6 cm ×0.64 cm). The light pipes are adiabatic. The gaps in each spark chamber are 5.1 cm wide. The top absorber was 59.2 g/cm^2 Fe and the bottom 7 g/cm^2 (mostly iron) for this experiment. As is shown here, the design of the telescope for the present experiment differs somewhat from that of Ref. 1.

measurements were made with a traveling microscope using the constant fraction technique, and all measurements were made relative to the oscilloscope's (internal) graticule. The telescope itself was calibrated in several "muon runs" and "proton runs" as described below.

The speed measurements were calibrated in nine muon runs, each of about 50 events, which were held during the course of the experiment. The trigger for these was a coincidence (within ± 30 nsec) from the first and fifth scintillators at about $\frac{1}{4}$ the average pulse height for muons. For those events for which the pulse heights were consistent with traversal of the telescope by a muon the spacings between the pulses on the oscilloscope traces, and also the pulse heights, were measured. The average of the intervals between the first and fifth pulses and between the second and sixth pulses, i.e., $\frac{1}{2}(\tau_{15,\mu} + \tau_{26,\mu})$, which is nearly independent of the muon direction and position, was found to be distributed with a standard deviation of about 0.5 nsec about its mean value for each run. The mean, i.e., $\frac{1}{2}(\overline{\tau}_{15,\mu} + \overline{\tau}_{26,\mu})$, drifted by $\lesssim 100$ psec during the course of the experiment. The speed measurements depend on this mean (see below). No large drifts in the gains of the photomultipliers were observed in these runs.[3]

In previous work the pulse-height measurements were also calibrated in the muon runs. However, for the data reported in this paper, they were calibrated in two proton runs, of about 20 hours duration each, which were held during the experiment. For these two runs the main absorber was reduced in thickness to 10.3 and 15.5 g/cm^2 Fe respectively. (This is analogous to reducing the magnet current in a conventional mass spectrometer.) The trigger requirement for both proton runs was a pulse ($\geqslant 1.5 \times$average muon pulse) from the top scintillator followed in approximately 12–32 nsec by one from the fifth scintillator ($\geqslant 1.5\,\overline{\mu}$), and also a pulse ($\geqslant 0.7\,\overline{\mu}$) from the third scintillator within ± 30 nsec of that from the first. Constant fraction discriminators were used for the first and fifth scintillators.[1]

In analyzing the data for the proton runs the following tests were applied to eliminate multiparticle events: (i) Six pulses were required, with heights consistent with traversal of the telescope by a single particle; (ii) The spacing between the fourth and sixth pulses, τ_{46}, was required to be equal to its average in the muon runs, $\overline{\tau}_{46,\mu}$, to within a standard-deviation accuracy of 0.7 nsec; (iii) $\tau_{13} - \frac{1}{2}\tau_{15} = \overline{\tau}_{13,\mu} - \frac{1}{2}\overline{\tau}_{15,\mu}$ with a standard-deviation accuracy of 0.6 nsec; (iv) A spark in the top spark chamber was required within a standard-deviation accuracy of 5 cm of the position predicted by the difference $\tau_{12} - \overline{\tau}_{12,\mu}$ assuming an effective speed of light in the scintillators of $0.5c$; (v) A spark in the bottom spark chamber was required within a standard-deviation accuracy of 5 cm of the position predicted by $\tau_{56} - \overline{\tau}_{56,\mu}$;[4] (vi) The angles between the above sparks and the line joining their centers were required to be $\lesssim 2°$ as viewed by the single nonstereoscopic camera shown in Ref. 1 (2° is about the accuracy with which sparks follow particles in the spark chambers used here[1]); (vii) No other sparks which could reasonably be correlated with the oscilloscope pulses were allowed to be present.[5] We remark that in very nearly all cases one glance at the oscilloscope photograph for an event sufficed to determine if it was a single-particle event or not.

For each event in the proton runs which satisfied the above tests the particle's time of flight was obtained from the difference $\frac{1}{2}(\tau_{15} + \tau_{26}) - \frac{1}{2}(\overline{\tau}_{15,\mu} + \overline{\tau}_{26,\mu})$. This difference is the excess of the particle's time of flight over the average for muons. The latter quantity was calculated assuming a common muon speed of $0.99c$.[1] The time of flight as measured above was assumed to be accurate to a standard deviation of 0.5 nsec. To calculate speeds the same flight path was assumed for all events, i.e., the average flight path for muons between scintillators one and five (or two and six), i.e., 196 cm.

All single particles with $0.455 < \beta < 0.56$ in the first proton run and $0.49 < \beta < 0.56$ in the second were retained for further analysis. There was a total of 47 such particles. At the above speeds muons could not have penetrated the main absorber, whereas protons would have quite easily, and all 47 particles were assumed to be protons. This assumption leads to a proton flux which is quite consistent with that found using different techniques by Brook and Wolfendale.[6] The pulse-height response of each scintillator was then calibrated by comparing the observed pulse heights with tabulated[2] values of rate of energy loss for protons of known speeds. The (slightly) nonlinear response of scintillators was folded into this calibration.[1] The above procedure indicated that the dE/dx and $(dE/dx)'$ measurements were subject to statistical errors of about 12% for unit charge particles with speeds $\simeq 0.5c$. The 12% includes errors due to nonuniformity of the scintillators.

The above calibration procedure for measuring $(dE/dx)'$ is subject to two uncertainties. A small percentage of the calibrating particles will have been deuterons,[1] and a similarly small percentage will have been protons which interacted in the main absorber and still survived to the bottom scintillator. These two small effects tend to cancel, and they were neglected here because the results reported do not depend very sensitively on $(dE/dx)'$.

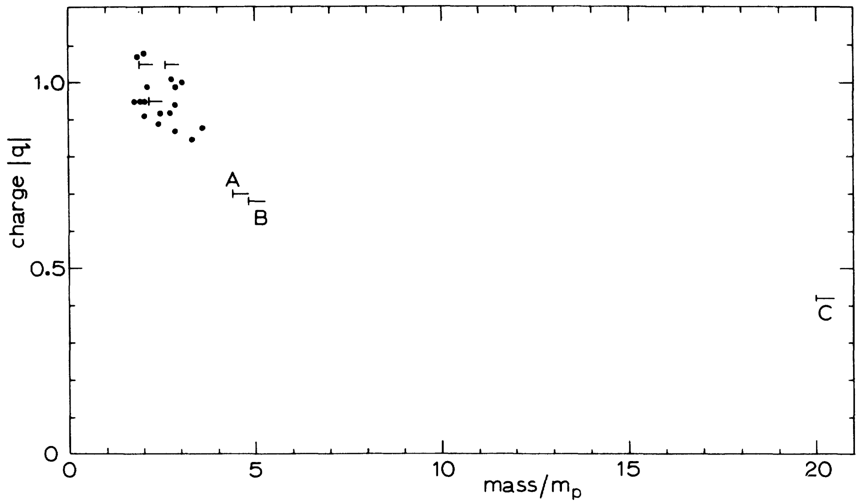

FIG. 2. Masses and charges for all particles observed in 4000 hours with $\beta < 0.59$. For those events where $(dE/dx)'$ did not exceed dE/dx by more than three standard deviations a lower limit (90% confidence) for the mass is given only. For all events except A, B, and C the masses have been computed from Eqs. (2) and (3) with q^2 set equal to unity.

III. RESULTS

The data obtained in 4000 hours with the main absorber $= 59.2$ g/cm^2 Fe and the same trigger as was used in the proton runs are now reported. Those events which satisfied tests (i)–(vii), and for which the measured value of β was <0.59, were retained for analysis. There were 23 such events. Their measured values of charge and mass, as given by Eqs. (1)–(3), are shown in Fig. 2. All but three of the events are clearly consistent with deuteron or triton identifications. The remaining three events (labeled A, B, and C in the figure) stand out as candidates for heavy, fractionally charged particles. These events all had very low measured values of β, namely 0.393 ± 0.012 (event A), 0.401 ± 0.012 (B), and 0.218 ± 0.004 (C). The oscilloscope trace and spark chamber trajectories for event A are shown in Figs. 3 and 4. The other 20 particles all had $\beta \geq 0.51$ which apparently reflects the fact that the minimum β's required for

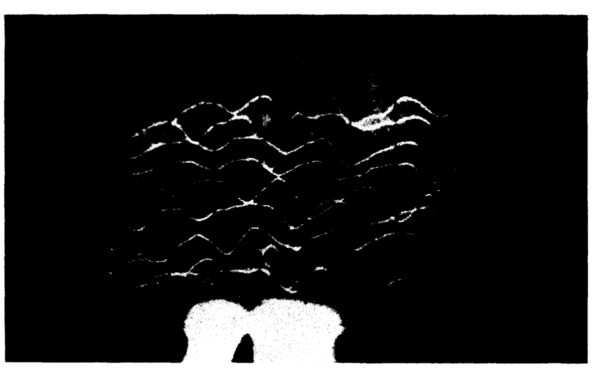

FIG. 3. Typical oscilloscope traces, including that for event A. The pulses are negative (i.e., anode pulses). Event A is the sixth one down. The top two events are multiparticle events and the next three are single-particle events all with $\beta > 0.59$. The seventh and eighth events are multiparticle, and the three superimposed at the bottom not analyzable. This 23-hour time exposure was taken in May 1977.

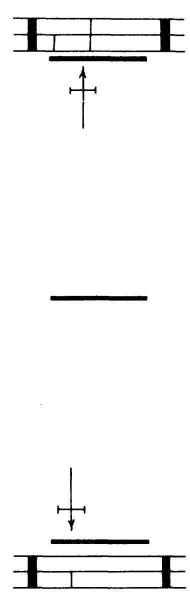

FIG. 4. Spark-chamber trajectories for event A. The arrows indicate the predicted spark positions (with their accuracies) according to the timing measurements as discussed in the text. There is an extra (out-of-geometry) spark in the top chamber. Also shown are the top, bottom, and center scintillators.

tritons, deuterons, and protons to penetrate the telescope are 0.51, 0.56, and 0.65, respectively.

Before commenting on background phenomena which may account for the three anomalous events we note the following. If $q^2 = 1$ for particles A, B, and C, which is most unlikely, then their masses as indicated in Fig. 2 are far too low. Also, if any of them underwent nuclear interactions in the main absorber, then again the computed masses are too low. But if their inelasticities are low, corresponding to their high masses, this could be a small effect. Finally we note here that the data of Fig. 2 do not rule out the possibility that some of the particles depicted there which apparently had unit charge could have had masses $>m_t$.

It is of course possible that the three anomalous events were actually tritons with very poorly measured values of β. The above quoted minimum speed required for tritons to penetrate the telescope implies that timing errors of at least 3.7, 3.5, and 17.1 nsec for events A, B, and C respectively are required for this explanation. In view of the accuracy of the time-of-flight measurements (0.5 nsec) the probability for this appears to be negligible for each event. Similar conclusions may be drawn for other particles (e.g., d's, p's, μ's). It is not possible that timing errors of the above magnitude could have arisen from a malfunction of the oscilloscope's timebase, because such a malfunction would yield results which would obviously fail test (ii) for all three events, and also tests (iv) and (v) for event C.

It may be possible to account for events A and B as 90–95 MeV protons which "leaked" around the main absorber. Such protons could just satisfy the timing requirements and also penetrate the bottom absorber. However, two elastic large-angle scatterings, one in a 300-g part of a flange supporting the main absorber and one in the fourth scintillator, would be required. Knowing the flux of protons (from the calibration runs) a probability of $\lesssim 10^{-5}$ may be deduced for this interpretation for each of events A and B. Similarly the probabilities that they were 180–190 MeV deuterons which broke up in the top 2 mm of the main absorber with the neutrons suffering charge exchange in the forward direction in the bottom 2 mm of the main absorber may be shown to be $\lesssim 10^{-6}$ for each event. Both estimates above exclude the probability that singly charged particles would produce the observed pulse heights for events A and B. The probability for explaining event C in either of the above ways is negligible.

It may perhaps be possible to account for these events as multiparticle events (i.e., as events where the pulses and sparks which satisfied tests (i)–(vi) were produced by more than one particle). The pulse heights for these events were 2–3 times those for fast muons and consequently the most likely multiparticle explanation would involve one slow particle penetrating the top three scintillators and another slow particle penetrating the bottom three. In such cases the directions and positions of the sparks in the top and bottom spark chambers would be expected to be uncorrelated. However, they appear to be obviously correlated in these events, all of which satisfied test (vi) above. The probability that any one of them satisfied this test by chance is <10% for each spark and therefore <1% for each event. Also, no events were detected in the experiment which appeared to be single-particle events according to the oscilloscope photographs but multiparticle according to the spark chamber photographs. This implies an overall probability $\lesssim 10^{-2}$ for accounting for any of the above events in this way, and apparently a negligible probability for accounting for all of them in this way.

To summarize, three cosmic-ray events have been observed which can be interpreted as particles with $|q| = 0.70 \pm 0.07$, 0.68 ± 0.07, and 0.42 ± 0.04 respectively, and $m > 4.4 m_p$, $4.8 m_p$, and $20 m_p$ respectively, at the 90% confidence level. (The errors for charge measurements quoted here are inferred from Fig. 2; they may not be entirely statistical.) All other explanations that have been considered by the author involving previously known particles lead to small probabilities. The remaining remarks apply to the interpretation as heavy, fractionally charged particles.

IV. DISCUSSION

The times taken by the particles to traverse the telescope were $>10^{-8}$ sec and this is a lower limit for their lifetimes. If they had been created just above the telescope then they would have had β values close to unity, in sharp contrast to the measured values. This almost certainly implies that they were not created just above the telescope, and that their lifetimes were $\gg 10^{-8}$ sec. They could be stable.

Two other time-of-flight telescopes have been constructed to study slow, heavy, vertical cosmic rays.[7,8] The experiment of Ref. 7 was carried out at mountain altitude. The aperture × running times for Refs. 7 and 8 are 10^7 and 3×10^9 cm^2 sr sec respectively. These figures may be compared with 10^9 cm^2 sr sec for the present experiment and a similar value for the underground experiment of Ref. 1. In each of these experiments singly charged particles (or particles with $|q| \simeq 1$) were detected for which the data do not rule out, but do not require, a mass $>m_t$, and this may reflect a limitation of the time-of-flight technique. In Refs.

1, 7, and 8 no evidence for fractionally charged particles is reported. However, after the original version of this manuscript was submitted for publication the authors of Ref. 8 (independently) reported an event which can be interpreted in terms of a slow, fractionally charged particle.[9] It is also noted that the efficiencies of the above telescopes for detecting accompanied slow particles will differ for various reasons, and that the anomolous events reported above all involved accompanying sparks in the spark chambers [a total of one or two for each event, clearly consistent with test (vii) above].

The nonobservation[10] of fractionally charged particles in accelerator experiments to date may simply indicate that they are too massive to be pair produced by existing accelerators. If such is the case then they could well have a small cross section for pair production and this could account for their nonobservation[10] as relativistic secondary cosmic rays. They could possibly be heavy, medium-energy primaries with low inelasticities. However, this would imply the presence of a very much greater concentration of fractionally charged particles in the primary cosmic-ray mix than known upper limits for terrestrial matter. Alternatively, they could have an extremely small cross section for direct pair production if they have relatively complex structures. The existence of nonintegrally charged, stable, abnormal states of nuclear matter was proposed previously.[11] Such states could conceivably be present in the cosmic radiation, and could undergo charge exchange in nuclear interactions. The observations reported here do require[10] the presence of a possibly detectable concentration of fractionally charged particles in matter. Unfortunately, however currently available publications on searches for fractional charges in matter are not in general agreement with one another.[12]

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[1] C. R. Alcock *et al.*, Nucl. Instrum. Methods 115, 245 (1974); Nuovo Cimento 22B, 43 (1974); P. C. M. Yock, Nucl. Phys. B76, 175 (1974); B86, 216 (1975).

[2] J. F. Janni, U. S. Air Force Report No. AFWL-TR-65-150, 1966 (unpublished).

[3] To minimize drifts in the characteristics of the photomultipliers they were operated at fairly low voltages. In no events reported here were they saturated (Ref. 1).

[4] In the proton runs this test was relaxed to accept protons which stopped in the bottom absorber.

[5] The helium-filled spark chambers used in this work are sensitive for about 50 μsec prior to being triggered, and particles accompanying slow particles were sometimes registered by them.

[6] G. Brook and A. Wolfendale, Proc. Phys. Soc. 83, 843 (1964).

[7] H. B. Barber *et al.*, in *Proceedings of the Fourteenth International Conference on Cosmic Rays, Munich, 1975* (Max-Planck-Institut für Extraterrestische Physik, Munich, 1975), Vol. 7, p. 2437.

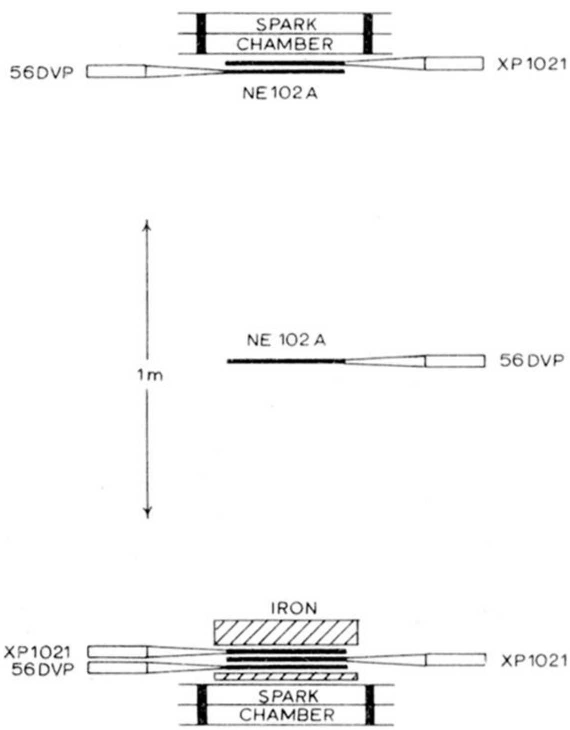
[8] A. M. Bakich and L. S. Peak, J. Phys. E 11, 123 (1978). These authors report measurements of the deuteron and triton cosmic-ray fluxes which are in agreement with those of Ref. 1 and Fig. 2 of the present paper.

[9] L. S. Peak, paper delivered to the Workshop in High-Energy Physics, Australian National University, Canberra, 1977 (unpublished).

[10] L. W. Jones, Rev. Mod. Phys. 49, 717 (1977).

[11] P. C. M. Yock, Ann. Phys. (N. Y.) 82, 449 (1974); Phys. Today 29 (No. 11), 91 (1976).

[12] E. D. Garris and K. O. H. Ziock, Nucl. Instrum. Methods 117, 467 (1974); C. M. Stevens *et al.*, Phys. Rev. D 14, 716 (1976); G. S. La Rue *et al.*, Phys. Rev. Lett. 38, 1011 (1977); G. Callinaro et al., ibid. 38, 1255 (1977); R. Bland et al., ibid. 39, 369 (1977); G. D. Putt and P. C. M. Yock, Phys. Rev. D 17, 1466 (1978).



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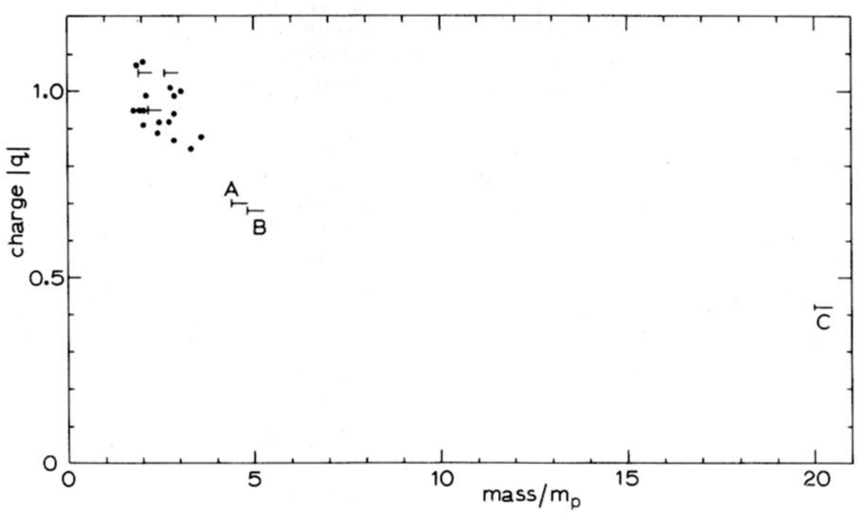

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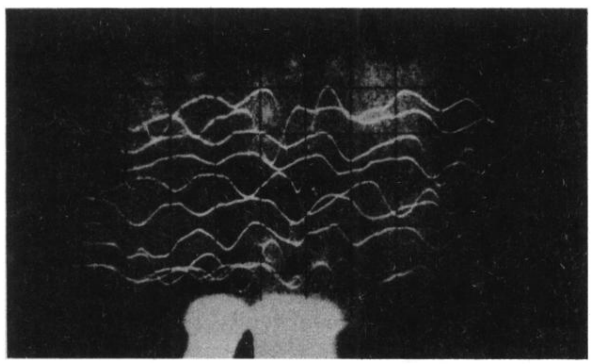

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