and the condition that the energy density of relativistic electrons in the sphere be much less than the energy density of cosmic radiation in the disk, has shown[4] that the most plausible values of the parameters are $\rho$ (material density in the halo)$\simeq 10^{-26}-10^{-27}$ g/cc, $H$(halo magnetic field)$\simeq 1-2\times 10^{-6}$ gauss, $v$ (hydromagnetic turbulent velocity)$\simeq$200 km/sec, and $E$ (energies of the electrons producing radiation at this frequency) $\simeq 10^{9}$ ev. We have assumed that there is rough equipartition between the kinetic and magnetic energy modes. In the disk rough equipartition exists between the kinetic, magnetic, and cosmic-ray energy modes. It seems plausible that the same may also be true in the sphere, and if this is the case the whole halo will be effective in accelerating cosmic-ray particles.[5]

The radio observations suggest that the relativistic electron density is roughly uniform, and whether they are of primary or of secondary origin, if they were produced in the disk where there is a greater density of matter and radiation they can only achieve uniformity if they are both losing energy by radiation and gaining it by Fermi collision processes in the halo. The figures given above suggest that the average distance apart of the irregularities $\leq$100 parsecs.

Fermi[6] showed that the energy of a particle after $N$ collisions would be $W=Mc^2\exp[(V/c)^2N]$, so that only about $2.5\times 10^{-3}$ of the number of collisions demanded in the disk will be needed in the halo to give the same energy spectrum. Also energies $\gg 10^{15}$ ev, which has been shown to be near the upper limit of the original Fermi mechanism,[7] are possible using these new acceleration parameters. The mean free path for a nuclear collision of a proton in the halo is so large (corresponding to lifetimes of $10^{10}$–$10^{11}$ years) that there is small probability of a collision in the galactic lifetime ($\sim 5\times 10^9$ years). On the other hand, one interpretation of the mass spectrum[7] which does not take into account nuclear effects in the primary acceleration in stellar atmospheres[8] suggests that the corresponding mean free path in the disk cannot be greater than $4\times 10^6$ years. Thus, while the gain in energy will be obtained primarily in the halo, the final destruction will take place in the disk. The effective path lengths for nuclear collision in disk and halo will depend both on the ratios of the masses ($M_{\text{disk}}/M_{\text{halo}}$) and on the particle orbits which will be defined by the magnetic fields. For the halo densities suggested above, $M_{\text{disk}}/M_{\text{halo}}\sim 10-10^2$. $H_{\text{disk}}/H_{\text{halo}}$ may be about 5,[9] and in the disk the field tends to be oriented along the spiral arms in the plane with leakage points into the halo.[10] It may be possible, therefore, to reconcile the estimates of the distance apart of the turbulent elements in the halo deduced from the radio observations, and hence the efficiency of the cosmic-ray accelerating mechanism, with the efficiency of the destructive processes of nuclear collision in the disk.

The major difficulty associated with the model is the source of the energy of the diffuse gas in the halo. Because of its distribution and motions it cannot be supposed to originate in the way proposed by Oort and Spitzer,[11] but it may be derived from the total energy of rotation of the galaxy through turbulent hydromagnetic frictional effects.

[1] J. E. Baldwin, Nature **174**, 320 (1954).
[2] J. E. Baldwin, in preparation, and paper read at Symposium on the large scale structure of our galaxy at the International Astronomical Union, Dublin, September, 1955 (to be published in Trans. I.A.U.).
[3] I. S. Shklovsky, Astron. J. S.S.S.R. **29**, 418 (1952); Astron. J. S.S.S.R. **30**, 15 (1953); Astron. J. S.S.S.R. **31**, 533 (1953); S. B. Pikelner, Doklady Akad. Nauk S.S.S.R. **88**, 2, 229 (1953); *Les particules solides dans les astres* (Institut d'Astrophysique, Cointe-Liege, 1955); V. L. Ginsburg, Uspekhi Fiz. Nauk **51**, 343 (1953).
[4] G. R. Burbidge, Astrophys. J. (to be published).
[5] Strictly speaking, for such a model the cosmic-ray pressure should be included when the stability of the sphere is discussed, but the uncertainties in the numbers are such that this refinement is not important at this stage.
[6] E. Fermi, Phys. Rev. **75**, 1169 (1949).
[7] Morrison, Olbert, and Rossi, Phys. Rev. **94**, 440 (1954).
[8] Fowler, Burbidge, and Burbidge, Astrophys J. Suppl. 2, No. 17 (1955).
[9] S. Chandrasekhar and E. Fermi, Astrophys. J. **118**, 113 (1953).
[10] L. Davis, Phys. Rev. **96**, 743 (1954).
[11] J. H. Oort and L. Spitzer, Astrophys. J. **121**, 6 (1955).

## Nuclear Emulsion Observation of Annihilation of an Antiproton*

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An event, which we believe has a reasonable probability of representing the creation and subsequent annihilation of an antiproton, has been observed in emulsions exposed directly in the proton beam of the Berkeley Bevatron.

A facsimile drawing of the event is shown in Fig. 1. Star $A$ is caused by a 6.2-Bev beam proton, and although this star has not yet been fully analyzed its visible energy is approximately 2 Bev. Emerging from star $A$ is a high-energy track which makes an angle of 6.5° with the direction of the beam protons and which causes a secondary star, $B$, after traversing 1.4 mm in the same emulsion strip.

Star $B$ has 16 prongs, apart from the incoming track. An analysis of the nature and energy of each track in star $B$ is shown in Table I. The total visible energy in star $B$, including rest energy of the pions and binding energies of the protons, is 1410 Mev. The total momentum of the visible tracks in the direction of the incident particle is 840 Mev/$c$.

The track of the incident particle of star $B$ is very flat (0.2$\mu$ dip per 100$\mu$), approximately 1.4 mm in length. Its blob density has been accurately compared with ten proton tracks at the same depth in the emulsion and running closely parallel to the incident track. No part of a calibrating proton track was more than $15\mu$ in depth or $100\mu$ laterally from the track in question and care was taken to count all tracks under the same conditions. The incident track has a blob density of 25.40 blobs per $100\mu$ and the protons a blob density of 22.14 blobs per $100\mu$. The blob density of the incident track is thus 9% above the plateau blob density of 23.31, assuming that the 6.2-Bev proton blob density is 5% below the plateau value.[1] Thus the incoming track may be a proton of $750\pm150$ Mev, a $K$-particle of 400 Mev, or a pion of 110 Mev. One is therefore led to believe that star $B$ may result from the capture and annihilation of an antiproton by a heavy nucleus in the emulsion. The energy available from annihilation of an antiproton of 750 Mev is approximately 2600 Mev. Star $B$ exhibits an energy of 1410 Mev and if the assumption is made that as much energy is emitted in the form of neutrons as of protons ($\sim$550 Mev including binding energies), then the energy unaccounted for is $\sim$650 Mev. Some of this energy could be absorbed in the production of one or two $\pi^0$ mesons. A multiplicity of four charged mesons and one or two uncharged mesons appears to be in keeping with current ideas of antiproton annihilation.

Attention should be drawn to the momentum balance of star $B$. If the incident particle is an antiproton of 1400 Mev/$c$, only $\sim$560 Mev/$c$ forward momentum need be taken off by the neutral particles. This is approximately the same as the forward momentum shown by the protons (620 Mev/$c$). An interesting feature of the star, however, is the large lateral momentum exhibited; for instance, the average momentum per charged particle in a direction perpendicular to the incident particle is 153 Mev/$c$, whereas the average momentum per particle in the direction of the incident particle is only 102 Mev/$c$. This seems to lend support to the picture that the star may have resulted from the release of a large amount of energy by annihilation. It is of interest also to point out that all four charged pions move to one side in a relatively small cone.

Two alternative possibilities of explaining the event must now be considered. The first is the possible alternative that the incident particle to star $B$ is a deuteron of $1500\pm300$ Mev. It seems, however, improbable that a 17-prong star which has a visible energy of 1410 Mev should distribute practically zero energy among its neutral particles. Nor would a momentum distribution in which the incident deuteron has as much momentum as 2800 Mev/$c$, whereas the exhibited forward momentum is only 840 Mev/$c$, appear very likely; especially when the neutral particles must have practically zero energy.[2]

TABLE I. Analysis of star $B$.

| Track | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| Identity | $(\bar{p})$ | $p$ | $p$ | $p$ | $p$ | $p$ | $\pi$ | $\pi$ | $\pi$ |
| Energy (Mev) | 750 | 5.3 | 5.0 | 22.5 | 12 | 13.5 | 129 | 42 | 70 |
| $R$ ($\mu$) or $g/g_{plat}$ | | $194\mu$ | $173\mu$ | $2320\mu$ | $763\mu$ | $964\mu$ | 1.04 | 1.77 | 1.41 |
| Track | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | |
| Identity | $\pi$ | $p$ | $p$ | $p$ | $\alpha$(?) | $p$ | $p$ | $p$ | |
| Energy (Mev) | 77 | 114 | 128 | 2.7 | 1.6 | 15 | 87 | 33.5 | |
| $R$ ($\mu$) or $g/g_{plat}$ | 1.36 | 2.7 | 2.5 | $63\mu$ | $4\mu$ | $1180\mu$ | 3.2 | $4660\mu$ | |

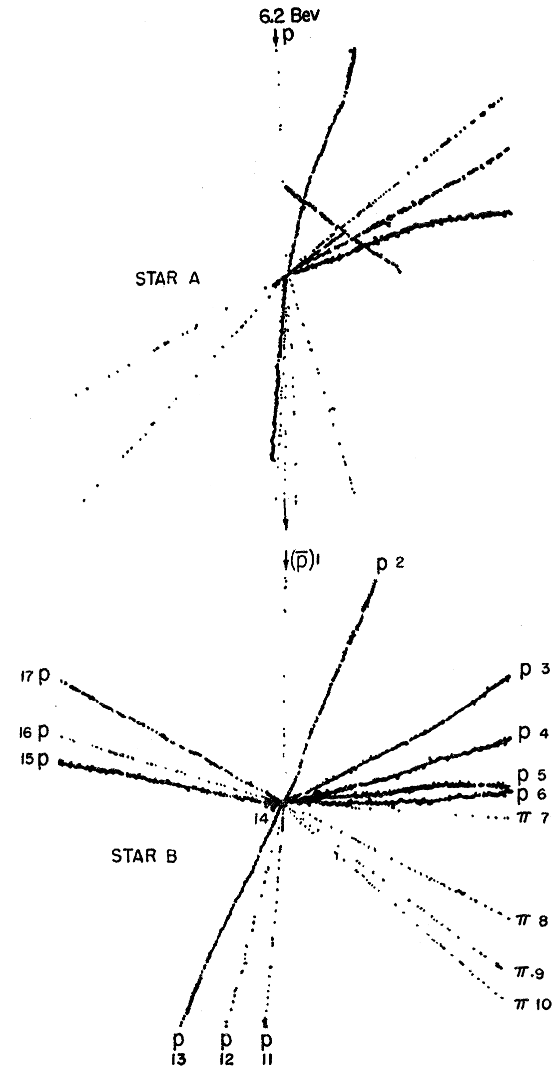


FIG. 1. Facsimile drawing of the observed event. Star $B$ probably results from the annihilation of an antiproton, track 1, captured in a heavy nucleus. Track 1 arises in a primary star, $A$, created by an incident proton, $p$, of 6.2 Bev.

The second alternative explanation is that star $B$ is produced by a high-energy pion. If we assume that there is as much energy carried away by neutrons as by protons, the energy of the incident pion would be approximately 2 Bev. The blob count of the incident track to star $B$ is 11% above that of a pion of 2 Bev. On the basis of the probable error of the observed blob density of the incident track, we estimate the statistical chance to be 1 in 50 that a 2-Bev pion will have a blob density as high as the incident track.

From the number of high-energy secondary pion stars relative to 6.2-Bev stars in our emulsions and from a plausible theoretical estimate of 0.004 mb ($g^2/4\pi \approx 1$) for the antiproton production cross section,[3] we believe that the expected number of 2-Bev pion stars may be as high as 50 times the number of antiproton stars. Thus, combined with the probability factor from blob-density considerations, there may be roughly an equal probability that star $B$ arises from the interaction of an antiproton as from a 2-Bev pion. However, since the momentum of a 2-Bev pion is 2140 Mev/$c$ and the observed forward momentum of star $B$ is visible only 840 Mev/$c$, there is again considerable doubt cast on the possibility that the incident particle could be a high-energy pion.

It should perhaps be pointed out that, since the visible energy evolution in star $B$ is only 660 Mev in excess of the incident particle energy, the event is not incompatible with the absorption of a hypothetical boson of approximately protonic mass.

We are deeply indebted to the members of the Radiation Laboratory, University of California, and especially to Dr. E. J. Lofgren and Dr. G. Goldhaber, for the irradiation of the emulsions.

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[1] B. Judek and E. Pickup (private communication); A. Husain and E. Pickup, Phys. Rev. **98**, 136 (1955). Using electrons from $\mu-e$ decays, we have checked the ratio of plateau density to 6.2-Bev proton blob density and find a value of approximately 1.03, which, within experimental error, agrees with value of 1.05 used above. Although there is some disagreement [see Kaplon, Klarmann, and Yekutieli, Phys. Rev. **99**, 1528 (1955)] as to the value of the plateau to minimum blob-density ratio, most observers are in agreement on the form of the blob-density curve above the plateau. Above the plateau, we have used a combination of the curves of Husain and Pickup and of J. R. Fleming and J. J. Lord [Phys. Rev. **92**, 511 (1954)].

[2] The possibility that star $B$ is created by an Eisenberg type of particle seems no more likely than in the case of a deuteron; unless perhaps the normally emitted $K$ particle decays to pions or is converted directly into kinetic energy.

[3] D. Fox, Phys. Rev. **94**, 499 (1954); R. N. Thorn, Phys. Rev. **94**, 501 (1954); G. Feldman, Phys. Rev. **95**, 1697 (1954).

## Antiproton Star Observed in Emulsion*

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In connection with the antiproton investigation at the Bevatron, we planned and carried out a photographic-emulsion exposure in a magnetically selected beam of negative particles. The magnetic system was identical to the first half (one deflecting magnet and one magnetic lens) of the system used in the antiproton experiment of Chamberlain, Segrè, Wiegand, and Ypsilantis.[1] The selected particles left the copper target in the forward direction with momentum 1.09 Bev/$c$.

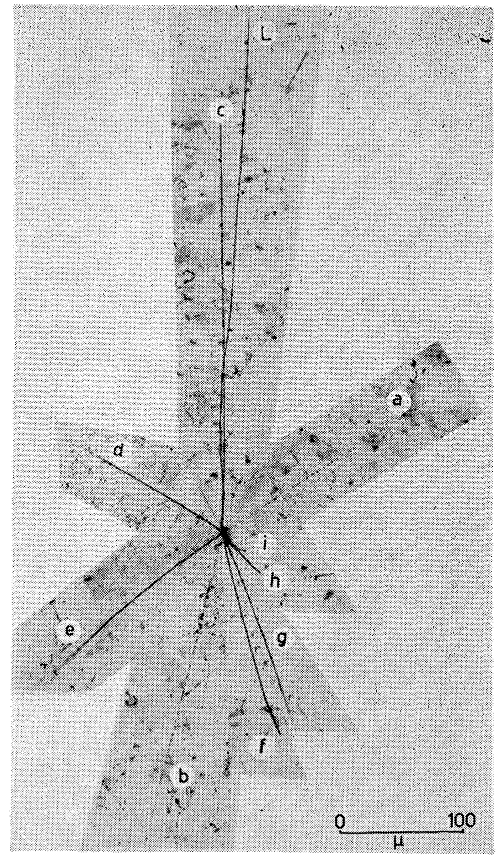


Fig. 1. Reproduction of the star. $L$ is the incoming track (9.31 cm of range). For the explanation of the other tracks see Table I.

Cosmic-ray events possibly due to antiprotons had been observed previously by Hayward,[2] Cowan,[3] Bridge, Courant, DeStaebler, and Rossi,[4] and (in nuclear emulsion) by Amaldi, Castagnoli, Cortini, Franzinetti, and Manfredini.[5] We were hopeful of finding events similar to the last one in our experiment as reported here.

When the antiproton concentration in the beam used was measured[1] (one for about 50 000 pions), it became possible to make a rough estimate of the number of antiprotons that should come to rest in the nuclear emulsion stacks. Since the range of antiprotons from the selected beam was considerably greater than the length of the stacks, it was necessary to slow the antiprotons in an absorber (132 g cm$^{-2}$ of copper) before allowing them to enter the stacks in which they were to come to rest. The estimate of the number of antiprotons stopping in the stacks is hence rather drastically affected by the assumption made about their nuclear attenuation cross section in the copper absorber. If the attenuation cross section is assumed equal to that for protons we could expect about 7 antiprotons, while if it were twice that for protons we could expect only about 2.5 anti-