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ANTIPROTONS IN COSMIC RAYS

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1. INTRODUCTION

Our experience with particle physics on the microscopic level at high energy accelerators has shown that particles are produced symmetrically with antiparticles. The extension of earlier nonrelativistic quantum mechanics to include relativistic effects led Dirac [1928] to predict the existence of positrons, subsequently discovered in cosmic ray experiments [Anderson, 1933]. High energy experiments with the collision of protons with other nuclei led to the discovery of antiprotons [Chamberlain et al., 1955]. These observations could be understood as conservation of baryon numbers and lepton numbers in nuclear interactions. These symmetry laws, as well as the phenomenon of annihilation of particle-antiparticle pairs when they interact, imply that if matter and antimatter exist in macroscopic quantities, they must be isolated from each other. The scale sizes of regions separating matter and antimatter are of fundamental importance in the study of cosmology [Stecker 1982, 1983; Steigman, 1976; and Zeldovich, 1965].

Recent experimental observations [Golden et al., 1979; Buffington, Schindler, and Pennypacker, 1981b; and Bogomolov et al., 1979] of antiproton fluxes larger than expected [Gaisser and Maurer, 1973] in the cosmic corpuscular radiation have stimulated the interest of physicists in several disciplines to consider their implications.

On astrophysical scales, the interfaces between regions of matter and antimatter might be revealed by the emission of gamma rays from annihilation processes.

However, other electromagnetic radiation from a source composed of antimatter would have identical characteristics to those from a source composed of ordinary matter. Consequently, X-ray, UV, optical, infrared, or radio observations are incapable of differentiating between sources composed of matter or antimatter. The cosmic radiation contains direct samples of matter from regions far beyond the solar system. Some fraction of these nuclei may be extragalactic in origin. If we were able to unambiguously identify samples of antinuclei ($Z \geqslant 2$) in the cosmic radiation (they cannot have been produced in collision processes), we would have an unambiguous signature of a large region of antimatter. Thus, cosmic ray composition measurements and gamma ray background observations have a very important bearing on the fundamental question: Is the universe symmetric in matter and antimatter?

2. EXPERIMENTAL RESULTS ON ANTIPROTONS

Table I, following Steigman [1976], lists experiments and techniques used to search for antiprotons and antihelium. Generally speaking, the techniques can be classified as either magnetic deflection or annihilation. The annihilation experiments can be further subdivided into those exploiting topology [Buffington, Schindler, and Pennypacker, 1981b] and those sensitive to the total energy release or calorimetry (emulsions).

The emulsion experiments have information on both energy and topology. In practice, however, the investigators [Apparao, 1967] look for an incoming slow proton-like track ($E < 200$ MeV) coming to the end of its range and causing a nuclear interaction of energy larger than the kinetic energy of the incoming particle.

Apparao [1967] looked for annihilation interactions in emulsion flown on balloons and from the absence of detection of annihilation interaction placed an upper limit for $\overline{P}/P$ at $< 9 \times 10^{-3}$ for rigidity < 0.6 GV/c.

Golden et al. [1979], using their balloon-borne superconducting magnet spectrometer, reported finding 46 antiproton candidates in the rigidity interval

TABLE 1
COSMIC RAY ANTIMATTER SEARCHES

	Rigidity (GV/c)	$\bar{N}/N$	Reference	Technique
Antiproton	.5 to 1	$2.2 \pm 0.6 \times 10^{-4}$	Buffington, Schindler, and Pennypacker, 1981b	Annihilation Topology—Counter
	< 0.6	$<9 \times 10^{-4}$	Apparao, 1967	Annihilation—Emulsion
	< 1.3	$<3 \times 10^{-3}$	Aizu et al., 1961	Annihilation—Emulsion
	3-6	$<1 \times 10^{-2}$	Bogomolov, Lubyanaya, and Romanov, 1971	Permanent Magnet
	5.6 to 12.5	$5.2 \pm 1.5 \times 10^{-4}$	Golden et al., 1979, 1984	Superconducting Magnet
	> 16	< 0.13	Durgaprasad and Kunte, 1971	Geomagnetic—Counters
Antihelium	0.25 to 0.5	$< 2.2 \times 10^{-5}$	Buffington, Schindler, and Pennypacker, 1981b	Annihilation Topology—Counter
	1-10	$< 1 \times 10^{-3}$	Evenson, 1972	Permanent Magnet—Spark Chamber
	10-25	$< 8 \times 10^{-3}$	Evenson, 1972	Permanent Magnet—Spark Chamber
	4-33	$< 5 \times 10^{-4}$	Smoot, Buffington, and Orth, 1975	Superconducting Magnets
	33-100	$< 2 \times 10^{-2}$	Smoot, Buffington, and Orth, 1975	Superconducting Magnets
	< 2.7	$< 7 \times 10^{-3}$	Aizu et al., 1961	Annihilation—Emulsion
	< 100	$< 7 \times 10^{-3}$	Damle et al., 1973	Permanent Magnet—Emulsion

5.6 to 12.5 GV/c. From these 46, 18 events were subtracted as due to atmospheric and instrumentation background. They interpret their data as resulting in a $\overline{P}/P = (5.2 \pm 1.5) \times 10^{-4}$. In a later publication Golden et al. [1984] have revised P/P to $(6.8 \pm 1.7) \times 10^{-4}$. In a joint experiment with the authors, Golden has plans to lower the threshold energy of his Cherenkov detector so that measurements with the balloon superconducting magnet can be made to lower energies.

Golden et al. [1984] have recently analyzed their balloon data to provide a differential spectrum of antiprotons in the few GeV range of energies. The poor statistics of the data make it difficult to see any clear pattern of correspondence of data with the various models. The data are more consistent with the shape of the $\overline{P}/P$ ratio expected from a secondary origin model than with a constant $\overline{P}/P$ ratio, but the flux is higher than expected by a factor of about 4.

Bogomolov et al. [1979] used a permanent magnet and spark chamber system to detect two events identified as antiprotons. Given the fact that the geometry factor of the system was only 1.1 cm^2, the derived flux is consistent with the results of Golden et al. [1979]. This result is limited by statistical uncertainties rather than by possible background effects.

The 1979 experiment of Buffington, Schindler, and Pennypacker found an unexpected result at odds with current theories of origin and propagation of cosmic rays. The energies of these observed antiprotons are below the production kinematic threshold and their flux is high, $\overline{P}/P = 2 \times 10^{-4}$. The results have been controversial. Detailed criticism of the experimental work has been made [see, for example, Stephens, 1981a]. Figure 1 shows the existing results on the measurement of the $\overline{P}/P$ ratio.

3. THEORETICAL INTERPRETATIONS

These antiproton observations, at the very least, force us to reexamine our current picture of the origin and propagation of cosmic rays, and they may imply evidence for more exotic processes.

We now survey the various theoretical ideas which have been suggested to interpret these unexpected experimental observations.

A. Secondary Production In Matter

The experimental data on the nuclear composition of cosmic rays has resulted in the development of several models for the propagation of cosmic rays in the interstellar medium [Cesarksy, 1980]. The crucial experimental observation of the (L/M) ratio of secondary nuclei (produced in nuclear collisions

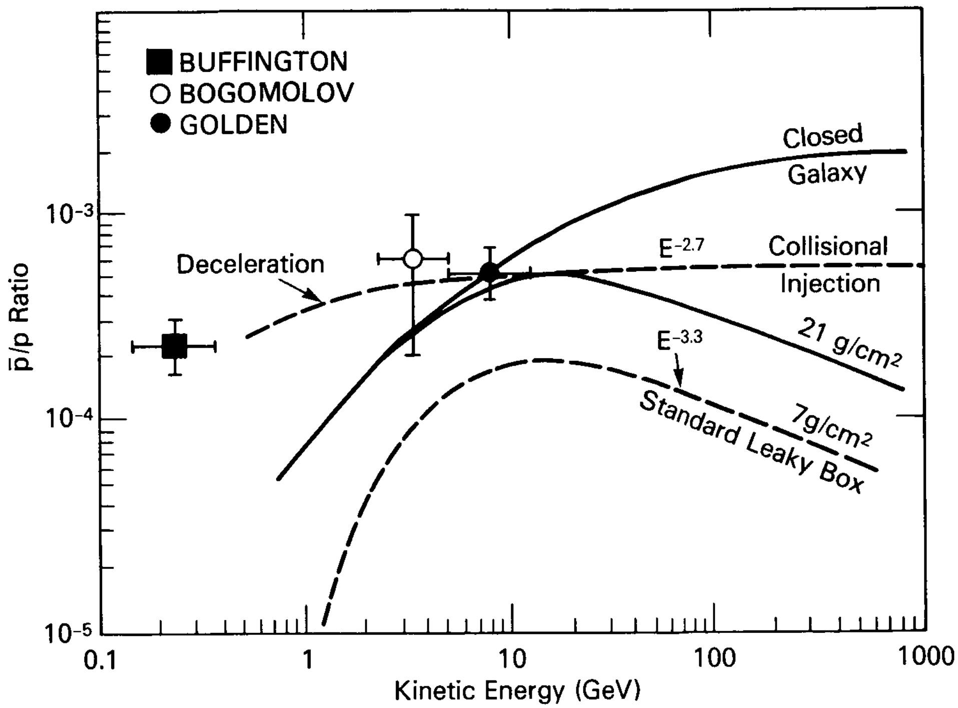

Figure 1. The data of Golden et al. [1979], Bogomolov et al. [1979], and Buffington, Schlindler, and Pennypacker [1981b] are compared with expectation from the class of models in which the antiprotons arise as secondaries of interactions.

of heavier nuclei with interstellar matter) to the primary nuclei has been the starting point of all the models. Antiprotons may be produced in collisions of protons with interstellar hydrogen. Given the observed proton flux, the $\overline{P}/P$ ratio can be calculated from known cross-sections and from the target thickness implied by studies of the heavier nuclei. An important feature of these studies is the variation of the target thickness as a function of energy. The behavior of the ratio at higher energies where no observations are available form the subject matter of the predictions from these models. In a separate paper [Cesarsky and Ormes, this volume] these models have been discussed, and for details the reader is referred to that paper.

In Figure 1 the observed $\overline{P}/P$ is compared to the predictions from the more prominent of these models. It is apparent that the $\overline{P}$'s are present in cosmic rays with a greater abundance than predicted [see curve labeled Standard Leaky Box]. The production of $\overline{P}$'s demands a much larger passage of matter than one would expect based on an analysis of the data from heavy nuclei. The curve labeled 21 g/cm^2 has been scaled up to fit the observations. This has motivated some workers [Cowsik and Gaisser, 1981; Mauger and Stephens, 1983; and Ginzburg and Ptuskin, 1981] to speculate on scenarios where more matter is traversed by cosmic rays in a certain phase of their acceleration. Essentially, these models suggest a separate source of protons (and possibly He nuclei), a source or sources surrounded by a large thick shroud (~ 50 g/cm^2). If heavy nuclei were accelerated in these sources, they would be broken up in this thick shroud of material and only protons and their secondaries will escape. (The mean free path for proton interaction is about 50 g/cm^2). Assuming these sources act like the sources of heavier cosmic ray nuclei, the predicted spectral exponent of these models for antiprotons is $E^{-3.3}$.

Recently Morfill, Meyer, and Lust [1985] have developed a model where shocks, produced by supernova remnants, interact with nearby clouds. The enhanced cosmic ray abundances accelerated in the shock produce secondaries when the shock interacts with the cloud. If clouds fill 8% of the interstellar medium and hot, low density gas makes up the remainder of the medium, they claim an agreement between the calculated secondary to primary ratios with observations. The energy dependence of the secondary to primary ratio comes from the energy dependent escape from the waves near the shock. This model predicts that the $\bar{P}/P$ ratio will fall with increasing energy up to some energy (perhaps about 100 GeV) at which the ratio will flatten to a component due to interactions with the averaged interstellar material. This paper did not present quantitative predictions.

Another class of models separates the origin of protons from the heavier nuclei. These are generally models in which the population of protons (and perhaps helium) is old and has traversed more matter than the heavy nuclei which are presumably younger and produced in a nearby source. These are sometimes known as closed galaxy models [Peters and Westergaard, 1977] (closed galaxy curve). Protheroe [1981] has shown that the antiproton flux in the energy range above 1 GeV is consistent with the predictions of the closed galaxy model, but the low energy data are inconsistent with this model. Stephens [1981] has postulated a three-tier model which is a combination of the closed galaxy and the leaky box models. About one-half the protons are young and reach us promptly from the spiral arms whereas the other half is trapped in the outer galaxy. Being trapped, they traverse a lot of matter and so produce a larger amount of secondary antiprotons. Stephens' model is capable of matching the observations of both P and e^+. These models generally produce spectra which are not power laws as they admix components with different exponents.

The observed antiproton data demand not only large matter traversal but also a mechanism of energy degradation from the GeV range to a few hundred MeV, as pointed out by Buffington and Schindler [1981a], Eichler [1982], Ginzburg and Ptuskin [1981], and Mauger and Stephens [1983].

There is a class of models in which antiprotons are produced in collisions, and then injected into an accelerator along with protons. Those models produce the same asymptotic spectra for protons and antiprotons.

Ginzburg and Ptuskin [1981] have considered production of antiprotons in young supernova envelopes where cosmic ray protons pass through appreciable amounts of matter. The antiprotons would undergo adiabatic energy losses in turbulent regions in the envelope and their spectrum is weighted towards low energy. These regions, being surrounded by large amounts of matter, would not let heavy nuclei leave the sources, as they would break up by nuclear and photonuclear reactions at this active stage. Nuclei could be accelerated at a later stage from these remnants or as Cowsik and Gaisser [1981] postulate, the sources of heavy nuclei and protons and He nuclei could be different.

Moraal and Axford [1983] and Mauger and Stephens [1983] produced the antiprotons in the early dense phase of a supernova explosion. The details differ, but these models feature the injection of antiprotons at low energy as secondaries and then accelerate them along with protons so the spectra should be the same ($E^{-2.7}$) at high energy. (See curve labeled Collisional Injection.)

Tan and Ng [1983] attempt to interpret the observed antiprotons as arising from the interactions of protons in the dense molecular H_2 cloud regions concentrated in a ring of radius 5 Kpc around the galactic center. The gamma ray data and molecular H_2 density distribution derived from molecular CO distribution lend credence to a nonuniform density distribution in the galactic disc. Tan and Ng claim that all the available data on antiprotons, including the low energy data of Buffington, Schindler, and Pennypacker [1981b], can be explained by their model. The antiprotons are secondaries produced in the 5 Kpc molecular ring. Subsequent adiabatic deceleration due to the expansion of the ring decreases their energies below the kinematic threshold. Secondaries of heavier nuclei are produced on scales comparable to the disc and are not affected by these special effects. If matter concentration is important for the production of antiprotons, it should have important contributions to secondaries and of Fe and ultraheavies. Unless there are special sources of antiprotons as Cowsik and Gaisser [1981] speculate, it is hard to discount effects on heavier nuclei. What happens to He nuclei, for example, in this model? Does one expect a large $^3He/^4He$ ratio at low energies? Details are not available from the work of Tan and Ng.

Lagage and Cesarsky [1985] have examined the general problem of explaining antiproton fluxes by production in thick sources. They conclude that while such sources may contribute as little as 25 percent of cosmic rays, minimum source grammages of about 30 g cm^{-2} are needed to avoid production of light secondary nuclei in excess of observation. They calculate that gamma rays from these sources would then be expected to contribute somewhat more than half of the observed gamma ray flux above 100 MeV. This is barely tolerable as one can already account for at least half of the gamma ray flux by diffuse emission from cosmic rays interacting with ambient interstellar medium [Lebrun et al., 1983]. The problem of overproduction of gamma rays in thick sources is exacerbated if cosmic rays are adiabatically decelerated in the sources, increasing the source luminosity.

Only models with collisional injection are able in a natural way to explain the abundance of antiprotons at 200 MeV. Other models must add substantial deceleration in some manner or other to produce antiprotons an order of magnitude below the kinematic threshold, even including solar modulation effects.

Dermer and Ramaty [1985] investigated the possibility that antiprotons are produced in (p-p) collisions in relativistic plasmas. In their model, both projectile and target protons are in motion, and the antiproton production kinematic threshold is lower in the frame of the plasma. The spectrum in this case would extend to much lower energies compared to the production of secondary particles in cosmic ray collisions with ambient matter. As possible production regions they consider matter-accreting condensed objects. Excessive gamma ray production from π° decay is avoided in their scenario by having the surrounding gamma ray density large so that gamma-gamma collisions make it optically thick for gamma rays. Antiprotons might be trapped by magnetic fields, but antineutrons could escape from the region and then decay into antiprotons thus providing for their injection into the interstellar medium.

B. More Exotic Explanations

1. Primordial Black Holes and Their Evaporation

Kiraly et al. [1981] and Turner [1983] consider a model involving evaporating primeval black holes (PBH) in the galaxy, first suggested by Hawking [1974]. PBH's with original masses $\sim 5 \times 10^{14}$ g, if created in the early universe, would have evaporated already. Higher mass black holes evaporating and losing mass could contribute to a quasi-equilibrium density of black holes of mass 5×10^{14} g which might contribute to antiprotons observed. Following Carr [1975], Kiraly et al. show that the solar demodulated antiproton spectrum could be consistent in slope and intensity with current ideas regarding black holes. The low energy flux of antiprotons of Buffington, Schindler, and Pennypacker [1981b] has been demodulated by Kiraly et al. assuming adiabatic energy losses of 400, 600, and 900 MeV, respectively, as shown in Figure 2. This $\overline{P}$ spectrum from primordial black holes would be a power law ($E^{-3.0}$). This type of a power law spectrum for antiprotons could arise either from acceleration of nearly thermal antiprotons or emission from primordial black holes. The acceleration of antiprotons from nearly thermal antiprotons from the galaxy is ruled out because the annihilation gamma ray background would be much larger than observed. The black hole model according to the authors is consistent with the gamma ray background, the electron and positron fluxes, and the low abundance of antihelium. Kiraly et al. also pointed out that if black holes are confined to galaxies, the antiproton data reduce their upper limit by a factor of 30 compared to the present limits set by gamma ray background.

2. Galactic Nuclei, SS433 Type Objects and Their Environment

Eichler [1982] points out that while solar modulation may enhance $\overline{P}/P$ at low energies, the modulation effect alone is not strong enough to account for the value claimed by Buffington, Schindler, and Pennypacker [1981b]. In solar modulation, while there is energy loss, the intensity of antiprotons would be even higher outside the heliosphere than the observed values. According to Eichler, antiprotons could be produced in dense compact regions where the radiation density is sufficiently high to block gamma ray escape through photon-photon collisions and to degrade electron energies. Adiabatic deceleration of the produced antiprotons is postulated. Following Ramaty and Lingenfelter [1981], Eichler suggests that the environment around objects such as active galactic nuclei or those like SS433 may be suitable candidate sources for injecting antiprotons into the interstellar medium.

3. Baryon Symmetric Cosmologies

The observed particle/antiparticle symmetry in accelerator experiments and the conservation of baryon and lepton numbers in particle interactions leads one to question why this symmetry is not observed in the universe. Several

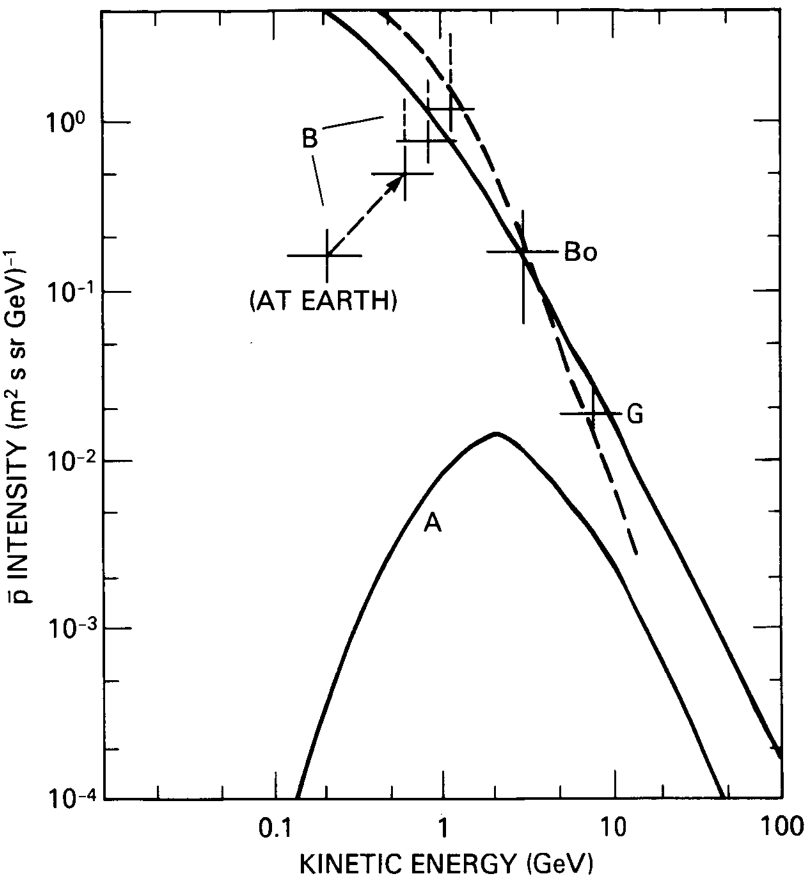

Figure 2. Following Kiraly et al. [1981] and Stecker and Wolfendale [1984] the data are shown with antiproton spectra expected from primordial black holes (dashed curve) and extragalactic antiprotons (solid curve). The differential flux represented by the [Buffington, Schindler, and Pennypacker, 1981b] point has been demodulated assuming three different mean energy losses (see text), adiabatic deceleration, and the applicability of Liouville's theorem. The vertical dashes on the three demodulated points represent plausible uncertainties in this procedure. Both spectra have been normalized at 9 GeV. For comparison, curve A shows the spectrum expected from a leaky box model with 5 g/cm^2.

cosmologists have taken the view that the symmetry is a fundamental one; but the separation of matter and antimatter into different regimes prevents the total annihilation of matter. Among the early models, we refer to those developed by Omnes [1970] and studied by Stecker and Puget [1972] and Combes, Fassi-Fahri, and Leroy [1975].

The development of the Grand Unified theories has resulted in the development of models [Stecker, 1982] where the exact manner in which charge parity (CP) violation is incorporated in gauge theories determines the nature of the resulting cosmology. If CP violation is spontaneous, random sign changes in casually independent regions will split the universe into domains of baryon or antibaryon excesses. Stecker has used this scenario to postulate an explanation of the cosmic gamma ray background spectrum. If these regions are separated on a galactic scale, a small flux of extragalactic $\overline{P}$ and $\overline{He}$ could be expected.

Stecker, Protheroe, and Kazanas [1983] examined the possibility that the observed antiprotons are primary particles from active galaxies and found this hypothesis consistent with the antiproton observations. Baryon symmetry would naturally seem to result in $\overline{P}/P = \overline{He}/He$; whereas, the results of Buffington, Schindler, and Pennypacker [1981b] imply $\overline{He}/He < \overline{P}/P$ by at least a factor of 10. This result requires destruction of antihelium relative to antiprotons. This is done by fragmentation loss of antihelium by interactions with matter or radiation. Stecker et al. presume that the $\overline{He}$ produced in active galaxies is destroyed, so that any $\overline{He}$ surviving would come from normal (anti) galaxies. Estimating leakage from such galaxies, they predict $\overline{He}/He \sim 5 \times 10^{-6}$ to 5×10^{-5}, close to the Buffington, Schindler, and Pennypacker limit of 2×10^{-5}.

More stringent experimental limits on $\overline{He}/He$ would be of great value in the context of baryon symmetric models.

Stephens [1983] observed that the high energy $\overline{P}/P$ ratio in our galaxy should vary as E^{δ}, when the leakage of cosmic rays from galaxies is assumed to vary as a power law $E^{-\delta}$. This assumes: (1) that the source spectra in our galaxy and in an extragalactic source are the same and (2) that the source spectral index of protons in our galaxy is harder than that observed by an amount δ. As a consequence, extragalactic antiprotons arrive at Earth with a spectrum $E^{-2.7+\delta}$ and the $\overline{P}/P$ ratio observed rises as E^{δ}. (See Figure 3.) Stecker and Wolfendale [1984] then suggest that the increasing flux of extragalactic antiprotons and protons might account for the "bump" in the cosmic ray spectrum observed around 10^{15} eV.

Stephens [1983, 1985] has examined the question of constraints on the high energy antiproton spectrum derived from the observed sea level muon charge ratio. He derives upper limits on the $\overline{P}/P$ ratio such that the extragalactic hypothesis would conflict with values of δ greater than about 0.6 for energies above 10^4 GeV.

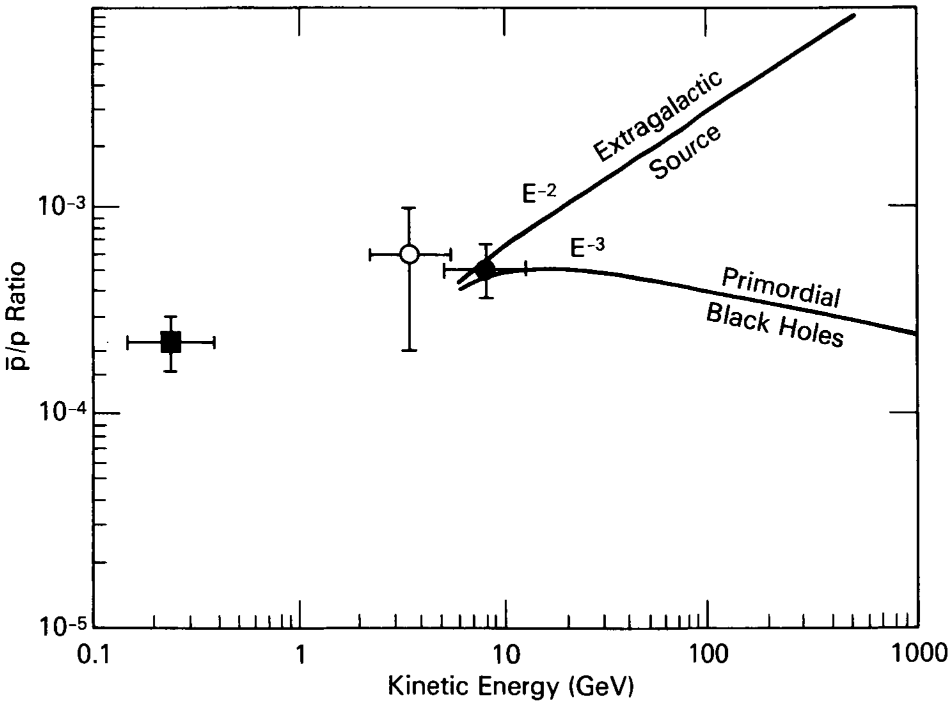

Figure 3. The expected high energy behavior of antiproton spectra from extragalactic sources and primordial black holes are shown.

Measurement of the P spectrum above 10 GeV would either decisively rule out the extragalactic origin of antiprotons or provide evidence for its validity.

4. Supersymmetric Theories and Photinos

In supersymmetric theories, for every boson there is a corresponding fermion partner. Silk and Srednicki [1984] suggested that the photino, the supersymmetric partner of the photon, could be a candidate for the invisible mass in the universe and could help in a viable scenario for galaxy formation and clustering of galaxies. The signature of the presence of vast amounts of photinos in the early universe could be looked for in the larger flux of antiprotons produced in the annihilation of photinos and antiphotinos. Stecker, Rudaz, and Walsh [1985] calculate that the available data on antiprotons are consistent with photinos of several GeV mass, Figure 4. Their calculations are normalized to fit the existing data, but the shape of the $\overline{P}/P$ ratio is calculated for the photino masses indicated. Assuming all the observed antiprotons are due to this process, and ignoring for the moment the large uncertainties in the existing experimental data, Stecker et al.'s calculation seems to suggest a photino mass of 15 GeV or higher. More precise $\overline{P}$ data which showed a sharp cutoff in the antiproton spectrum would be strong evidence for photinos or other Majorana fermions in the galaxy. Some recent calculations indicate that gamma ray lines may also be a signature of these photinos [Srednicki, Theisen, and Silk, 1986; Rudaz, 1986; and Eichler and Adams, 1987].

4. CONCLUSION

From the summary presented, we can see that the approximately 50 antiprotons collected in balloon experiments to date have generated considerable theoretical interest. Clearly, confirmatory experiments and measurements over an extended energy range are required before definite conclusions are drawn. We can see that antiproton measurements have a bearing on astrophysical problems ranging from cosmic ray propagation to issues of cosmological import. The next generation of balloon experiments and the Particle Astrophysics Magnet Facility being discussed for operation on NASA's Space Station should provide data and new insights of the highest interest.

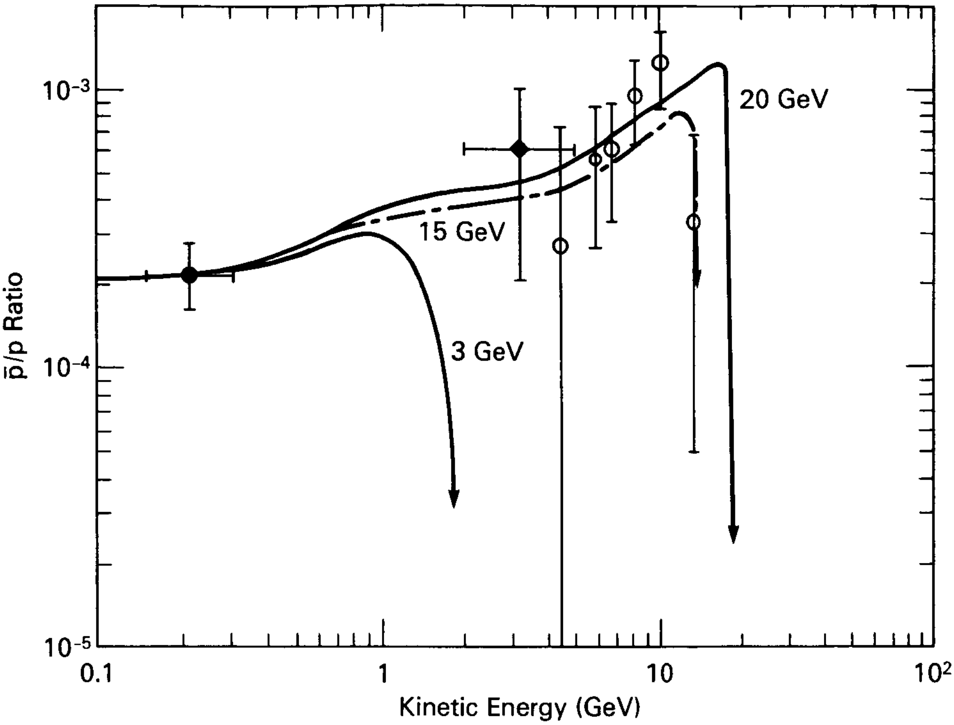

Figure 4. Stecker, Rudaz, and Walsh [1985] compare P̄/P ratios predicted from photino annihilation in the galactic halo with the data, including Golden et al.'s 1984 presentation of his data (open circles). Curves are shown for assumed photino masses of 3, 15, and 20 GeV.

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