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MAGNETIC MONOPOLES*

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In this talk on magnetic monopoles, first I will briefly review some historical background; then, I will describe what several different types of monopoles might look like; and finally I will discuss the experimental situation.

In relating the history of the magnetic monopole and the ideas which led up to its prediction, I like to start with Maxwell. As you all know, building upon the pioneering work of Coulomb, Ampère, and Faraday, Maxwell in 1865 introduced the displacement current and wrote down what we now call Maxwell's equations.[1] In contemporary notation, these are:

$$\begin{aligned} \vec{\nabla}\cdot\vec{D} &= 4\pi\rho \qquad \vec{\nabla}\times\vec{H} - \frac{1}{c}\frac{\partial\vec{D}}{\partial t} = \frac{4\pi}{c}\vec{j} \\ \vec{\nabla}\cdot\vec{B} &= 0 \qquad -\vec{\nabla}\times\vec{E} - \frac{1}{c}\frac{\partial\vec{B}}{\partial t} = 0. \end{aligned} \tag{1}$$

I use here Gaussian units, which are particularly convenient; one sets the vacuum parameters $\mu_0 = \epsilon_0 = 1$ and, as a consequence, electric and magnetic charges are expressed in the same units.

It is well known that this system of equations can be solved by introducing the potentials ϕ and $\vec{A}$, which are derivable from the source terms $4\pi\rho$ and $4\pi\vec{j}/c$, and then solving for the electromagnetic fields by using

$$\vec{E} = -\vec{\nabla}\phi - \frac{\partial\vec{A}}{c\partial t} \; and \; \vec{B} = \vec{\nabla}\times\vec{A}. \tag{2}$$

In covariant notation one writes Eq. (2) as

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu, \tag{3}$$

where $A^\mu = (\phi, \vec{A})$; μ and ν are the usual indices which range from 0 to 3.

While Maxwell introduced the electric displacement current $\partial\vec{D}/c\partial t$ in analogy to the magnetic term $\partial\vec{B}/c\partial t$, Eqs. (1) are still not completely symmetric with respect to electricity and magnetism. They have only electric source terms — no magnetic source terms. This, of course, was quite reasonable, since there was no evidence whatsoever for magnetic sources.

I believe that Heaviside[2] was the first to publish (in 1893) a symmetrical set of Maxwell's equations:

$$\begin{aligned} \vec{\nabla}\cdot\vec{D} &= 4\pi\rho \qquad \vec{\nabla}\times\vec{H} - \frac{1}{c}\frac{\partial\vec{D}}{\partial t} = \frac{4\pi}{c}\vec{j} \\ \vec{\nabla}\cdot\vec{B} &= 4\pi\sigma \qquad -\vec{\nabla}\times\vec{E} - \frac{1}{c}\frac{\partial\vec{B}}{\partial t} = \frac{4\pi}{c}\vec{g} \end{aligned} \tag{4}$$

Here we see that the magnetic source terms which Heaviside introduced are $4\pi\sigma$ and $4\pi\vec{g}/c$. But if you read Heaviside's book, you will see that he didn't really believe there were physical magnetic sources. He called these terms "ficticious"; he had only included them as a convenient way to describe the "magnetification" of materials.

It is also interesting to note here that the minus sign in front of the $\vec{\nabla}\times\vec{E}$ term indicates that a left hand rule governs the fields associated with magnetic currents, in contrast to the right hand rule associated with electric currents. Thus one easily sees here the basis for the oft repeated statement that magnetic charges violate parity.

Dirac[3] in 1931 was the first to suggest that we should consider the possibility of a particle which would carry magnetic charge. In order to describe the "Coulomb" field from a magnetic charge g, situated at the origin of a coordinate system, Dirac proposed the vector potential

$$\vec{A} = \frac{g}{r}\frac{\vec{r}\times\hat{n}}{(r - \vec{r}\cdot\hat{n})}, \tag{5}$$

where $\hat{n}$ is an arbitrary unit vector. It is a good exercise for the student to show that using the standard formula, $\vec{B} = \vec{\nabla}\times\vec{A}$, Eq. (5) will indeed give the "Coulomb" field, $\vec{B} = g\vec{r}/r^3$.

But there is a problem here. Everyone knows that the divergence of a curl is identically zero. That is :

$$\vec{\nabla}\cdot\vec{B} = \vec{\nabla}\cdot(\vec{\nabla}\times\vec{A}) = 0. \tag{6}$$

Thus, there can be no magnetic charge in Maxwell's system of equations if we insist that $\vec{B} = \vec{\nabla}\times\vec{A}$. A related aspect of this difficulty is evident in a glance at Dirac's potential. The denominator of his expression for $\vec{A}$ equals zero for any $\vec{r}$ along $\hat{n}$. This zero in the denominator leads to a divergence in the magnetic field which has come to be known as Dirac's string — or simply a string.

Essentially what Dirac's formulation led to was the appearance of a Coulomb-like magnetic field, but one in which there is no actual magnetic charge. It is easy to show mathematically that in Dirac's formulation all of the flux which appears to terminate upon (or emanate from) a monopole really goes down along the string which is connected to the "charge." As a consequence, there is no magnetic charge as a source, and since there is no magnetic charge in this formulation, Maxwell's equations have not really been symmetrized.

In Fig. 1 we have an artist's conception of Dirac's monopole with its string attached. Here you see the magnetic Coulomb-like field of a north pole with the string going off to the right either to infinity or to a companion south pole. One can think of the string as very much resembling a tube of quantized flux in a superconductor. We shall see below that the minimum charge on a Dirac monopole is $g_o \cong 68.5e$, where e is the positron charge. Such a charge would be associated with a string containing two of the superconducting fluxons (of magnitude $\phi_0 = hc/2e$). In the context of QCD it is sometimes proposed that such strings connect the color charges of quarks. Another way to look at Dirac's monopole is that it is just the end of an infinitely long, infinitely thin solenoid. In the figure, the little rings along the string are just an artist's conception of some mechanism for

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holding the string together. If the string has zero radius, it would have an infinite amount of energy per unit length. This, of course, is an additional difficulty.

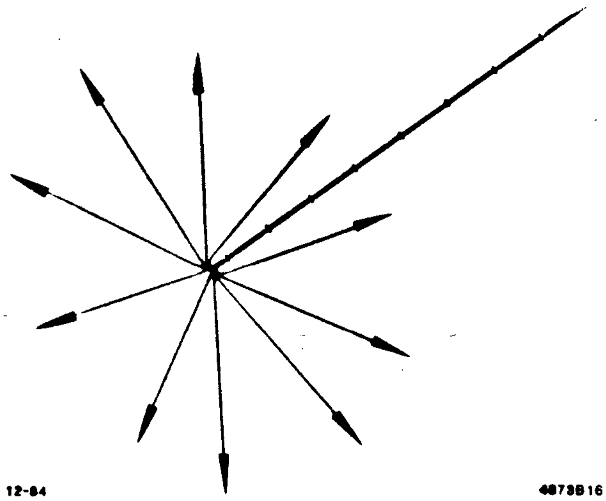

Fig. 1. Dirac monopole.

In order to make a more tractable theory, Dirac[4] introduced an additional term in the formulation of the field tensor, $F_{\mu\nu}$. That is, he modified the relationship between the fields and their potentials by writing

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu + 4\pi \Sigma_g \left(G^\dagger\right)_{\mu\nu}, \tag{7}$$

where the additional term accounts for the string variables. But this approach is not entirely satisfactory, even though it was asserted that the string should be unobserable. For example, in his quantum mechanical formulation Dirac had to veto any electron contact with the string. This notion of a veto is inconsistent with that of unobservability.

But in spite of these difficulties which one finds with Dirac's formulation, his 1931 paper is properly viewed as a major paper in theoretical physics; it initiated monopole physics. Furthermore, it introduced the extremely important idea that there is a definite relationship between electric and magnetic charges. He derived this relationship by using simultaneous gauge transformations of the electromagnetic field and the electron wavefunction. Assuming that the wavefunction of the electron must be single valued under these transformations in the presence of a magnetic charge g, Dirac obtained the relationship

$$eg/\hbar c = n/2, \tag{8}$$

where n is any integer. The smallest nonzero magnetic charge, then, occurs when $n = 1$.

Schwinger,[5] who much later invented the notion of a dyon, a particle carrying both electric and magnetic charge, derived a similar relationship:

$$\frac{e_1 g_2 - e_2 g_1}{\hbar c} = n, \tag{9}$$

where e_i and g_i are the electric and magnetic charges of the i^{th} dyon, and again n is an integer. Thus the minimum Schwinger monopole ($n = 1$) would have twice the magnetic charge of the minimum Dirac monopole (assuming in both cases that e is the charge of the positron). It is now generally believed, however that from the point of view of quantum mechanical gauge transformations the Dirac formulation is correct. To be consistent, then, Eq. (9) would have an $n/2$ on the right hand side.

These relationships tell us two very important things. First, the magnetic monopole is expected to carry a very large charge. Using the empirical fact that the fine structure constant $\alpha = e^2/\hbar c \cong 1/137$, one deduces that the (smallest) monopole has a charge equivalent to about 68.5 electrons. Thus the Dirac magnetic charge $g_o \cong 68.5e$. Second, and even more important—and this was pointed out by Dirac in 1931—the existence of a magnetic monopole of this magnitude could account for fact that elementary particles are observed to have charges which are quantized in units of e. Furthermore, the empirically observed value of e would now have a quantative explanation.

A more physical way to understand the Dirac quantization condition was suggested by Saha[6] in 1936. Saha's heuristic picture for the quantum relationship between electric and magnetic charge is depicted in Fig. 2. One first imagines that an electric charge e and a magnetic charge g are separated by a (vector) distance $\vec{d}$. Then one forms the Poynting vector

$$\vec{P} = c\vec{E} \times \vec{B}/4\pi. \tag{10}$$

$\vec{P}$, which carries electromagnetic momentum, can be seen to circulate around $\vec{d}$, as indicated in Fig. 2 by the large arrow. This leads to an angular momentum along $\vec{d}$. The integral of this angular momentum over all space has a magnitude equal to eg/c —independent of the length of d! Thus, Saha said all we have to do is think in terms of quantum mechanics and quantize this angular momentum in units of $\hbar/2$ and voilà, we have Dirac's relationship. If one believes that this angular momentum should be quantized in units of $\hbar$, one obtains the original Schwinger relationship.

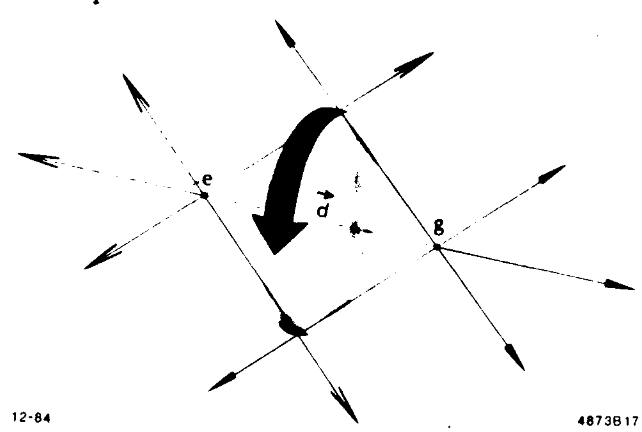

Fig. 2. Illustration of Saha's calculation. The full arrows represent the magnetic field from the (north) magnetic monopole g. The open arrows represent the electric field from the (positive) charge e. The heavy arrow indicates the direction of circulation (around $\vec{d}$) of the momentum carried by the Poynting vector.

You will recall that the original motivation for this analysis was the idea that Maxwell's equations should somehow be symmetrized—that E and H should play symmetrical roles, as would electric and magnetic charges. A manifestation of this symmetry is that the simultaneous substitutions

$$\begin{array}{ll} \vec{E} \rightarrow \vec{H} & \vec{H} \rightarrow -\vec{E} \\ \rho \rightarrow \sigma & \sigma \rightarrow -\rho \\ etc. & etc. \end{array} \tag{11}$$

will leave the symmetrized Maxwell's equations invariant. That is, if one replaces all electric quantities by their magnetic counterparts and all magnetic quantities by minus their electric counterparts, then one regains Maxwell's equations. Obviously a second application of these substitutions yields minus the original Maxwell's equations. This invariance has been called duality invariance.

Before exploring duality invariance further, for completness I would like to remark that there are other important invariance properties of Maxwell's equations which have been known for a long time. It was shown by Lorentz[7] in 1892 that Maxwell's equations are invariant under the six parameter group now known as the Lorentz group. The operators of this group generate the three possible rotations in three-space and the three possible Lorentz transformations in a four dimensional Minkowski space (3 space, 1 time). More generally, Maxwell's equations are also invariant under the operators of a ten parameter group called the Poincaré group. This group contains the six operators of the Lorentz group as a subgroup as well as arbitary displacements along the four coordinate axes of Minkowski space. And finally, it was shown[8] in 1910 that Maxwell's equations enjoy invariance under the operations of a 15 parameter group called the conformal group. This group contains the ten transformations of the Poincaré group as a subgroup as well as five more: four called the special conformal transformations plus one called the dilitation transformation, which just changes the scale of the coordinate system. It follows from dilitation invariance that equations which are invariant under the operations of the conformal group can contain nothing which represents a scale. Consequently, such equations can only describe massless particles. The photon, of course, is considered to be a massless particle.

Returning to duality invariance, it was pointed out in 1925 by Rainich[9] that this discrete "reflection" symmetry could actually be generalized to a symmetry of continuous rotation by an arbitrary angle Θ. Thus, in a plane in which the x-axis is the magnetic direction and the y-axis in the electric direction one can rotate all of the terms of the symmetrized Maxwell's equations by an arbitrary angle Θ. For example,

$$\begin{aligned} \vec{E}' &= \vec{E}\,\cos\Theta + \vec{H}\,\sin\Theta \\ \vec{H}' &= -\vec{E}\,\sin\Theta + \vec{H}\cos\Theta\,. \end{aligned} \tag{12}$$

When one then collects all the primed terms (which relate to the newly chosen magnetic and electric directions) one sees that one again has the set of symmetrized Maxwell's equations, just as before, but this time in terms of the primed quantities. So we can see that the distinction between electric and magnetic charge is merely one of definition. If it had been asserted the early days that the electron was magnetically charged, then my colleagues and I would presently be engaged in searches for objects carrying what we would then call electrical charge.

In considering duality invariance, Cabibbo and Ferrari[10] have shown that if one introduces a second four potential

$$M^{\mu} = (\psi, \vec{M}), \tag{13}$$

one can eliminate the Dirac string. This is done by modifying the relationship between the electromagnetic field tensor and the potentials. They write

$$F_{\mu\nu} = \partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu} + \epsilon_{\mu\nu\alpha\beta}\ \partial^{\alpha}M^{\beta}, \tag{14}$$

where $\epsilon_{\mu\nu\alpha\beta}$ is the totally antisymmetric tensor. Han and Biedenharn,[11] who continued the study of these ideas,[♯1] showed that Eq. (14) is equivalent to

$$\begin{aligned} \vec{E} &= -\vec{\nabla}\phi - \frac{\partial\vec{A}}{c\partial t} - \vec{\nabla}\times\vec{M}, and \\ \vec{B} &= -\vec{\nabla}\psi - \frac{\partial\vec{M}}{c\partial t} + \vec{\nabla}\times\vec{A}. \end{aligned} \tag{15}$$

One can easily see the "reflection" symmetry mentioned above is maintained by the substitutions

$$\begin{array}{ll} \phi \rightarrow \psi & \psi \rightarrow -\phi \\ \vec{A} \rightarrow \vec{M} & \vec{M} \rightarrow -\vec{A}. \end{array} \tag{16}$$

Using the two potential approach, it is easy to see why there are no strings attached to magnetic charges; magnetic charges and magnetic currents are associated with the vector potential M^{μ}, while electric charges and currents "generate" A^{μ}. With this dual system of potentials we have no problem with maintaining $\vec{\nabla}\cdot(\vec{\nabla}\times\vec{A}) = 0$ simultaneously with $\vec{\nabla}\cdot\vec{B} = 4\pi\sigma \neq 0$.

It is appropriate to mention, however, that the two potential approach of Cabibbo and Ferrari does entail some possible difficulties. For example, it has been shown[12] that except under very restrictive conditions there is no single Lagrangian from which one can derive Maxwell's equations and the equations of motion for massive particles.[♯2] This problem also extends into quantum electrodynamics (QED) because the Lagrangian and its associated Hamiltonian play a fundamental role in its formulation.

With this discussion as background material, I would like to describe to you another sort of monopole called a vorton.[13] This object is a semiclassical configuration of generalized electromagnetic charge and its associated electromagnetic fields, which satisfy the symmetrized Maxwell's equations. It is constructed to be invariant under a certain 0(4) = 0(3)×0(3) subgroup of the conformal group. 0(4) is the orthogonal group of rotations in four dimensions, and 0(3) is the orthogonal group of rotations in three dimensions. One of these 0(3) groups is just the group of rotations in three dimensional space. The other 0(3) describes toroidal rotations, akin to the vortex motion of a smoke ring.[♯3] Thus the vorton carries two different kinds of angular momentum — the usual kind, and a toroidal angular momentum.

An artist's conception of a section of a vorton is shown in Fig. 3. Here we see a doughnut-like object, which is simply one of the coordinate surfaces of a toroidal coordinate system.[15] There is no specific size predicted for this doughtnut-like object. One expects that vortons can come in any size, just as photons can come with any wavelength. These results are directly tied to the dilitation invariance of Maxwell's equations.

♯1 but called the invariance by the name "dyality invariance."

♯2 This result is perhaps not unreasonable, since massive particles break conformal invariance, while Maxwell's equations enjoy conformal invariance.

♯3 This kind of motion is called poloidal, and the moments associated with them, anapoles.[14]

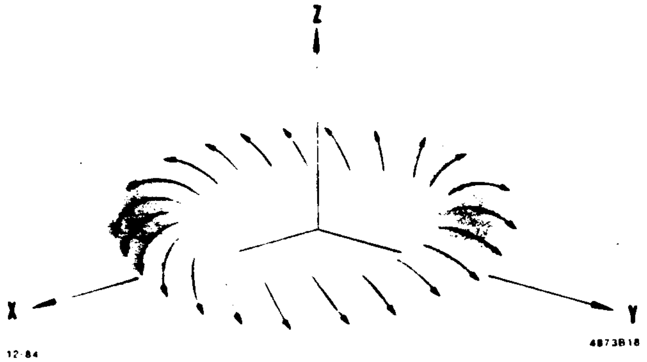

Fig. 3. Vorton.

The arrows in Fig. 3 indicate that the rotational motion is comprised of two components—one around the z-axis (along lines called parallels) and the other around the surface of the doughnut (along lines called meridians). One can apply the Bohr-Sommerfeld quantum condition to these angular momenta, (semi-classically) quantizing them in units of $\hbar$. Then, setting the energy of the configuration to a minimum, one obtains specific values for the magnitude of the electromagnetic charge Q of the vorton as a function of the angular momentum quantum numbers. For one unit of angular momentum in each rotation, the result is

$$\frac{Q^2}{\hbar c} = 2\pi\sqrt{\frac{3}{5}}, \tag{17}$$

which using $e^2/\hbar c \cong 1/137$ is equivalent to $Q \cong 25.83e$.

Since the symmetrical Maxwell's equations do not single out any specific direction in the electromagnetic plane, this charge Q can be electric, magnetic, or in fact, any combination of electric and magnetic, as long as the magnitude is $25.83e$. One obtains, then, a circle of radius $25.83e$ in the generalized electromagnetic charge plane, where the duality angle Θ is arbitrary, as shown in Fig. 4. As indicated, the intersections of this circle with the axes are where one would place electric or magnetic vortons. To set the scale of this circle, the locations of the electron and a (north) Dirac monopole are also shown.

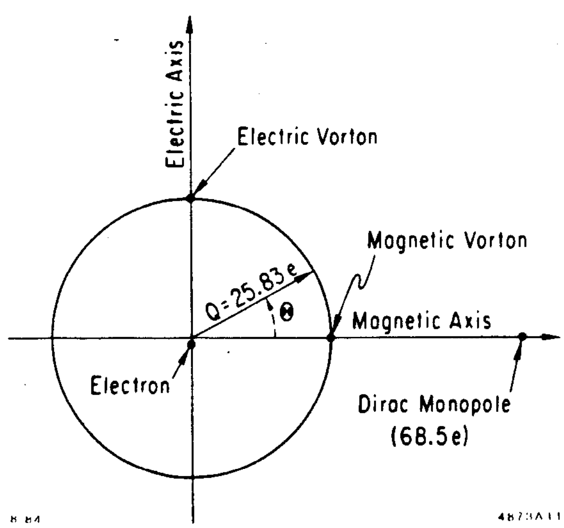

Fig. 4. Generalized electromagnetic charge plane with electric and magnetic vortons, a Dirac monopole, and electron indicated.

Vortons have another interesting feature. It turns out that as a result of the two rotations, the vorton carries what is called topological charge. Topological charge is a global property of a field. That is, it cannot be localised to any specific location, but rather is a function of the entire field distribution. A simple everyday analogy is a knot in a string. The knot isn't located at any particular point on the string, but rather its existence depends upon the configuration of the string as a whole. Another, perhaps better, analogy is the twist in a Möbius strip. Fig. 5 illustrates this idea. The strip labelled b has no twist and hence is equivalent to an object carrying a topological charge of zero. The strip labelled c is the usual Möbius strip with one half twist[‡4] to the left and hence can be thought of as having a topological charge of minus one. (I am tacitly assuming right hand twists are positive.) Strip d, then, with two (half) twists to the left, has a topological charge of minus 2. If one now looks at strip a, one sees that it also has two (half) twists, but in opposite directions. It is easy to convince yourself that like a rubber band, one can untwist this strip and obtain at a strip like that labelled b. That is, negative and positive topological charges can cancel each other.

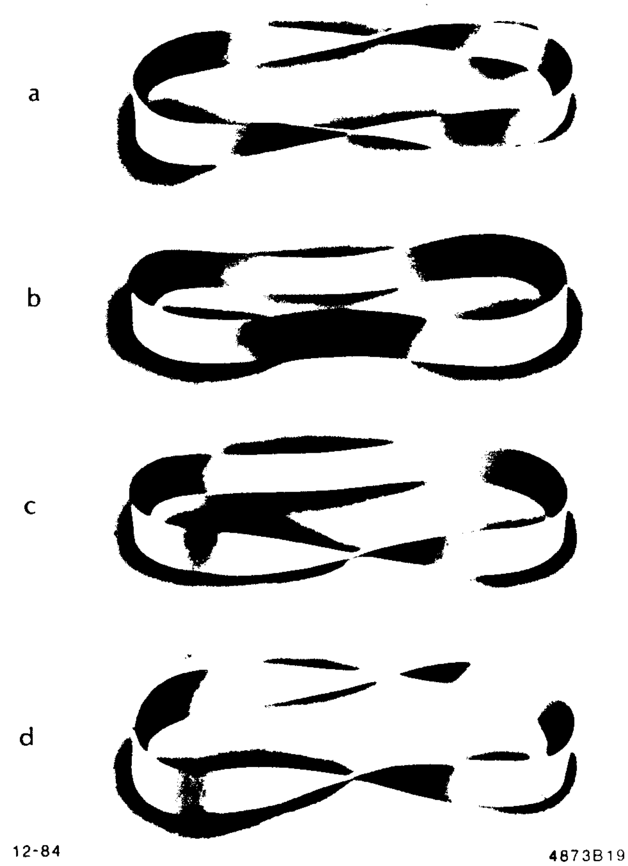

Fig. 5. Topological charge illustrated by Möbius strips.

Now it has been shown that topological charge is a conserved quantity.[16] Thus, one expects an object which carries topological charge to be stable, unless it should encounter another such object carrying an opposite topological charge. One concludes, then, that if vortons are more than a mathematical curosity, they would be stable.

‡4 Actually it would be more appropriate to use a full twist as equivalent to a unit of topological charge, but it is more convenient to depict half-twists in a slide.

In summarizing their features, vortons could come with any mass, but with a specific electromagnetic charge magnitude $Q = 25.83e$. If one considers the duality angle Θ to be a true degree of freedom, this Q could be anywhere on the circle shown in Fig. 4.

Let us now turn to the mainstream of present monopole efforts. These are based upon what are called non-Abelian gauge theories. These theories are extensions of electromagnetism, which is an Abelian gauge theory. I won't go into any details of gauge theories here, but for background, some of you may be interested in reading one of the many articles which have been published on the subject. For example, there is an excellent discussion of gauge theories by Gerard 't Hooft in Scientific American.[17]

It appears that particle interactions are amenable to a group theoretical description for which

$$SU(3) \times SU(2) \times U(1) \tag{18}$$

is the shorthand. SU(3) is the color group which governs quantum chromodynamics, the underlying theory of the strong interaction. SU(2) governs the weak interaction and U(1) quantum electrodynamics—that is, electromagnetism.

The idea is that these three groups are subgroups of some larger group, and that the interactions which they describe are merely different facets of one basic or fundamental interaction, which would be associated that larger group. (It is appropriate to point out that the correct designation of this larger group has not yet been made. It is fair to say, however, that there are numerous theoretical candidates.) It is in this way that a Grand Unification of the interactions would be achieved, and the theories which do this are called Grand Unified Theories or GUTs.

All of this is interesting for monopole hunters, because it turns out that these Grand Unified Theories have monopoles as solutions to the field equations—grand unified monopoles, or GUMs for short. In 1974 't Hooft[18] and Polyakov[19] independently showed that non-Abelian field equations had finite energy monopole solutions. These theories also avoid the Dirac string problem by elaborating the relationship between the field tensors and the potentials. In this case the relationship is

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + f_{abc} A^b_\mu A^c_\nu \tag{19}$$

where $a, b,$ and c are group indices, labelling the gauge fields—that is, the photon as well as all of the other fields which are described by the group—and f_{abc} are the structure constants of the group.

There is a good discussion of Grand Unification for the interested layman by Howard Georgi in Scientific American.[20] The theory he describes is an SU(5) theory, which breaks down into the subgroup product shown in Eq. (18). In this theory one expects monopole solutions which might look as shown in Fig. 6. As a core, this monopole has an X boson, which carries a force which can transmute quarks to leptons. The X boson is expected to be very massive. It's mass is estimated to be $\sim 10^{15} GeV/c^2$. Outside this core are virtual photons, gluons, weak interaction bosons, as well as quark-antiquark pairs. The monopole is depicted to be in layers (which are not to scale), where each layer extends out from the central core by an amount equal to the Compton wavelength of its major component. Thus, the radius of this monopole is on the order of the size of a nucleon even though the monopole itself is estimated to be even heavier than the X boson—10^{16} GeV/c^2, say.

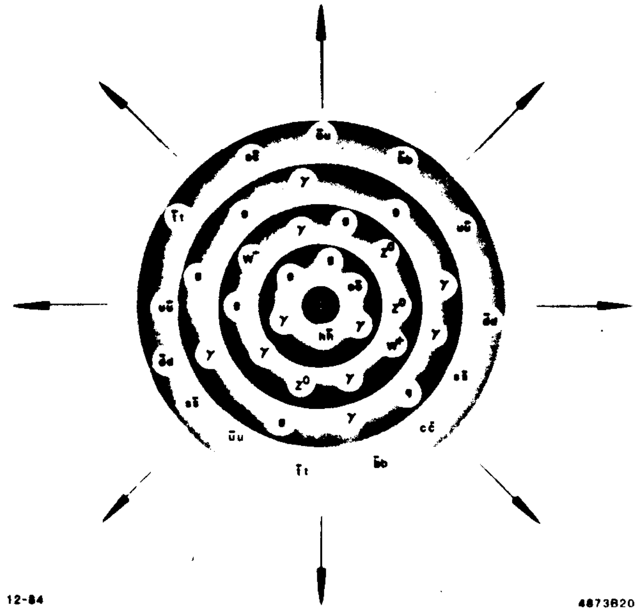

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Fig. 6. Schematic representation of a Grand Unified Monopole (GUM).

Outside the monopole is a standard Coulomb-like magnetic field. As one follows these magnetic lines of force from the outside back through the surface of the monopole and into the interior, one finds that through the extra term on the right had side of Eq. (19), the magnetic field begins to "twist" in group space, gradually taking on the qualities of the "magnetic" field associated with the other bosons. Again, there is no magnetic charge.

One would expect that instead of a Dirac string there would be these other magnetic-like fields coming back out from the monopole. But this does not, in fact, happen. Through a spontaneous symmetry breaking process the intermediate vector bosons of the weak force have acquired mass, and hence their associated fields are of limited range ($\lambda = \hbar/mc \sim 2 \times 10^{-16} cm$). In the case of QCD, the color forces are thought to be confined—though this has never been conclusively demonstrated mathematically. Thus the QCD magnetic lines cannot emanate from the monopole either, and one is left with an object which carries only the usual Coulomb-like magnetic field. It looks like a magnetic monopole from the outside, but inside there is no magnetic charge as such, just a twist or kink in the fields. And there are no strings attached.

The large mass of these GUMs results in behavior patterns which are qualitatively different from those of conventional particles, which have masses on the scale of a few GeV or less. For example, if a GUM is travelling at a small fraction of the velocity of light, it carries an enormous amount of energy and momentum. Consequently, GUMs are very penetrating; a monopole travelling with a velocity v such that $\beta = v/c = 10^{-3}$ or even 10^{-4} can penetrate the entire earth. This penetration, of course, is aided by the fact that at low velocities, the energy loss per centimeter is very much reduced. Another feature is that at the surface of the earth non-magnetic binding forces of GUMs to ordinary atoms will be overcome by the graviational force. Thus, monopoles at rest would not be expected to remain at rest, but

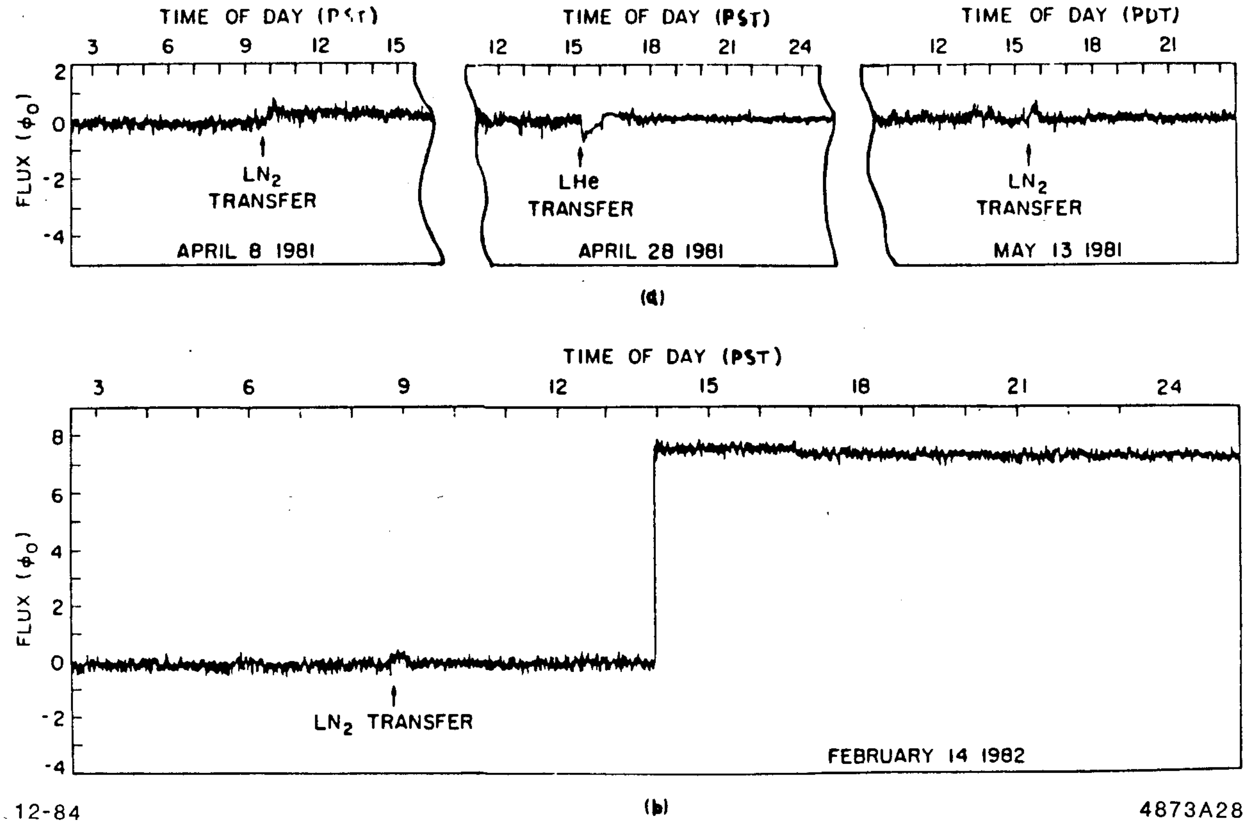


Fig. 7 The Stanford monopole candidate event. This figure is taken from the Stanford preprint that was subsequently published as Ref. 24.

would fall toward the center of the earth. It does turn out, however, that the magnetic binding forces between a monopole and an atom or molecule with a large magnetic moment[21] such as magnetite iron ore, are strong enough to resist the gravitational force. Thus one anticipates that over the millennia GUMs may have become trapped in such materials. These rather novel aspects of anticipated monopole behavior have lead to novel experiments, at least by past standards, to detect them.

The question is now, "Where are we with respect to the discovery of monopoles?" We know that in 1886 Hertz demonstrated the physical existence of radio waves, about 20 years after Maxwell wrote down his equations which predicted electromagnetic waves. On the other hand, now in 1984, it is over 50 years since Dirac predicted magnetic monopoles.

After Dirac's seminal paper, there followed a few monopole search experiments over the next several decades, but they all gave negative results. While this is an interesting history, I won't have time to cover it here. For those wish to pursue it, a good discussion of the history of monopole theory and experiment has been published by Amaldi.[22]

I will pick up the story in 1981 when Blas Cabrera at Stanford University realized that if there were a low velocity component of GUMs in cosmic rays, that it would be quite conceivable, even probable, that for various reasons searchers up until that time would not have detected them. But more important, he realized that he had at his disposal all of the apparatus, already built, with which he could detect these cosmic GUMs. He had a four turn flip coil of 20 cm^2 area (which was designed to measure the magnetic field in a magnetically shielded dewar), a SQUID and a chart recorder.

Detection of the monopoles would take place using the induction principle.[23] This principle derives from a straight-forward application of Maxwell's equations. Each time a GUM passes through a superconducting loop,[‡5] there would be a small jump in the current flowing in that loop. This jump would be equivalent to that which would be caused by a flux change of two fluxons threading the coil. To set up his experiment all Cabrera had to do was use his SQUID to monitor the current in the coil and feed its output to the recorder.

On February 14, 1982 he was rewarded with the spectacular data shown in Fig. 7. At about 2 PM the current in the coil jumped by almost exactly the amount one would expect as a result of an object carrying one Dirac monopole ($2\phi_0$) going through the four turn coil. From the chart recorder trace, one can easily see that system noise is very low and is not a problem. From the three inserts in Fig. 7 one can conclude that normal routines such as transfer of liquid nitrogen or liquid helium would not lead to such an event. Cabrera also tried various mechanical perturbations but was not able to generate any spurious events of comparable magnitude. News of this event spread quickly. So much interest and spectulation was generated that Cabrera decided to publish[24] all he knew about it. Since he was not yet convinced that it was not some sort of background that he couldn't think of or that he couldn't produce upon command, he made no claims of discovery, but only labelled the event a monopole candidate. As a possible background, he used this candidate event to set an upper limit on the cosmic ray GUM flux of $6.1 \times 10^{-10} cm^{-2} s^{-1} sr^{-1}$.

‡5 Actually superconductivity is not an essential feature of the induction principle, but it makes the technique practical.

Figure 8 shows us what this event did to the interest in monopole physics. In left hand histogram the ordinate, labelled "Interest," is the total number of papers in a given year that have the word "monopole" or "dyon" in the title. Prior to 1973, there were only a few papers on monopoles, and in many years there were no papers at all. Since that time the interest in monopoles has grown enormously. There are now on the order of 200 papers per year being published on various aspects of monopole physics. While the present interest in the theory of monopoles was initiated by the monopole solutions found by 't Hooft and Polyakov, by now monopoles are seen to have important implications in many other disciplines, such as astrophysics and cosmology. It is clear, then, that the discovery of a monopole would be extremely important and would have far-reaching consequences, indeed.

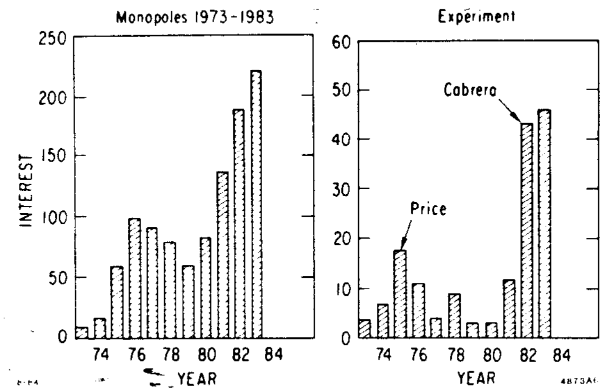


Fig. 8. This figure, which histograms the number of published monopole papers, is an updated version of one compiled by J. Preskill.[25] The data comes from the SPIRES data base at SLAC, and I wish to thank R. Gex for assistance in its preparation.

The right hand histogram is the subset of the total number of papers (given in the left hand histogram) that one would call "experimental." That is, they either propose an experiment, describe a specific experiment, or discuss some aspect of monopole experiments, such as energy loss. One sees here the peaks engendered by the Price announcement[26] of the discovery of a monopole in a cosmic ray experiment using a track-etch technique, now retracted,[27] and the 1982 Cabrera monopole candidate event obtained using the induction technique. Today there are many different techniques being used to search for monopoles, and even if no events at all are found in the next several years, I expect the interest level will contunue to remain high.

Of these various experimental techniques, I would like to start with a brief description of the induction technique. It is such an elegant application of the phenomenon of superconductivity, and as such is an appropriate topic for this conference. The principle follows directly from the symmetrised Maxwell's equations, that is, from the equation involving $\vec{\nabla} \times \vec{E}$ and the magnetic current $\vec{g}$.

A physical representation of the theory is given in Fig. 9. In the upper picture we see a north magnetic pole approaching a superconducting loop. The motion of the pole, of course, means that there is a magnetic current flowing from left to the right. As the pole gets closer to the loop, we see, as a result of the Meissner effect, the flux lines deforming to avoid the loop. After the pole has passed through the loop, we see that some flux lines are left linking the loop, and as a consequence there is an associated electric current flowing in the loop. The sense of this current is indicated by the usual arrow head and tail symbols. As advertised, we see that the sense of this electric current in relation to the generating magnetic current is given by a left hand rule. Finally, in the bottom picture we see the monopole moving away from the loop. The loop remains with a residual current flowing in it to maintain the increment of additional flux now linking it. The flux from the monopole itself no longer threads the loop; it has broken away by a process depicted in the insert. The current increment ΔI is given by

$$\Delta I = 4\pi n g/L, \tag{20}$$

where n is the number of turns in the detection coil, g is the monopole charge, and L is the inductance of the coil and its associated detection circuitry.

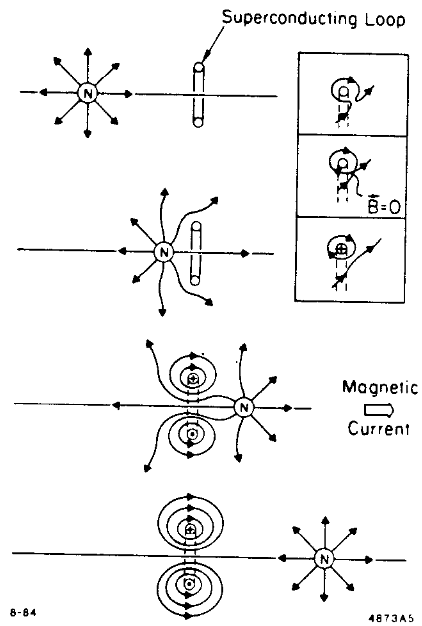


Fig. 9. Principle of induction technique, after Cabrera.[28]

Figure 10 is a schematic depiction of a typical induction experiment. Inside a superconducting shield the detection coil is shown feeding a SQUID, also inside a superconducting shield. These two components must be well shielded in order to avoid spurious signals or large noise backgrounds due to fluctuations in the ambient magnetic field. To give you an idea of the care that experimenters will take, the shielding in the initial Stanford experiment provided 180 db of isolation from external magnetic field changes, and the field at the detector coil was about 50 nanogauss. You will recall that the earth's magnetic field is about half a gauss.

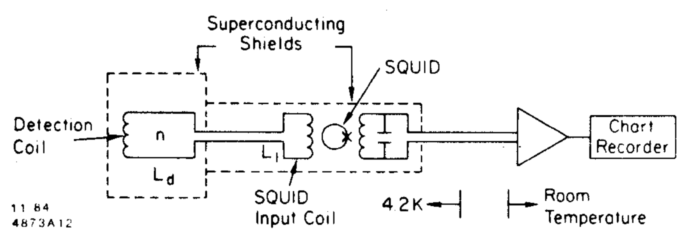


Fig. 10. Schematic of a typical induction detector.

The SQUID, which stands for Superconducting QUantum Interference Device, is the key component of the induction detector. As most of you know, it is a most elegant application in the macroscopic domain of the quantum mechanics of superconductivity. And since SQUIDs are extremely sensitive devices, they are perfectly adapted to the challenge of directly detecting an individual elementary particle. But it would be presumptuous of me to tell this group how a SQUID operates, so I shall refrain. For those of you who would like to know about recent developments in SQUID technology, I see from the conference program that there will be several sessions on SQUIDs and their applications. And, in fact, some of the papers will be discussing SQUIDs in conjunction with monopole detectors.

When an induction experiment is properly set up, one only has to look at the recorder output once a day, say, and make sure that the liquid nitrogen and helium levels are adequate. Liquid transfers can be automatic, or made manually as required. Typically, for experiments now in progress, on the chart recorder there are also records of magnetic fields, mechanical vibrations, line voltages, etc. These are referred to as "counter insurgency" measures. For example, the accelerometers are sensitive enough to detect the slamming of laboratory doors. If an event should occur, the first thing the experimenter would do would be to check the traces of all of the counter insurgency records to see if the event could be associated with some kind of background disturbance.

Figure 11 depicts the configuration of the Stanford group's present detection apparatus. This apparatus has been operating since January 1983. The major improvement in this experiment over their initial one is the use of three orthogonal detection loops, complete with a calibration coil. They periodically pulse the calibration coil to assure themselves that the detection loops are functioning and the amplifiers are set to the proper gain. The present arrangement has an effective sensing area of 476 cm^2 (averaged over 4π steradians) for double coincidence events. The direct detection area for a monopole passing through two (or three) of the loops, which will give a coincidence signal, is 71 cm^2. It turns out that if a monopole passes near the loops but does not go through any of them, one stills expects an induced signal, though considerably smaller than the direct signal. This leads to a near miss signature which is still adaquately above background, contributing another 405 cm^2 of effective detector area.

In November of last year, they published[29] a description of this detector and the results of about four months of data taking. The results were negative and gave an upper limit of $3.7 \times 10^{-11}\ cm^{-2} sec^{-1} sr^{-1}$ (with a 90% confidence level) for monopoles of any mass at any velocity passing through the earth's surface. This result lowered their previous flux limit[24] by a factor of 38. This number includes the near miss detection area. But since there are no events, one does not need to become embroiled in questions about the validity of any near miss events. There aren't any events to argue about.

By now they have added in excess of another year to this data sample and still have not seen any events. Thus, they have reduced the upper limit yet further —by more than a factor of 150 below the rate implied by the initial event candidate.

In order to set yet lower rate limits using the induction technique, one must make larger loops and put them in larger dewars. But these larger loops have more area and consequently are more sensitive to fluctuations in the background fields. This problem is compounded because larger loops tend to have larger inductance and hence by Eq. (20) will yield smaller signals.

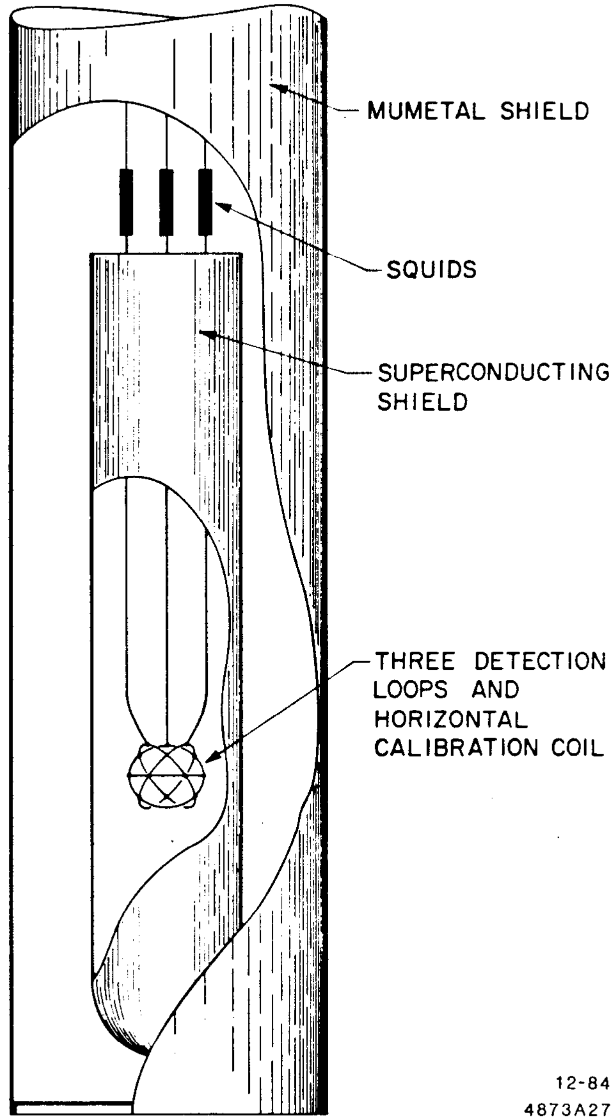


Fig. 11. Present Stanford monopole detector apparatus.[29]

One technique to ameleorate the problem of greater vulnerability of large coils to noise, which was suggested by Claudia Tesche and her collaborators at IBM,[31] is called a high-order gradiometer. The idea of a high-order gradiometer is to wind the detection loop in such a way that the sense of the coupling to a uniform magnetic field alternates over the surface area of the loop. The more alternations there are, the higher the order of the gradiometer. Through careful construction one can use this idea to cancel out not only the uniform field coupling, but also as many of the higher order terms in the Fourier expansion of a more general field as one wishes.

This idea is demonstrated in Fig. 12. One starts with a single (square) loop, as shown at the upper left hand corner, labelled *a*. The plus sign indicates the sense of the coupling. One can then combine this loop with one of equal area, but of opposite sense as shown in Fig. 12*b*. It is clear that there is no coupling of this (composite) loop to a uniform field. One can then replicate the loop again, to achieve additional cancellation, as shown in Fig. 12*c*. In Fig. 12*d* this step is carried one step further in both the x and y directions. At this point, one sees that if one is clever, some of the wires can be eliminated, because certain of the adjacent areas have the same coupling sense. Carrying this step out yields the configuration shown in Fig. 12*e*. This last step is useful because it not only simplifies the loop construction but also reduces the loop inductance, increasing the expected signal level.

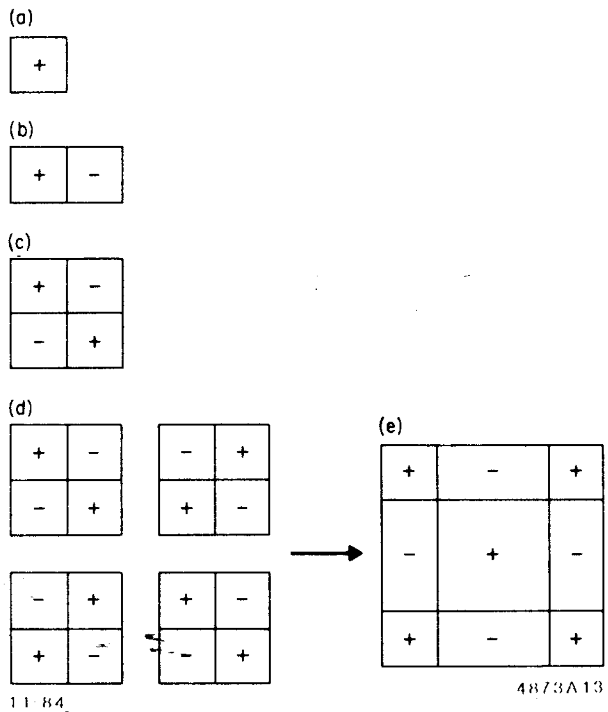


Fig. 12. Representation of gradiometer principle, after Ref. 31.

A similar idea has been independently suggested by Henry Frisch and his collaborators at the University of Chicago, Fermilab, and Michigan.[32] Their variation, which they call macramé, is illustrated in Fig. 13. Again the full loop area is subdivided into smaller areas or cells with opposite coupling senses; the word macramé was chosen because the wiring was originally strung by hand on a 1.6 *mm* circuit board. The solid lines represent wires on the front side of the board, the dashed lines, wires behind. The arrows indicate the sense of the current flow through the wires.

Subdividing the loop area, as illustrated in Figs. 12 and 13, also has the advantage that the total loop area can be made larger with respect to the cross section of any given dewar. When a monopole penetrates the superconducting shield it will leave trapped fluxons, which will tend to cancel out the signal directly induced by the monopole in the detector loop. The decoupling distance between an ordinary loop and the fluxous trapped in the superconducting shield goes like the loop diameter, while the decoupling distance for a subdivided loop goes like the cell size. Conseqeuently, for given a dewar size, gradiometer coils can be made larger, and hence more sensitive, than simple coils.

There is another very simple way to improve the performance large induction detectors; it is called a series-parallel gradiometer,[33] and is sketched in Fig. 14. In Fig. 14*a* one sees two loops in parallel with a common diagonal, in which one connects the SQUID input as shown. It is a gradiometer because the coupling these two loops to a uniform field is of opposite sense. In Fig. 14*b* one sees how the diagonal can be rerouted to give a higher order gradiometer. With this scheme, as one goes to larger loops the signal falls as $1\sqrt{L}$ rather than 1/L, where L is the inductance of the loop. This approach also enables one to improve the impendance match between the detector loop and the SQUID, eliminating the need for a matching transformer.

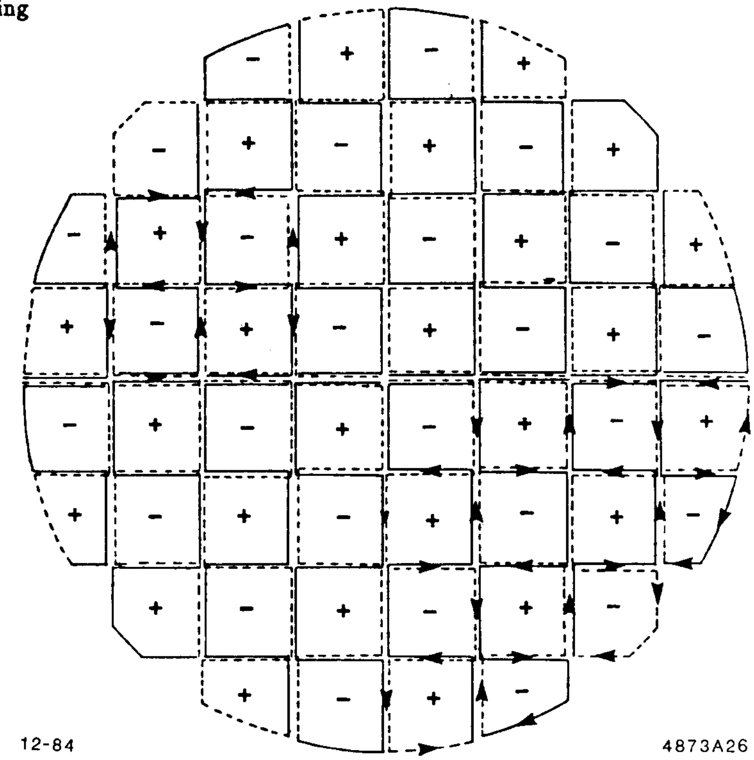
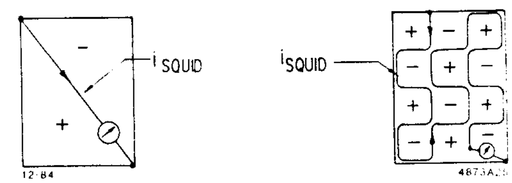


Fig. 13. Macramé gradiometer pattern, taken from Ref. 32.



(a) Two Loops in Parallel (b) Distributed Parallel Gradiometer

Fig. 14. Distributed series-parallel gradiometer, taken from Ref. 33.

With this rather short summary of the induction technique used for monopole detection, I would now like to show you some of the operating and projected induction experiments. Two of these have data samples roughly comparable in magnitude to that of the second generation Stanford detector shown in Fig. 11.

Figure 15 depicts a monopole detector constructed by the IBM group. It has planar gradiometer detectors on the six sides of a rectangular parallelepiped as shown, and a valid monopole signal requires a coincidence between any two of these planes. Its area of 10^3 cm^2 makes it about twice the (effective) size of the present Stanford device shown in Fig. 11. The IBM group started data taking with this device on October 3, 1983, somewhat later than the Stanford detector, and has run essentially continuously without any monopole signal. Since they have seen no events, the present data of this experiment itself reduces the limit by a factor of about 200 times below that implied by the original event candidate.

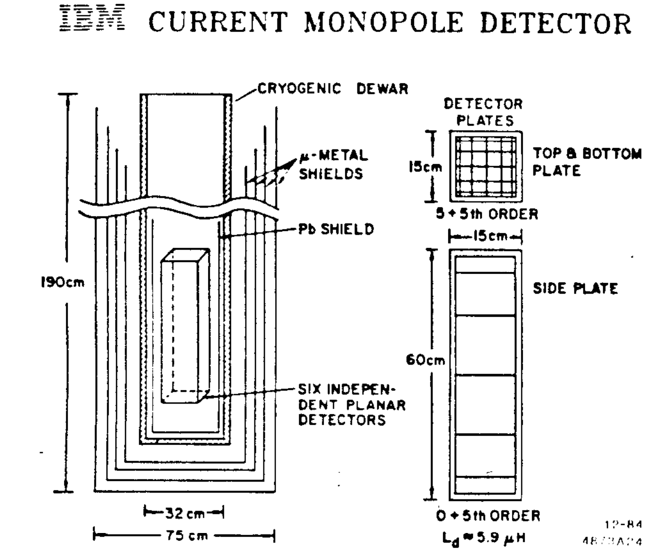


Fig. 15. Current IBM monopole detector, furnished by P. Chaudhari.

The other major contribution to the reduction of the present cosmic GUM flux limit by the induction technique comes from a device being operated by the Chicago-Fermilab-Michigan collaboration. Details of this detector were reported[32] at the Monopole '83 Conference at Ann Arbor.[‡6] The detector consists of two 60 *cm* diameter loops of the macramé design. The effective area of these loops taken together is 2100 cm^2, about twice that of the present IBM device. The ambient field at the detector coil in this device is in the range of 1 to 10 milligauss. This means that when one constructs larger detectors, such heroic shielding efforts, such as implemented in the first Stanford experiment, will not be required.[‡7]

The collaboration started taking data on August 29, 1983, and have been operating the detector for over a year now. Since they have seen no monopole events, this accumulated area-time product is also about 200 times the original Stanford sample. Together these three induction experiments reduce the cosmic GUM flux limit by an estimated factor of about 500, or almost to $10^{-12}\ cm^{-2}s^{-1}sr^{-1}$.

This implies strongly, but not conclusively, that the original Stanford monopole candidate was some kind of background. Consequently, the motivation for more sensitive experiments tends to become decoupled from that original Stanford event and focusses on a much smaller flux, the so-called Parker limit,[35] which is $\sim 10^{-15}\ cm^{-2}s^{-1}sr^{-1}$.

The Parker limit is derived from the fact that the galactic magnetic field is observed to have a mean strength in the neighborhood 3 to 5 microgauss.[36] The existence of such a field is incompatible with a magnetic monopole flux in excess of the Parker limit. The reason is simply that if there are too many monopoles moving through this galactic field, they will extract enough energy from the magnetic field to "quench" it. This limit, which turns out to be a function of monopole mass, is plotted in Fig. 16. Should monopoles turn out to be heavier than about 10^{17} GeV/c^2 their mass reduces this quenching effect and the upper limit increases. If monopoles should be heavier than the Planck mass, the flux limit is determined by the maximum amount of mass which monopoles could contribute to the mass of the galaxy and to the universe. In this range, if monopoles are assumed to be heavier, fewer of them are permitted, and the limit becomes smaller as the assumed monopole mass increases.

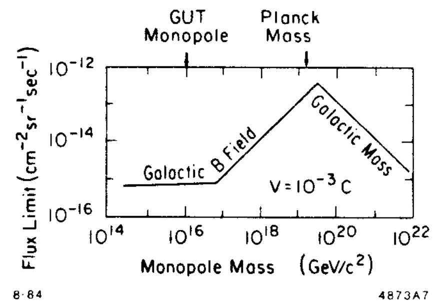


Fig. 16. Parker limit on cosmic ray GUM flux as a function of monopole mass. The information in this figure is extracted from Ref. 37. The estimated GUT mass of 10^{16} GeV/c^2 and the Planck mass of 1.22×10^{19} GeV/c^2, $(\hbar c/G)^{\frac{1}{2}}$, where G is Newton's gravitational constant, are also indicated. The velocity $v = 10^{-3}c$ is typical of what one might expect for cosmic monopoles. The shape of the curve will vary somewhat with velocity.

For completeness, I should mention that there are other astrophysical limits[38] on the possible monopole flux, some of which are considerably smaller than the Parker limit. But since the derivation of these limits usually entails additional assumptions and are consequently less secure, I will not cover them here.

With the thought of approaching the Parker limit, the IBM group has formed a collaboration with Brookhaven National Laboratory and is presently building a larger detector as shown in Fig. 17. It is essentially a scaled-up version of the present IBM device but with an effective coincident detection area of 3.6 m^2. They hope to start looking for monopoles with this device in 1985. If it operates successfully, they would view it as a

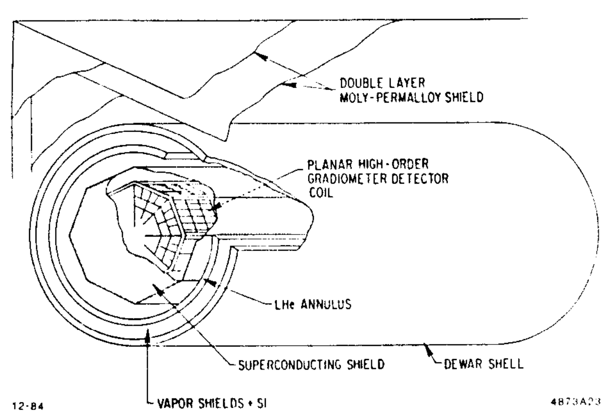


Fig. 17. Schematic of a prototype of future IBM monopole detector, furnished by P. Chaudhari.

‡6 This report is also an excellent reference for many of the other experimental efforts which are not covered here.

‡7 An NBS group at Boulder has successfully operated somewhat smaller induction detector in an ambient field of 3 milligauss.[34]

prototype for a proposed detector farm comprised of perhaps as many as 20 such units. Such a group of detectors could reach the Parker limit in a couple of years of operation.

Figure 18 schematically depicts the detector which the Stanford group is presently constructing.[39] The detector apparatus will be placed in a dewar measuring 3 feet in diameter by 22 feet long, having a 4.2°K cryogenic compartment 20 inches in diameter by 20 feet long. These dimension are dictated by the fact that the dewar already exists; it was used to house a prototype gravitational wave antenna. Using a secondhand dewar has at least two advantages. It saves some money, and it enables the group to get on the air sooner. As shown, they presently plan to use an eight sided array of series-parallel gradiometer panels, each feeding its own SQUID. A two-fold coincidence signal will be used. The large length to diameter ratio of their geometry permits them to leave off end panels without significant loss in effective area. The effective sensing area of this proposed detector, averaged over 4π steradians, is 1.5 m^2. They plan to be on the air in early 1985.

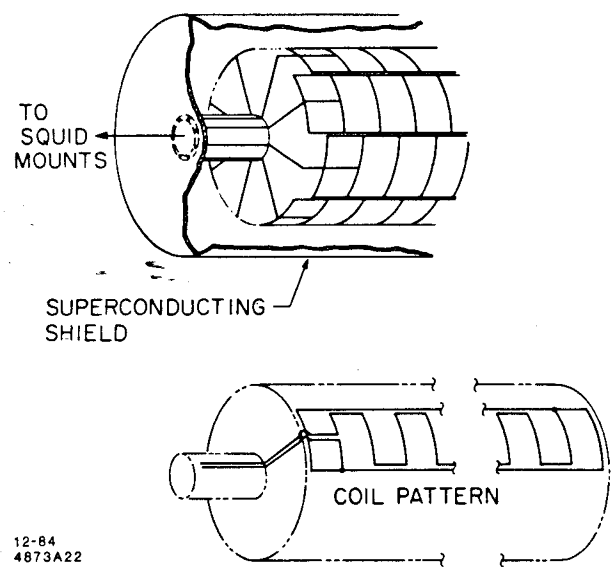


Fig. 18. Future Stanford monopole detector, furnished by M. Taber.

There is a very interesting series of induction experiments being carried out by a group at Kobe University in Japan.[40] Schematics of their first two detectors are given in Fig. 19. Kobe I is a three turn superconducting coil of 8 cm diameter, and Kobe II is a 2 turn coil of 14 cm diameter. These detector coils were placed below ovens which contained charges of old iron ore, magnetic sand, and maghemite. These charges were then heated to above their Curie temperatures, the point at which they lose their natural magnetism. The idea is that if there should be any monopoles trapped in these materials, they will become unbound at the Curie temperature. The monopoles, responding to the earth's gravitational force, will then fall toward the center of the earth, passing through the detection coils. Kobe I has examined 428.4 kg of material and Kobe II, 514.5 kg. Taken together, these two experiments set an experimental[#8] limit of almost 10^{-6} monopoles/g.

#8 These experiments have run a total of 1010 + 795 = 1785 hours. Consequently, they also serve to set a limit on the cosmic ray GUM flux, but it is much smaller than the already discussed.

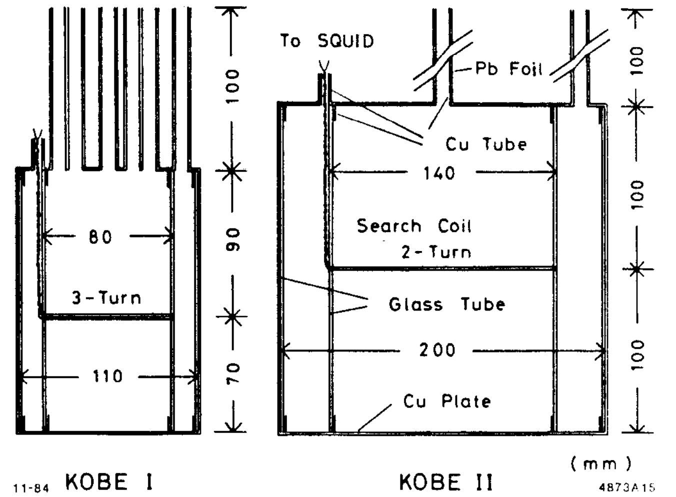


Fig. 19. Schematic depictions of the KOBE I, and KOBE II detectors, furnished by T. Watanabe.

The Kobe group is now planning along these lines a much larger experiment in conjunction with Kobe Steel Ltd. They plan to place two 21 cm diameter, 2 turn coils below the conveyor of a sintering furnance.[#9] In this way they can examine iron ore for monopoles at a rate of about 50 tons/month. They hope to have this apparatus operating by the summer of 1985.

I would now like to take a few moments to tell you about a monopole search experiment that Steve St. Lorant and I are working on at SLAC. It is a low budget experiment featuring a used superconducting magnet obtained from Argonne National Laboratory. A schematic of the experimental arrangment is shown in Fig. 20. The magnet is about 2 m long has a 7 cm warm bore, and a central field of 50 kilogauss. The idea is that this magnetic field can accelerate monopoles from a source into an electron multiplier tube (EMT), which is used as a detector. In the present configuration we are using a tungsten filament as a source. Small samples can be placed on this filament and heated, "boiling off" the monopoles. They will then be accelerated by the solenoidal field and detected by the EMT. To eliminate any multiple scattering or energy loss, the source is in a common vacuum system with the EMT; the vacuum is better than 10^{-6} torr, which corresponds to a mean free path of ≥ 50 m.

It is amusing to calculate the capability of this apparatus as a monopole accelerator. The kinetic energy KE (in electron volts) picked up by a monopole of strength g in travelling a distance $\ell(cm)$ along a magnetic field B (gauss) is given by

$$KE = 300B\ell g/e, \tag{21}$$

where the factor 300 is used to convert statvolts to volts. Eq. (21) tells us that for Dirac monopoles we have a 200 GeV accelerator — not bad, considering its size in comparison to more conventional accelerators.

But more to the point, we can use Eq. (21) and the fact that the EMT can detect ions carrying (even less than) 1 keV to ascertain the capability of this apparatus as a monopole detector. The region of sensitivity of our apparatus in terms of monopole charge and monopole mass is indicated by the shaded part of Fig. 21. For light objects, the limiting factor for detectability

#9 A similar experiment has been proposed by a Wisconsin group.[41]

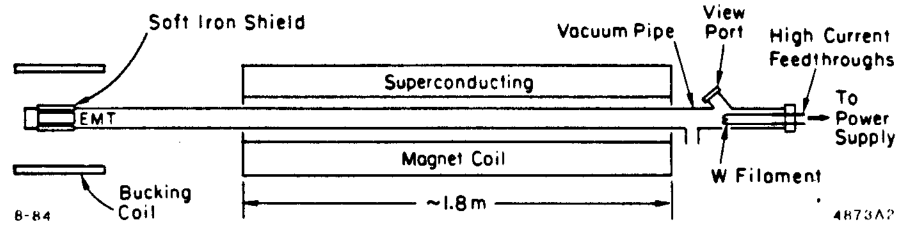


Fig. 20. SLAC monopole accelerator and detector.

is kinetic energy, and we have arbitrarily taken this limit to be 4 keV, well above the energy of detectable ions from the tungsten filament. (Actually, electrons of only 200 *eV* are detectable; they yield about two secondary electrons.) For objects heavier than a tungsten ion ($\sim$170 GeV/c^2), we assume that to be detectable they must have a velocity at least equal to that of a 4 keV tungsten ion ($\beta \simeq 2 \times 10^{-4}$).

Unfortunately, we see from Fig. 21 that this apparatus cannot detect a GUM; even with an energy of 200 *GeV*, it would have a $\beta \sim 2\times10^{-7}$, much too low for detectability. Actually, we don't consider this to be a serious problem; we believe that there are already enough people looking for GUMs. Rather, we view our experiment as adding diversity to the search for monopoles. The experimental regions that this detector is uniquely capable of exploring is the region of very small magnetic charge. One sees that this apparatus can detect monopoles with charge almost as small as $10^{-8} g_0$.

This is virgin territory[‡10] and as such is the experimental motivation for this effort. However, we note that there are also some theoretical proposals which fall within the shaded region of Fig. 21. One is the electro-weak monopole, shown with a unit Dirac charge and a mass of about 10^5 GeV/c^2. Such an object might be expected in an SO(3) theory, such as that explored by 't Hooft.[18] Another possibility is a vorton atom.

One arrives at the notion of a vorton atom by the following line of reasoning. If the angle Θ is a true degree of freedom, then one could suppose that a vorton would seek a potential minimum by becoming electrically positive and binding electrons to it. This minimum is at $\Theta = \pi/2$, for which the vorton charge will be $+25.83e$. In such a situation, one expects it to bind 26 electrons, making a quasi-iron atom. But if Θ is a true degree of freedom, then it should have associated with it $\frac{1}{2}$ kT, where k is Boltzman's constant and T is temperature. It is shown in Appendix A that one expects such an atom to have an rms magnetic charge equivalent to $\sim 10^{-2}e$, well below the range of sensitivity of prior monopole searches.[‡11]

In fact, the best experimental limit to the abundance of such atoms is given by quark searches in bulk matter. Such searches would give a signal because a vorton atom cannot be electrically neutral; the quasi-iron vorton atom would have a charge of $-0.17e$. If one wishes to avoid questions of what various refining processes might do these atoms, one should focus primarily on searches in unrefined natural materials. The best published search that I know of in this category, which addresses the question of quark charges at the $\pm e/6$ level, yields for objects carrying a charge of either $5e/6$ or $-e/6$ a limit (with a 95% confidence level) of no more than 8 (and consistent with sero) in 85 μg of native mercury.[44]

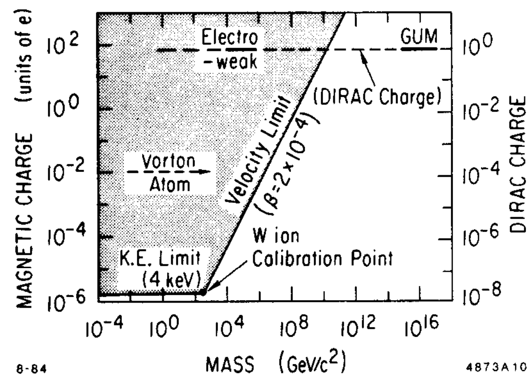


Fig. 21. Plot showing the region of sensitivity of SLAC monopole detector, with monopole magnetic charge and monopole mass as the coordinates. The tungsten ion calibration point, which gives the limits of detectability, is indicated.

As one might surmise, in our experiment it turns out that the size of the (natural) sample which one heats with the filament is severely limited by outgassing and the loss of a good vacuum. Consequently, our present efforts consist of trying to devise ways to concentrate monopoles from natural materials onto our tungsten filament. So far we have seen no monopoles.

A very simple and inexpensive method that has general application for detecting monopoles is the track-etch technique, which was pioneered by P.B. Price and his associates. This technique has been used in experiments to search for monopoles in natural materials, accelerator experiments, and cosmic rays. The detection technique depends upon the radiation damage that is done when a highly ionising particle, either electrically or magnetically charged, passes through certain materials.

The principle of the experimental process shown in Fig. 22. In Fig. 22*a*, a particle of (electrical) of charge Z and initial β_i is shown entering the detector material. Above a certain threshold, ionization damage for electrically charged particles is a function of Z/β_i; for magnetically charged particles, (to first order) there isn't any velocity dependence. The little wiggly lines along the (dotted) track denote radiation damage along the track. This track damage can remain dormant in the material over extended periods of time—even many thousands of years. It has been found that the chemical etch rate of certain materials is increased in the region of radiation damage.

‡10 This fact was noted some years ago by Usachev,[42] who at the same time pointed out that all of the derivations of the Dirac quantization condition [*i.e.*, Eqs. (8) or (9)] had flaws and should not be fully trusted.

‡11 The most extensive monopole searches in bulk matter have been done at Berkeley.[43] They have examined about 50 kg of various materials with a sensitivity ranging to as low as 0.03 g_0, which is equivalent to a lower limit of $\sim 2e$. These searches would, of course, have detected magnetic vortons with $\Theta = 0$ or π, but would not be able to see vorton atoms carrying $g \sim 10^{-2}e$.

The detection material is "developed," much as a photographic negative is developed. Plastics such as Lexan and CR-39 are examples of detection materials; for these, sodium hydroxide is the chemical that is used as the etching solution. As shown in Fig. 22*b*, when the material is put into an etching solution, some of the material dissolves. At the same time, due to the increased etch rate, pits are formed along the track. If the sheets are left in the etching solution long enough, then holes will be etched through the sheets, as shown in Fig. 22*c*. The minimum detectable charge, which will result in such a hole, depends upon the strength of the solution, the etching temperature, and the duration of the etch. It is an easy matter to scan large areas for such holes.

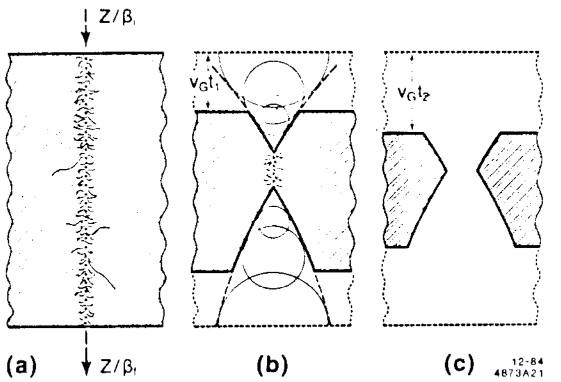


Fig. 22. Illustration of charged particle detection by the track-etch technique, furnished by P. B. Price.

Track-etch experiments are very suitable for use in an accelerator environment because they are essentially insensitive to minimum ionizing particles. Thus, sheets of plastic can be wrapped around a possible monopole source, such as the interaction point of a storage ring, and left for extended periods of time —even as much as a year or more. They can then be removed, etched, and scanned for tracks.

The limits set by several track-etch experiments, as well as some other accelerator experiments[‡12] are given in Fig. 23. Except for the SPSC experiment,[45] these limits reach well below the QED point cross section and the weak interaction cross section. Therefore, to search further in the mass range accessible to present accelerators would have to be motivated by thoughts of some more exotic production mechanism. Of course, as new, more energetic accelerators become available, it is important to search their products for monopoles (as well as other possible particles).

Track-etch experiments looking for cosmic ray monopoles, in particular GUMs, have also been performed. Relative to induction experiments, however these experiments have the disadvantage that they are not sensitive to monopoles with low velocity. A recent experiment reported by a collaboration of Japanese groups,[54] which has exposed cellulose nitrate (CN) sheets of a total area of about 100 m^2 for 3.3 years, estimate their sensitivity to cut off below $\beta = 0.03$. Their limit, labelled "DOKE (CN)", is plotted in Fig. 24. (My apologies to the "*et als*" of the experiments shown in Fig. 24; the full list of authors will be found in the references.) Experimenters at Berkeley[55,56], who have exposed arrays of CR-39 at high altitude, calculated that they were sensitive for monopoles with $\beta \geq 0.007$. Their flux limit, labelled "BKLY", is also plotted in Fig. 24. Their calculated velocity limit is indicated by a short vertical line at $\beta = 0.007$.

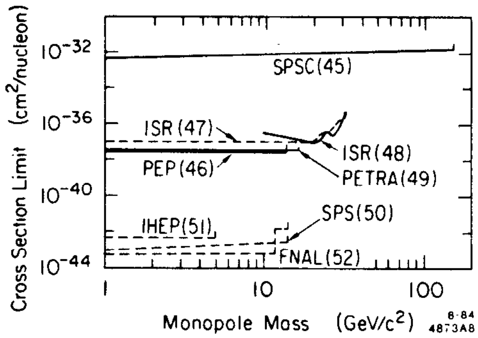


Fig. 23. Production cross section limits (at the 95% confidence level) of some magnetic monopole experiments performed at accelerators. Reference numbers are in parentheses. The solid lines represent direct searches by the track-etch technique and the dashed lines, indirect searches (generally involving magnetic extraction from samples subsequent to exposure).

Recently it has been argued[57] that the repulsive diamagnetic interaction between the GUM and atoms in the plastic detection sheets will result in a region of sensitivity in CR-39 at $\beta \sim 10^{-4}$. It is further argued that if the monopole should be bound to a proton, then the sensitivity would be enhanced even more; monopole-proton composites in the intervening velocity region would also be detectable, and the track-etch sensitivity in CR-39 would extend from $\beta = 1$ down to $\beta \sim 3 \times 10^{-5}$. This line of argument leads to an extension to the original Berkeley result. This extension, labelled "PRICE (CR-39)," has also been plotted in Fig. 24.

Such an extension finds some theoretical support, for it has been argued[58] that cosmic ray GUMs would, in fact, be bound to a proton. There is an additional complication, however. It has been pointed out that for certain GUTs, monopoles will catalize nucleon decay.[59,60] If this is true, the proton in the bound state of monopole and proton would decay, probably with a lifetime too short to be useful for the track-etch detection technique. But while this possibility would militate against the extension of the track-etch technique to low velocities, it affords another way to search for cosmic ray GUMs—a method called "catalysis." Monopole catalyis experiments are being performed as a by-product of experiments looking for the decay of the proton, which is predicted as a consequence of Grand Unified Theories. Several experiments utilizing this method have been reported.[61–63] The first of these[61] gives the best flux limit and is plotted in Fig. 24 labelled "ERREDE (CAT)."

Before going on to the ionization experiments, I should mention one other interesting track-etch experiment.[64] The detector is a 13.5 cm^2 piece of mica, etched with hydrofluoric acid. This experiment is of interest because of its very low flux rate limit, which is plotted in Fig. 24 as "PRICE (MICA)." The low rate derives from the long exposure time—4.6 x 10^8 years. However, when one contemplates the significance of this result, some caution is advised. Mica is not a particularly sensitive material

‡12 Fig. 23 is not a complete representation of all accelerator experiments; older results, and results yielding less restrictive limits are omitted. For a more complete coverage consult Ref. 53.

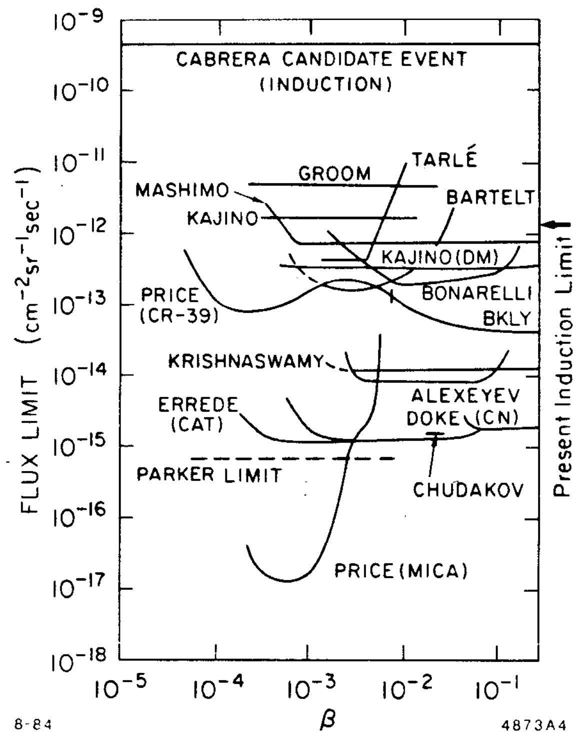


Fig. 24. Experimental limits on the cosmic ray flux (at the 1 event level). The Parker limit is indicated for purposes of comparison.

for the track-etch technique, and, in fact, is not sensitive enough to detect a monopole carrying (at any velocity) a Dirac charge. As a way around this problem, the authors have assumed that the monopole has captured a nucleus—aluminum, say. While the authors put forth arguments why nuclear capture should occur, one should bear in mind that even if these arguments are valid, there are a couple of difficulties with this assumption: 1) if the monopole has already captured a proton, as suggested by Bracci et al.,[58] then the necessary (subsequent) nuclear capture would probably not occur (and a GUM + proton would not leave an detectable track in mica) and 2) if monopoles catalyze nucleon decay,[59,60] then the monopole would probably not spend enough time bound to either a proton or to a nucleus to make an detectable track.

In addition to the induction and track-etch experiments, there are also numerous experiments that use ionization to furnish the GUM signal. Before the advent of the massive cosmic ray GUM, no one worried very much about whether there would be enough ionization along a monopole track; early calculations showed[65] that the energy loss of a monopole was comparable to that of a particle of charge q; the ratio (to first order) of their energy losses was shown to be $(g\beta/q)^2$. Consequently, for even moderate velocities, the large anticipated charge of the monopole would insure a sizable signal, which would be easy to detect.

But cosmic ray GUMs are expected to be slow, possibly even very slow, and the energy loss along the track of a low velocity monopole had to be considered in detail. This has now been done,[66,67] and the results are plotted in Fig. 25. Also indicated in Fig. 25 is the earth's velocity around the sun, $\beta = 10^{-4}$. Since for an earth borne detector, this velocity would add to that of any cosmic object, it affords a conservative target for the (lower limit of) velocity sensitivity of a cosmic ray monopole experiment. While there still may be some dispute about the lower cutoff of ionization detectors, it appears to be a safe bet that a carefully designed experiment looking for ionization by conventional techniques can see monopoles down to β equals a few times 10^{-4}.

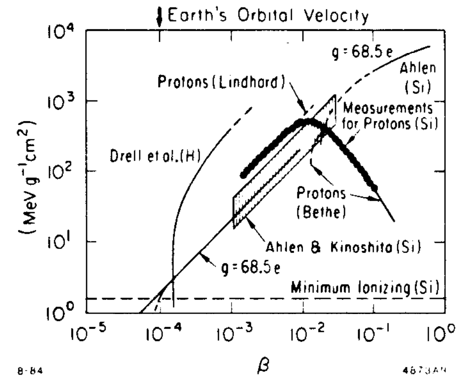


Fig. 25. Energy loss by ionization (See text).

The curve in Fig. 25 labelled "Drell et al." refers to what is now known as the "Drell Mechanism,"[67] a shifting of the atomic energy levels due to the large monopole field, which has a high probability of leaving the atoms along the monopole track in an excited state. This curve indicates that specially designed experiments based upon this mechanism can get down to perhaps $\beta \sim 2 \times 10^{-4}$. These considerations show that there is a velocity region where the induction experiments are unique, but it isn't very large. There is a recently reported experiment[68] which utilizes the Drell Mechanism, plotted in Fig. 24 as "KAJINO (DM)." This experiment, at 3.9 m (width) by 3.2 m (length) by 2.4 m (height), is large relative to present induction experiments, but it is small compared to its competition in ionization experiments. They report their lower velocity cutoff to be at $\beta \sim 3 \times 10^{-4}$.

Ionization experiments have the advantage that they can be made very much larger than the induction experiments. While a large size, of course means a large cost, such experiments can do more than just look for monopoles, making it easier to justify the large cost. The largest operating ionization experiment[♯13] —sometimes referred to as the Baksan experiment after its location in the Soviet Union—has a surface area of 16 m by 16 m and stands 11 m tall. There are some published results[69] from this experiment, which are plotted in Fig. 24 labelled "ALEXEYEV." Since that publication, additional data has been taken and these results have been updated.[70] This updated flux level limit is also indicated in Fig. 24, labelled "CHUDAKOV."

There are numerous other experiments using ionization to furnish the detection signal. Without going over these in detail, I have just plotted the more recent results in Fig. 24. For purposes of comparison, the rate implied by the original Cabrera event and an estimate of the present induction limit are also indicated. I include Table I to give a brief description of the apparatus of these experiments and indicate the appropriate references.

♯13 Actually, some of the proton decay experiments are larger, such as Errede *et al.*,[61] which has an effective area of 550 m^2. But these generally look for monopoles via catalysis, which is more tenuous as a signature.

TABLE I

Reference	Detector	Area × Solid Angle
Tarlé[71]	Scintillator	17.5 $m^2 sr$
Groom[72]	Scintillator	2.7 $m^2 sr$
Mashimo[73]	Scintillator	22 $m^2 sr$
Bartelt[74]	Prop. Cntr.	5.7 $m^2 \times 4\pi sr$
Kajino[68]	Scintillator (Stage I)	11 $m^2 sr$
Kajino (DM)[68]	Prop. Cntr. (Stage II)	24.7 m^2 sr
Bonarelli[75]	Scintillator	36 $m^2 sr$
Bkly[55]	CR-39	15 m^2
Bkly[56]	CR-39	16 m^2
Price (CR-39)[57]	Same as Bkly[55,56]	
Krishnaswamy[62]	Prop. Cntr.	218 $m^2 sr$
Alexeyev,[63] Chudakov[70]	Liq. Scint.	1850 $m^2 sr$
Errede (CAT)[61]	Čerenkov	550 $m^2 \times 4\pi$ sr
Doke (CN)[54]	Cellulose Nitrate	100 $m^2 \times \sim 6$ sr
Price (MICA)[63]	Mica	13.5 cm^2
Cabrera Candidate[24]	Induction	20 cm^2
Stanford[51]	Induction	476 $cm^2 \times 4\pi$ sr
IBM[31,32]	Induction	1000 cm^2
CFM[32]	Induction	2100 $cm^2 \times 4\pi$ sr

Unfortunately, I don't have time to describe some of the more exotic techniques, such as a acoustic detection,[76] detection by superconducting phase changes,[77] or by optical pumping magnetometry,[78] which various groups are investigating. In addition to these efforts, there are definite plans to build large detectors of a more conventional sort. For example, a Japanese collaboration[79] is setting up a 1000 m^2 track-etch detector using CR-39. Another very interesting proposal is one submitted by a collaboration of ten European groups as well as half a dozen from the United States. The proposal is to install a detector of 1000 m^2 sensitive area ($\sim 10^4$ $m^2 sr$) in the experimental hall of the Gran Sasso Laboratory in Italy.[80] In a year's operation of such a detector a flux at the Parker limit would yield three detected events. The Gran Sasso scheduling committee will be looking at this proposal (as well as others), and I am told that may make a decision as early as December of this year.

It is clear from the magnitude and diversity of these efforts we think that monopoles are important—perhaps even fundamental. I hope I have convinced you as well. If we could only find one.

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I have benefited greatly from discussions with many people. And I am grateful to those who have furnished me drawings and data prior to publication. In particular I would like to thank B. Barish, B. Cabrara, P. Chaudhari, M. Cromar, H. Frisch, D. Groom, C. Hodges, P. B. Price, S. St. Lorant, M. Taber, C. Tesche, and T. Watanabe.

APPENDIX A

An estimate of the rms magnetic charge of a vorton atom.

The vorton[13] has an electromagnetic charge $Q = 25.83e$ with an arbitrary duality angle Θ. If the vorton is electrically positive, it will then bind electrons to it, leading to a reduction in the overall potential energy. The potential energy will be a minimum when $\Theta = \pi/2$. This situation corresponds to the electric vorton designated in Fig. 4. It will have a $g = 0$ and a $Z =$ 25.83, binding to it 26 electrons (forming a pseudo-iron atom). The total binding energy for atoms has been calculated.[81] Interpolating between manganese and iron, this binding energy for $Z = 25.83$ is 34 keV.

Now if Θ is a true degree of freedom, then Θ will fluctuate about the minimum of potential energy at $\Theta = \pi/2$; by the equipartition theorem, the mean reduction in the total binding energy δE due to this motion will be $\frac{1}{2}$ kT.

One can estimate the resultant rms magnetic charge δg associated with these fluctuations. First note that the total binding energy as a function of Z goes like Z^3: one power due to the nuclear charge, one power due to a reduction in mean radius ($< \frac{1}{r} > \sim Z$), and one power because there are Z electrons. Since only two of these factors will vary for small fluctuations, one writes

$$\frac{\delta E}{E} = \frac{2\delta Z}{Z}, \qquad (A.1)$$

or

$$\delta Z = \frac{Z\delta E}{2E}. \qquad (A.2)$$

Figure 26 indicates that

$$(\delta g/e)^2 \cong 2Z\delta Z. \qquad (A.3)$$

Substituting (A.2) into (A.3) and setting $\delta E = \frac{1}{2}kT$ yields

$$(\delta g/e)^2 = \frac{Z^2 kT}{2E}. \qquad (A.4)$$

Using $Z = 25.83$, $kT = 1/40$ eV, and E = 34 keV yields

$$\delta g/e = 0.016 \sim 10^{-2}. \qquad (A.5)$$

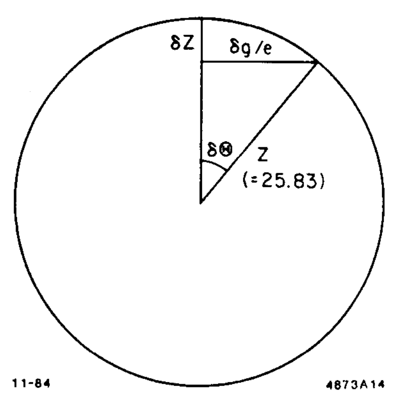

Fig. 26. Duality angle and magnetic charge associated with a fluctuation in the potential energy of a vorton atom.

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