SS-196
2026

QUARK AND MONOPOLE SEARCHES AT NAL

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"Now let's see," said Humpty Dumpty, "how much is 365 minus one?"

"364" said Alice.

"I'd like to see that on paper" said Humpty Dumpty doubtfully.

--Lewis Carroll

ABSTRACT

In this report we discuss the general field of quarks and monopole searches at NAL, recommend facilities which should be provided, and suggest priorities to be given to various types of experiments.

SUMMARY OF RECOMMENDATIONS

1. In general, most of the proposals discussed are simple experiments which do not compete with each other or with other types of experiments. Because of the fundamental importance that the discovery of the quark or monopole would have in physics, the committee recommends that as many quark and monopole searches as are feasible be run during the first generation of experiments at NAL.

II. Quark Search

A. Experiments should be approved whose primary aim is to search for quarks since such experiments will be designed to optimize their chances for success as opposed to those experiments which may find quarks as a byproduct of another type of study.

B. Quark searches should be performed with the highest energy beams and smallest production angles available.

C. Proposals for a chemical search for quarks in the water of the main beam dump should be solicited.

III. Monopole Search

A. Beam stops in both Area 1 and Area 2 should be designed to allow removal of the front end of the stop for analysis and so that solenoid magnets can be inserted into the stop to extract monopoles during running time.

B. Searches for bound monopole-antimonopole states, which we term monopolonium, should be encouraged since it seems probable that monopolonium will be produced more copiously than free monopoles.

INTRODUCTION

Under the heading of new particles we will discuss four different types. These are:

1. Conventional quarks--particles with fractional charge and baryon number and no anamalous magnetic properties.
2. Dirac monopoles--particles with magnetic charge but no anamalous electrical properties.
3. Dyons--dually-charged particles carrying fractional charge and baryon number in addition to a magnetic charge.
4. Integrally-charged quarks--heavy stable particles with integer charge.

Proposals have been submitted to search for the first three types of particles, while the fourth, which differs from ordinary particles only in its stability and, perhaps, its mass, could be seen in a beam survey.

The peculiar property of the conventional quarks (their fractional charge) means that they can be sought by looking either for high rigidity, for subminimal ionization, or for strange chemical properties of quarked atoms. The monopoles, on the other hand, exhibit a number of strange properties, all connected with the large strength of the magnetic coupling, and so a variety of experiments can be imagined, each one utilizing one or another of these properties. It is important to note that for virtually any of the proposals, one can imagine a world in which only this type of experiment would succeed in finding the particle which is being sought.

Finally, we note that because of the extreme strength of the magnetic interaction, the fractional charge on the dyons would have very little effect on the behavior of those particles so that any successful search for the Dirac monopole would also discover the dyon (or, more exactly, would discover the dyon instead of the Dirac pole). Thus, if any monopole search is successful, it is imperative that this success be followed by a measurement of the electrical charge of the particle.

In the discussion that follows, it is to be understood that by quarks we refer to the conventional quarks mentioned above, and by monopole we refer to either the Dirac monopole or the dyon. We will not consider ordinary beam surveys which would be appropriate for finding the integrally charged quarks.

I. QUARKS

In Table I we summarize the three proposals which have been submitted to search for fractionally charged particles. All of these experiments depend on measuring the ionization of the quark to provide a definite identification. Proposal 75 would look for particles with high rigidity in secondary beam lines in Area 2 and is a natural follow-up to the initial tuning of the beam. Proposal 72 would require a target and some analyzing magnets and could be done in any high-energy high-intensity beam. Proposal 11 requests space in the beam tunnel, but it is felt that because of the uncertainty about radiation background in the tunnel,[1] such a location may be inappropriate. All of these proposals could be realized with relatively little effort by the laboratory.

The technique of searching for high-rigidity particles, in which the beam is tuned so that only normal particles of energy higher than the incident energy would get through, has the advantage of very low background. Any particle that legitimately came down the beam line would be interesting. It has the disadvantage, however, that it accepts a very small momentum bite ($\Delta p/p \sim 1\%$) and can look only in a very restricted momentum range (for example, by tuning a beam in Area 2 to 210 GeV/c, one would get only one-third charged quarks of momentum 210/3 GeV/c), and this might not be the optimum momentum for a quark search. One could imagine, for example, a production process where quarks of this momentum are suppressed.

It should be noted that many proposals which are designed to look for other things (beam surveys or particle-production experiments, for example) also mention that a quark search could be incorporated into their procedure. In most cases, while this claim is true, the apparatus is really designed to do something else and might not be the best way to search for quarks. For example, an experiment which has a very good definition of particle momentum would take considerably longer to sweep the full momentum spectrum. This might be necessary since the production characteristics of quarks are not known, and to establish the existence of quarks, one needs to know the momentum only well enough to establish that the ionization is anomalously low.

Anyone with a magnet and a dE/dx counter could search for quarks and need not be discouraged from doing so. However, the task of finding and positively identifying a fractionally charged particle requires careful attention to details. Thus a search which is a byproduct of some other experimental program is no substitute for a comprehensive quark search. Therefore we recommend that experiments be approved by groups whose primary aim is to find quarks.

Because the existence of quarks would be of such fundamental interest, it is felt that the quark-search program should be carried out as soon as high-energy high-intensity beams are available. Because of the extreme simplicity of the experiments, they should be performed in the highest energy beams as soon as they become available. To avoid missing quarks because of some anomaly in their production characteristics, the search should cover a wide range of momenta and production angles (stressing small-angle production which would be kinematically favored for heavy quarks). The thin-target facility in Area 1 suggested by W. Lee[2] sould be an ideal place for these experiments.

Finally, we note that no proposals for chemical quark searches were submitted. The reason for this is probably the extreme difficulty of doing quark chemistry in solid beam dumps. The basic technique of chemical searches would be to take some material on which the beam has been incident and analyze it for captured quarks. It is very difficult to analyze large amounts of solids chemically, but large amounts of liquids are apparently much easier to do. The designs of the main beam dump now envision stacked iron ingots surrounded by water to provide thermal dispersion. It is not unreasonable to suggest that this water might, over a long period of time, come to contain some quarks, so that in the long run, a chemical analysis of the water from the main beam dump should probably be done if quarks are not found directly in the beam. Such a search would be interesting even if quarks were found in production-type experiments, since it would shed light on quark chemistry and would therefore be useful in conjunction with geological and astrophysical studies.

II. MONOPOLES

A. Theoretical Introduction

The existence of magnetic monopoles is of rather fundamental interest in physics. First, the existence of magnetic charge would restore the symmetry of the Maxwell equations. More importantly, the existence of a single monopole would explain the observed quantization of electrical charge, perhaps the best verified quantization law in existence. Finally, the existence of dyons,[3] which carry a magnetic charge, might explain many of the puzzling features of the quark model and other composite models of elementary particles.

The basic law linking magnetic and electrical charges was first derived by Dirac[4] who showed that in order for a wave function to be single valued when one went around a contour enclosing both an electric and a magnetic charge, g, the two charges must satisfy the condition

$$ge \sim n,$$

where n is an integer.

From this we can immediately see two things: (1) if one monopole exists anywhere in the universe, every electrical charge must be quantized (the committee expresses the hope that if this is the case, the monopole is somewhere near Chicago), and (2) the magnetic interaction is very strong indeed. In fact, we could make a ranking:

interaction	relative strength
electrical charge	1/137
strong	10
magnetic charge	137.

It is this aspect of the magnetic charge which is so striking. It represents an interaction stronger than the strong interactions. The search experiments to which we will now turn our attention without exception make use of this property in defining ways in which the monopoles, should they exist, could be detected.

B. Experiments

A summary of the proposals which have been submitted to search for Dirac monopoles is given in Table II. They can be broken up into three distinct classes, which we shall consider separately. As we mentioned earlier, each one depends for its success on some aspect of the strong magnetic force.

1. Monopolonium

It has been pointed out that because of the extremely strong interaction between a monopole and an antimonopole, it is very unlikely that they will be produced as free pairs.[6] They are much more likely to be produced in bound states, which we will term monopolonium. It has been estimated[7] that near threshold, the ratio of monopolonium to free pair production is on the order of 10^{10}. Thus, if the monopole production cross section is small, it might be better to look for indirect evidence of their existence, rather than to look for the monopoles themselves. The type of evidence for which one searches depends, of course, on what one assumes about the decay processes of monopolonium. The proposers of Proposal 22 assume that the monopolonium would decay in a shower of high-energy photons, which they would then detect. One could imagine other decay modes (for example, through a single photon or through strong or even weak interactions), so that this scheme is not comprehensive, but it is clear that a particle with such a strong coupling to the electromagnetic field as the monopole will most likely decay through photon emission of some sort.

It is the feeling of the committee that a high priority should be given to monopolonium experiments in any monopole search program.

We note that if the particle for which we are searching turns out to be the dyon, and not the simple Dirac monopole, then we have already seen monopolonium. We have simply misnamed it by calling it the pi meson. The relative ease with which the pion is produced, and the difficulty encountered in producing either dyons or quarks, illustrates the point we made above, namely, that it is often easier to make bound states of particle-antiparticle pairs than to make the pair itself.

We also note that it would be a good idea to look for production in beams other than the standard hadron beams since there is no guarantee that monopoles interact through the normal strong interactions. For example, the lead glass counters proposed for the inelastic Compton-scattering experiment (Proposal 24) would be able to measure the photon shower one supposes would come from monopolonium, and it would probably be fairly easy for the monopolonium search in a photon beam to be done as a simple extension of that experiment.

2. Beam-Stop Proposals

These proposals (3 and 76) propose to look for magnetic poles in the material which is irradiated by the high-energy beams. The first would look for monopoles which are created in the beam stop and then trapped in the paramagnetic or ferromagnetic material by techniques which have already been used to search for monopoles in samples of lunar material.[5] The second would insert a solenoid magnet into the beam stop and draw the monopoles out after they were created. In this proposal, the field would have to be great enough to overcome the internal fields in the metal, as well as whatever ambient field might exist.

There are two different areas where one could imagine doing such experiments. There is the main beam dump, located under the beam-transfer area, and there are the various beam stops located on the end of each individual target train. The first question to consider, then, is which of these is the more appropriate location for the experiments. The answer to this question, in turn, depends on whether one assumes that monopoles have not yet been seen because of their high mass or because of a low production cross section. In the former case, the first area to be struck by beams of highest energy would be the obvious place to begin the monopole search. The main beam dump will be in use first, but this is relatively inaccessible, so that extracting solid material from it would be rather difficult. Magnetic-extraction experiments such as proposed in Proposal 76 could conceivably be done in this area.

It is important to recall, however, that during tuneup the beam intensity will presumably be kept rather low so that the main beam dump will absorb only a small flux of protons. During later normal operations, the main beam dump would be used only sporadically so that the total number of protons deposited there will presumably be small. Thus for a magnetic-extraction experiment to work in this area, it would be necessary that monopoles be produced with a rather high cross section and that the searches of lunar material[5] have failed to detect them because of some error in the chain of calculations about the binding of monopoles in matter.

It should be noted that in the absence of such an error, rather stringent limits on monopole production cross sections have already been set by cosmic-ray data. To get a number in mind, a full day's run with 10^{13} 500 GeV/c/protons/pulse at NAL would just about equal the integrated flux of energetic cosmic rays striking the lunar surface. Thus it is important, if these experiments are worth doing at all, that they be exposed to a beam with a high intensity of protons. Consequently, the main beam dump should probably not be considered as a site.

The beam stops in the target areas, however, do not suffer from the low-flux problems outlined above. In addition, the target trains can be brought into an area where remote handling is possible so that the beam stops are accessible. We recommend, therefore, that the following two considerations be taken into account when these beam stops are designed:

1. The beam stop should be made in sections which the proposers of Proposal 3 can handle and facilities for removing the appropriate sections be provided.

2. Facilities for the insertion of a small solenoid magnet into the beam stop be provided. It should be noted that since this involves inserting a pipe into (not just up to) the beam stop, it is not necessarily a trivial thing to do.

Because of the simplicity and low cost of these two types of experiments, it is felt that beam stops in both Area 2 (with 200 GeV/c proton beams incident) and in Area 1 (with 400-500 GeV/c proton beams incident) should be designed according to the above recommendations.

A final point on beam-stop experiments should be made. It could be that monopoles can be created only by photons, for example. They might even be produced by neutrinos since their existence has been suggested as the explanation for CP violation.[3] Thus inserting beam stops with paramagnetic monopole traps into a neutrino or photon beam, as in Phase II of Proposal 76, would probably be useful.

3. Monopoles in Flight

Proposals 19 and 74 concern the detection of monopoles which have been created in a target. Proposal 19 proposes to measure the characteristic strong Cerenkov radiation of the monopoles, and Proposal 76 proposes to measure their ionization loss in a solid-state counter. Both experiments assume that free monopoles will be produced, and for 19 it would be necessary that they have a velocity sufficiently high to radiate in a Cerenkov counter. Either experiment could be done in any high-energy high-intensity beam and could be run parasitically.

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Table I. Quark-Search Proposals.

	Proposal 11 (Y. S. Kim)	Proposal 72 (Adair)	Proposal 75 (T. Yamanouchi)
Charge of quark sought	1/3 or 2/3	1/3, 2/3, 4/3 5/3, 7/3	1/3 or 2/3
Kinematics	Would see only backward-going quarks	Can sweep momentum intervals	Searches for quarks at fixed momentum ($\Delta p/p \sim 1\%$) e. g., 70 GeV for charge 1/3
Cross-section sensitivity	10^{-35} cm^2	10^{-39} cm^2	10^{-37} cm^2
Comments	Probability of success is very model dependent	Comprehensive	By tuning beam above incident energy, background is greatly reduced
Location of experiment	In any high-energy high-intensity beam requests tunnel space, but background may present problems		Done as part of tuning of secondary beams

Table II. Monopole-Search Proposals.

	Proposal 3 (L. W. Alvarez)	Proposal 19 (D. Tompkins)	Proposal 22 (G. Collins)	Proposal 74 (R. Fleischer)	Proposal 76 (R. Carrigan)
Location of experiment	Beam stop	Any high-intensity high-energy beam			Beam stop
Properties of monopole relied upon	Monopoles will be bound in iron	Characteristic Cerenkov radiation of monopole	Monopolonium will decay in an energetic γ shower	dE/dx of monopole in a solid-state counter	Monopoles can be extracted from metals by solenoid magnet
Comments		Monopoles must be relativistic	Looks for indirect evidence of monopoles	Could see very high magnetic charge	