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Can grand unification monopoles be detected with plastic scintillators?

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By drawing upon results from work dealing with the interactions of slow protons with matter, we estimate the light yield of grand unification monopoles from organic scintillators. It is shown that monopoles having velocities $\gtrsim 6 \times 10^{-4}c$ can be observed.

Cabrera has reported[1] the results of a search for moving magnetic monopoles with a superconductive loop detector. One event was observed for which the signal was consistent with that expected of a monopole having the Dirac charge ($g = \pm 137e/2$ in cgs units). An obvious course of action to follow up on Cabrera's observation would be to mount an experiment with several-orders-of-magnitude-greater collecting power than that of Ref. 1. If Cabrera's event was due to a monopole, a detector with an area of 2 m^2 would see monopoles at the rate of ~ 6/day. However, due to the extremely small velocity which grand unification monopoles are expected to have[2] ($\beta = v/c \lesssim 10^{-3}$ relative to the earth), it is not clear whether conventional particle detectors which respond to electronic excitation could detect them.[3] It will be impossible to interpret monopole-search experiments which utilize conventional detectors unless the detector response can be evaluated by using strong arguments which can be supported by theory and experiment. In this Communication we attempt to do this for the case of plastic scintillators. These detectors would be a logical choice for a large-area monopole search as they are relatively inexpensive and their required excitation energies are small compared to those of other classes of detectors that can be deployed in a large area. Birks has thoroughly reviewed the applications of organic scintillators and the basic principles which determine their behavior.[4] Plastic scintillators consist of an aromatic solvent, usually polyvinyltoluene (PVT), with a small admixture of dissolved fluor molecules containing two or more aromatic rings. Radiation is absorbed principally by the abundant solvent, and the energy is subsequently transferred with high efficiency to the fluors which thereupon decay by emitting scintillation photons.

In considering the response of scintillators to low-velocity particles, it will be convenient to regard the material as a gas of electrons.[5] For the velocities of interest here, the carbon K-shell electrons can be excluded from the gas insofar as their stopping cross section[6] is negligible compared to the total carbon stopping cross section.[7] The effective number of valence electrons which participate in energy-loss processes at low velocity should be the same as the number which take part in low-energy plasma excitations of solids.[5] This can be determined by studies of characteristic energy-loss spectra of energetic electrons transmitted through thin films.[8] These spectra are insensitive to the conductivity of the solid, and seem to reflect rather the valence properties of the atoms involved. For pure carbon, it is found[8] that ~ 4 electrons per atom participate in plasma excitations. Such studies have not been done for PVT. Since PVT has a composition $\sim$ CH, it is possible that as many as 5 electrons per carbon atom could participate. However, in the following we will estimate the number to be 4. None of our results would be seriously affected if we chose 5 electrons per carbon rather than 4. To take into account the fact that excitation of fluor molecules requires discrete quanta of energy, we impose the condition that the electron gas has an energy gap E_G above its filled valence states. We will set $E_G = 5.0$ eV, which corresponds roughly to the lowest-energy absorption line of benzene.[4] Since PVT has several crystallinelike features, including the capacity for exciton migration,[4] we do not feel that our introduction of a band gap is a bad approximation. Furthermore, the ability of σ electrons as well as π electrons to participate in the excitation of electron states with energies ~ 6 eV (Ref. 4) strengthens the validity of our assumption that all valence electrons of the carbon atoms participate in the scintillation process.

A number of workers[9,10] have calculated the stopping power $S_e \equiv (dE/dx)_e$ of slow, massive electrically charged particles in degenerate electron gases. All these calculations yield the result $S_e \propto Z_1{}^2 v$ for $v << v_F$, where $Z_1 e$ is the projectile charge, v is its velocity, and v_F is the Fermi velocity of the gas. Mann and Brandt[5] have compared these theories with experiment and have found excellent agreement for the calculation of Ref. 10. By calculating the frequency- and wavelength-dependent dielectric permeability for an electron gas with an energy gap, Brandt and Reinheimer[11] evaluated a correction factor to be applied to the zero-gap models[9,10] to determine the stopping powers for semiconductors and insulators. It is interesting to note that this correction factor is not required to explain the data of Ref. 12 in which the electronic stopping power of protons in vapor-deposited carbon foils is observed to have a linear velocity response down to $\beta = 6\times10^{-4}$. Since carbon prepared in this way should have an energy gap,[13] one might expect threshold effects to manifest themselves at such a small velocity. That they do not suggests that the yield of excited molecules ceases to be proportional to the electronic energy loss of a projectile at small velocities.

We have plotted a variety of functions relevant to the response of the plastic scintillator NE110 to slow protons in Fig. 1. The electronic stopping power S_e is taken from experiments quoted in Ref. 7 and from Ref. 12 in which carbon and hydrogen cross sections were added appropriately. We have also calculated and plotted the nuclear stopping power S_n from the Lindhard-Scharff-Schiøtt theory.[14] By using the results from Ref. 11 we have calculated the stopping power S_G which goes towards exciting the 5-eV band gap in NE110. The extremely rapid decline of S_G at $\beta\sim 7\times10^{-4}$ is due to kinematic constraints. To see this, note that the maximum possible energy transfer to an electron with velocity v_F $(=c/145$ for NE110) from a massive projectile with velocity v is $\epsilon_m = 2mvv_F$, where m is the electron mass. For $v = 7\times10^{-4}c$, $\epsilon_m = 4.93$ eV. Also shown in Fig. 1 are data on the scintillation efficiency dL/dE of NE110 in response to protons. These have been obtained by

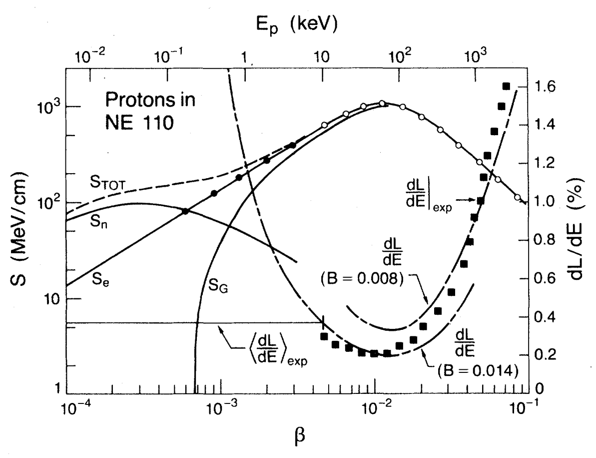

FIG. 1. Contributions to the stopping power of slow protons (left scale) and comparison of calculated and experimental scintillation-conversion efficiencies (right scale). Data for S_e (open circles from Ref. 7, solid circles from Ref. 12) have been linearly extrapolated to low velocities and have been added to S_n from Ref. 14 to obtain S_{TOT}. For scintillation efficiency, the solid squares have been obtained from experimental data (Ref. 15) on the response of scintillators to recoil protons produced by neutron exposure. The horizontal line marked $\langle dL/dE\rangle_{\mathrm{exp}}$ is the ratio L/E for 10-keV protons as measured in Ref. 15.

taking the derivative of the total-light-vs-total-energy curve in Ref. 15. The units of L in Fig. 1 are total photon energy. The decline in dL/dE as β decreases from 0.1 is due to radiation quenching[4] as can be seen by the coincidence of the location of the minimum of dL/dE with the energy of the Bragg peak. It has been shown[4,16] that radiation quenching near the particle track can be described by the expression $dL/dE = 0.03/(1+BS)$. It has been found that[16] $B = 0.010$ cm/MeV for Z_1 from 2 to 26 and β from 0.05 to 0.8. We use this function to fit the data in Fig. 1. For $\beta > 0.04$, the proton results require $B = 0.008$ cm/MeV while a higher value of 0.014 cm/MeV is required near the Bragg peak. The enhanced quenching at low velocity is probably due to the narrower column of excited material which occurs at low velocity due to adiabatic limitations. To test whether the above expression for scintillation efficiency can be extended to lower velocities, we use it to calculate the total light yield of a 10-keV proton in a scintillator:

$$L = \int \frac{dL}{dE}(S/S_{\mathrm{TOT}})\,dE_{\mathrm{TOT}} \ ,$$

where $S_{\mathrm{TOT}} = S_e + S_n$ is displayed in Fig. 1. By assuming that $S = S_G$ in the expression for L and dL/dE, we obtain $L_G = 40.3$ eV. If we let $S = S_e$, we find $L_e = 45.5$ eV. The experimental result from Ref. 15 is $L_{\mathrm{exp}} = 37.0 \pm 3.7$ eV which suggests that the scintillation model which includes the effect of the energy gap is valid.

It has been shown[17] that the stopping power of magnetic monopoles in degenerate electron gases is related to that of electric particles having charge Z_1e via

$$S_m/S_e \approx (g/Z_1e)^2(v_F/c)^2(\ln\psi_m)/(\ln\psi_e)$$

for $v \ll v_F$, where ψ_m and ψ_e are minimum electron-projectile scattering angles determined by eddy-current losses for monopoles and by static longitudinal screening for electric particles. Similar considerations can be applied to estimate energy losses in electron gases having band gaps. In this case, ψ_m and ψ_e would probably have similar values, since they would each be determined by kinematics so as to allow sufficient energy transfer to excite the gap. In any case $\psi_m \lesssim \psi_e < 1$ so that the above expression corresponds to a lower limit of monopole excitation energy loss in semiconductors and insulators if we set $\psi_m \approx \psi_e$. Since v_F is of order αc, the stopping power of a monopole with $g = 137e/2$ should be nearly the same as that of an electric particle with $Z_1 = \frac{1}{2}$. The value of S_G for such a particle is $\frac{1}{4}$ that of a proton. We have used this prescription to calculate S_G for slow monopoles. By assuming the same form for dL/dE that was used to evaluate the scintillation yield for protons, and by using the monopole value of S_G to evaluate dL/dE, we determined dL/dx for slow monopoles. This result is shown in Fig. 2 as curve B. We have also evaluated the scintillation yield of relativistic monopoles by taking the stopping-power calculation of Ref. 18 and by using the expression for scintillation efficiency in Ref. 16 which includes δ-ray effects. The rapid increase in dL/dx above $\beta = 0.1$ is due to the onset of the production of δ rays with sufficient energy to result in energy deposition far enough from the particle track so that quenching is sharply reduced.

If monopoles capture either electrons or protons,[19] their stopping power and scintillation yield will be increased at low velocities. Since the electron-monopole interaction is mediated principally by the monopole's induced electric field,[17] which is transverse to the electric field generated by a comoving electric particle, the stopping power of a composite system is just the sum of the separate stopping powers. The same is not true for the scintillation yield since the quenching is determined by the total stopping power. By taking this into account we have evaluated the dL/dx curve for a composite system consisting of a monopole with charge $g = 137e/2$ and an electric particle with charge e. The results are shown as curve A in Fig. 2. If monopoles are bound to heavier nuclei,[20] the composite stopping power will be even higher.

It has been suggested[21] that the yield of triplet states in scintillators might be considerably enhanced for a low-velocity monopole compared to that for an electric particle and that this could be used to discriminate against electric particles on the basis of the scintillation pulse shape.[4] However, by assuming a binary-encounter approximation and by taking the appropriate linear combinations of helicity-flip and -nonflip scattering amplitudes for electron-monopole scattering,[22] it can be shown that the total number of excited singlet states will always exceed the number of triplet states for the case of a Dirac monopole. Furthermore, any triplet states that are produced would not be observed in plastic scintillators or in poorly prepared liquid scintillators due to quenching by trace quantities of oxygen.[23]

We estimate that curve B in Fig. 2 is accurate at least to within a factor of 2. The actual monopole stopping power should be slightly larger than as-

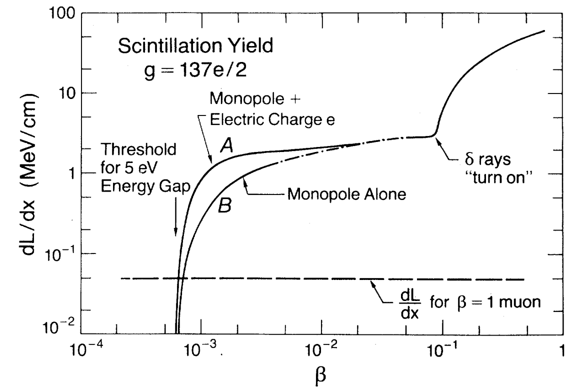

FIG. 2. Estimates of scintillation yield for magnetic monopoles. See text for a description of the different curves.

sumed due to slight differences between the electron-monopole cross section[22] and the Rutherford cross section. On the other hand, for velocities $\lesssim 10^{-3}c$ the yield of excited singlet states for a given energy loss will be less for monopoles than for electric projectiles due to the production of triplet states by the former which would be forbidden for the latter. This would tend to reduce the scintillation efficiency for monopoles. However, the limited production of triplet states would prevent the reduction of monopole scintillation by as much as a factor of 2. Thus, although it will be kinematically impossible to observe monopoles with velocities $\lesssim 6 \times 10^{-4}c$, the integrated signals for monopoles with velocities $\gtrsim 7 \times 10^{-4}c$ will be greater than the most probable signal for a relativistic muon (see Fig. 2). To extend monopole searches to lower velocities will require detection materials with small band gaps. For example, acrylic-based scintillators having large concentrations of naphthalene are probably sensitive to monopoles down to $5 \times 10^{-4}c$. With a band gap of only ~1.1 eV, silicon detectors would be able to detect monopoles moving as slowly as $10^{-4}c$.

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