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Energy Losses of Magnetic Monopoles and Dyons in Scintillators, Streamer Tubes and Nuclear Track Detectors.

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Abstract

A systematic analysis of the energy losses of magnetic monopoles of different magnetic charges and of dyons in three types of detectors are investigated for a large range of $\beta = v/c$ ($\beta > 10^{-5}$). More specifically we have computed the light yield in liquid scintillators, the ionization in streamer tubes and the Restricted Energy Loss in the CR39 nuclear track detectors. Also the total energy losses have been analyzed.

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1 Introduction

Many theories and models predict the existence of magnetic monopoles (MM) [1-5] whose magnetic charge obeys the Dirac quantization rule [6]

$$eg = \frac{n\hbar c}{2} , \quad (1)$$

where n is an integer, $n=1,2,3,\dots$. For $n=1$, assuming that the basic electric charge is that of the electron, one has $g = g_D = \frac{\hbar c}{2e} = 3.29 \times 10^{-8}$ u.e.s. Most theoretical papers concern superheavy magnetic monopoles predicted by Grand Unified Theories (GUT) of electroweak and strong interactions; there are also many papers concerning heavier and lighter MMs.

There are predictions for the existence of monopoles with $n=1$, $n=2$ and $n=3$ [1-3]. Moreover if the basic electric charge is that of the quark d the basic magnetic charge increases by a factor of three.

A magnetic monopole and an atomic nucleus N may form a bound system with both magnetic and electric charges. Some models predict the existence of states with both electric and magnetic charges (dyons) [7]. As far as the energy losses in matter, a dyon and a $(MM + N)_{bound}$ system behave in the same way. The system $(MM + N)_{bound}$ can be produced via radiative capture [8]

$$MM + N \rightarrow (MM + N)_{bound} + \gamma \quad (2)$$

or via the Auger process [8]

$$MM + (N, ne^-) \rightarrow ((MM + N)_{bound} , (n-1)e^-) + e^- \quad (3)$$

For MMs passing through ionized matter, the first channel is the only effective one for the formation of the system $(MM + N)_{bound}$; in non-ionized material, the second channel becomes important. The bound system may be subject to photodissociation [8]

$$(MM + p)_{bound} + \gamma \rightarrow MM + p \quad (4)$$

The capture cross section for reaction (2) is $1 < \sigma < 10$ mb for MMs with $10^{-4} < \beta < 10^{-3}$; therefore it is possible that most MMs [9] in the cosmic radiation can be in the state $(MM + p)_{bound}$. Neglecting the catalysis of proton decay, MM or $(MM + p)_{bound}$ systems with $\beta \geq 10^{-3}$ traversing

rock, probably reach an equilibrium mixture of about 50% MMs and 50% $(MM + p)_{bound}$ [8]. The minimum velocity of the $(MM + p)_{bound}$ system for which one may have a break-up reaction (4) is $\beta \sim 10^{-3}$, corresponding to the case in which all the three particles in the final state (MM, proton and target nucleus) are at rest in the center of mass frame of the MM.

Many experimental searches concern superheavy GUT magnetic monopoles. Most of the published flux limits apply to an isotropic flux of bare monopoles of unit magnetic charge (and the monopole catalyzed nucleon decay is not considered). In order to search for MMs and dyons over a large β -range it is necessary to know how these particles loose energy in different types of detectors.

In this paper we compute, in Section 2, the light yield in liquid scintillators, in Section 3 the ionization in the gas of streamer tubes and in Section 4 the Restricted Energy Loss (REL) in nuclear track detectors (CR39), for a large range of $\beta = v/c$ values ($\beta > 10^{-5}$) and for different magnetic and electric charges. More specifically we compute the energy losses for MMs with $g = g_D, 2g_D, 3g_D, 6g_D$ and $9g_D$, and for dyons (or composite MM-nucleus systems) with $g = g_D, Q = +e$ and with $g = g_D, Q = +13e$ (charge of the aluminium nucleus). Note that the detection methods for dyons and for MM-nucleus composite systems are the same.

In Section 5 are computed the total energy losses in scintillators, streamer tubes and nuclear track detectors for MMs and dyons (or MM-nucleus composites) of different magnetic charges. The conclusions are in Section 6.

2 Light Yields of MM and Dyons in Scintillators

The light yields of magnetic monopoles with $g = g_D$ and of dyons with $g = g_D, Q = +e$ have been computed for the plastic scintillator NE110 [10-11]. In this Section we present new calculations of the light yields in NE110 for the cases of MM and dyons of interest. We follow the approach of ref. [11]. We then apply the computation methods to the MACRO liquid scintillator keeping in mind the different densities and the different hydrogen/carbon ratios [H/C].

Table 1: Density and the H/C ratios for the MACRO liquid scintillator and the NE110 scintillator.

	NE110	MACRO Scintillator
Density	1.032	0.86
H/C ratio	1.104	2.02

The scintillator of MACRO is made of 96.4% mineral oil, 3.6% pseudocumene, 1.44 g/l of PPO, 1.44 mg/l of bis-MSB and 40 mg/l of an antioxydant [12].

A small difference in the energy losses between NE110 and the MACRO scintillator occurs, but it is smaller than the uncertainty in the calculations.

2.1 Light Yield in Scintillators for Magnetic Monopoles

For MM the light yield ($\frac{dL}{dx}$) in a scintillator is related to the energy loss ($\frac{dE}{dx}$) by [13]

$$\frac{dL}{dx} = A \times \left[\frac{1 - F}{1 + AB(1 - F)dE/dx} + F \right] \times \frac{dE}{dx} \quad (5)$$

where dE/dx is the total electronic energy loss. For relatively small dE/dx the light yield is proportional to the energy loss with the proportionality constant A of Eq. 2. B is the so called quenching parameter: the light yield from the energy deposited near the track (the first term in the parenthesis of Eq. 2) saturates for high energy losses. For high velocities ($\beta > 0.1$) of the incident particle some electrons have sufficient energy to escape from the region near the track core (δ rays); F is the fraction of energy loss which results from excitations outside the core; these excitations are assumed not to be quenched.

From ref. [13] we have $A=0.03$ for $\beta = \frac{v}{c} > 1.5 \times 10^{-2}$ and $A=0.067$ for $\beta < 1.5 \times 10^{-3}$; values of A were interpolated at intermediate values of β . Always from ref. [11] we assume $B=0.33$ cm/MeV for $\beta > 0.1$ and $B=0.66$

cm/MeV for $\beta < 0.005$; at intermediate β the B values are interpolated smoothly using a cubic polynomial in β .

The parameter F of Eq. 2 is given by [13]

$$F = \begin{cases} 0 & \text{for } \beta < 0.09 \\ \frac{1}{2} \frac{\ln(2m_e c^2 \beta^2 \gamma^2 / T_0) - \beta^2}{\ln(2m_e c^2 \beta^2 \gamma^2 / I) - \beta^2} & \text{for } \beta > 0.09 \end{cases} \quad (6)$$

where $T_0 = 8500$ eV is the minimum energy for an electron to escape from the track halo, and I is the average ionization energy of the medium (61 eV for NE110 and 55 eV for the MACRO liquid scintillator).

The energy loss dE/dx for a monopole is given at *high velocity* ($\beta > 0.05$) by the formula [14]

$$\left(\frac{dE}{dx} \right) = \frac{4\pi N_e g^2 e^2}{m_e c^2} \left[\ln \left(\frac{2m_e c^2 \beta^2 \gamma^2}{I} \right) - \frac{1}{2} + \frac{k}{2} - B_m \right] \quad (7)$$

where N_e is the density of electrons, m_e the electron mass and g the magnetic charge of the monopole. I is the mean ionization potential of the scintillator. The Bloch correction B_m and the k QED correction parameter have the following values [32]

$$k(|g|) = \begin{cases} 0.406 & \text{for } |g| = 137e/2 \\ 0.346 & \text{for } |g| = 137e \\ 0.3 & \text{for } |g| \geq 3 \times 137e/2 \end{cases}$$

$$B_m(|g|) = \begin{cases} 0.248 & \text{for } |g| = 137e/2 \\ 0.672 & \text{for } |g| = 137e \\ 1.022 & \text{for } |g| = 3 \times 137e/2 \\ 1.685 & \text{for } |g| = 6 \times 137e/2 \\ 2.085 & \text{for } |g| = 9 \times 137e/2 \end{cases}$$

At *low velocities* ($\beta < 0.01$) the energy losses of a MM in scintillators were taken to be $\frac{1}{4}(g/g_D)^2$ times the energy losses of a proton of the same β [10]; these were computed from the energy losses in hydrogen and carbon [15]), adding an exponential factor from the fit to the low-velocity proton data [11]. We obtain the following formula

$$\left(\frac{dE}{dx} \right)_{\text{proton}} = 1.3 \times 10^5 \beta \left\{ 1 - \exp \left[-(\beta/7 \cdot 10^{-4})^2 \right] \right\} \quad \frac{\text{MeV}}{\text{cm}} \quad (8)$$

for the energy losses of protons in both the NE110 and the MACRO scintillators. For $0.01 < \beta < 0.05$ we use a smooth interpolation (it is not critical to know with precision the dE/dx in this β -range, because the light yield is saturated). As already stated, the energy losses of monopoles are

$$\left(\frac{dE}{dx}\right)_g = \frac{1}{4} \left(\frac{g}{g_D}\right)^2 \left(\frac{dE}{dx}\right)_{\text{proton}} \quad (9)$$

The results of the calculations are shown in Fig. 1. We notice that at *very low velocities* ($\beta < 0.0005$ for $g = g_D$) the light yield increases with β , then it saturates at a value of 1.2 MeV/cm (region A of Fig. 1). The increase in the light yield observed in region B of Fig. 1, is due to changes in the quenching parameters. For $\beta \geq 0.09$ the production of delta rays becomes possible, and the light yield increases again with β (region C of Fig. 1).

At intermediate β values ($0.003 < \beta < 0.1$) *the light yield is thus independent of the magnetic charge value*; at low and high β the light yield increases quadratically with g . The light yields in NE110 and in the MACRO liquid scintillator are approximately equal (within a few percent) and only one curve is drawn. The light yield at low beta has to be considered a lower limit, since the present calculations do not take into account possible contributions that can arise from the mixing and crossing (Drell effect) of molecular electronic energy levels at the passage of the magnetic charge; this could result in molecular excitations and emission of light.

The Ahlen-Tarlé curve shown in Fig. 1, refers to the calculation of [10] which predicts a kinematical cut off at $\beta = 7 \times 10^{-4}$ due to the excitation energy of benzene molecules (5 eV); however experiments with low energy protons [11] have shown that in fact no such cut off occurs.

2.2 Light Yield in Scintillators for Dyons

For dyons we distinguish two contributions to the light yield in scintillators : primary and secondary light yields.

The *primary light yield* is due to the direct excitation and ionization produced by the dyon. The energy losses are the sum of the magnetic contribution already considered and of the electric contribution.

For $Q = e$ the electric contribution is given by Eq. 8 for $\beta < 4.6 \times 10^{-3}$. For $\beta > 4.6 \times 10^{-3}$ we computed (Eq. 7) the electric contribution to dE/dx

from the parametrizations used in refs. [15,16]. At high velocities ($\beta > 0.01$) these parametrizations reduce to the familiar Bethe-Bloch formula.

For an incident electric charge ($Q = Z_1 e$) we have the following energy losses [15,16]

$$\left(\frac{dE}{dx}\right)_{Z_1} = \begin{cases} \frac{8\pi e^2 a_0 \beta}{\alpha} \frac{Z_1^{7/6} N_e}{(Z_1^{2/3} + Z_2^{2/3})^{3/2}} \left\{1 - e^{-(\beta/7 \times 10^{-4})^2}\right\} & \text{for } \beta < 10^{-2} \\ \text{a smooth interpolation} & \text{for } 10^{-2} < \beta < 0.05 \\ \left(\frac{dE}{dx}\right)_{Z=1} Z_1^2 \left(1 - e^{-\frac{0.92\beta}{\alpha Z_1^{2/3}}}\right) & \text{for } \beta > 0.05 \end{cases} \quad (10)$$

where Z_2 is the atomic number of the target atom, N_e the density of electrons, α the fine structure constant. The weighted sum over the different atomic species (C and H) was made.

For dyons the energy losses are larger than for MM, and a *secondary light yield* from the elastically recoiling hydrogen and carbon nuclei of the medium must be considered. The primary light yield L_p of a hydrogen or carbon nucleus of given initial energy E is computed as

$$L_p(E) = \int_0^E \frac{dL}{dx}(\epsilon) S_{\text{tot}}^{-1} d\epsilon \quad (11)$$

where S_{tot} is the sum of electronic and nuclear energy losses. The nuclear energy losses are given in ref. [18]. The secondary light yield is then

$$\left(\frac{dL}{dx}\right)_{\text{secondary}} = N \int_0^{T_m} L_p(T) \frac{d\sigma}{dT} dT \quad (12)$$

where T_m is the maximum energy transferred and $\frac{d\sigma}{dT}$ is the differential scattering cross section, given in ref. [19].

In Fig. 2 the results of the computation for $g = g_D$ and $Q = e$ and $Q = 13 e$ (corresponding to the detection threshold in mica [32]) are shown. The contribution from the primary light yield has a behaviour similar to that for MMs, see curves labeled MM and M+p (the contribution from the secondary yield is small and does not alter the shape of the curve). For M+Al ($g = g_D$, $Q = 13e$) the secondary contribution is much higher and it is the main cause of the difference between the M+p and M+Al curves for $\beta < 0.1$.

At higher β the δ rays contribute and the saturation is removed: the separation between the two curves occurs because of the different electric energy losses; but at very high velocity $\beta \simeq 1$, where the electric energy losses and the nuclear scattering cross section are very small, the two curves join together again.

The light yield at low beta is a lower limit as explained for MMs. Thus one could extend to lower velocities the scintillator searches for dyons.

3 Energy Losses of MM and Dyons in the Streamer Tubes

The composition of the gas in the MACRO limited streamer tubes is 73% helium and 27% n-pentane in volume [10]. The pressure is about one atmosphere and the resulting density is very low (in comparison with the density of the other detectors): 0.856 mg/cm^3 .

The energy losses of MMs in the streamer tubes have been discussed in refs. [21,22] while the energy losses of dyons are given in refs. [23,24].

3.1 Energy Losses of MMs in the Streamer Tubes

At *high velocities*, $\beta > 0.05$, formula (4) holds for the energy losses of MMs in the streamer tubes. The ionization potential of the medium is 50 eV; the resulting energy losses are given in Fig. 3, as curves A.

At *low velocities*, $10^{-4} < \beta < 10^{-3}$, and for $g = g_D$ in helium, the Drell effect occurs: the energy levels of the helium atoms are changed by the presence of a magnetic charge, and at the passage of the magnetic charge an electron can make a transition to an excited level [23]:

$$\left(\frac{dE}{dx}\right)_{Drell} = 11(\beta/10^{-4})[1 - (9.3 \times 10^{-5}/\beta)^2]^{3/2} \text{ MeV cm}^2/\text{g} \quad (13)$$

Such energy losses lead to the atomic excitation of helium atoms; these lead in turn to the ionization of the n-pentane molecules via the Penning effect. The results of the calculation performed in ref. [23] are valid for $10^{-4} < \beta < 10^{-3}$. When considering the Drell effect for magnetic charges greater than g_D one

encounters several difficulties. In the computation one must use the wave functions of electrons in helium atoms with a monopole at the centre (dyonic helium); the validity of the method is uncertain, since many approximations on which the classical approach is based, break down. In particular the MM is assumed to be near the nucleus during the interaction (dipole approximation) but the resulting cross section becomes larger than the squared Bohr radius (a_0^2) for increasing magnetic charge (it is quite large even for $g = g_D$). We prefer to use the estimates of Kroll et al. [21] who predict that the cross section for $g = 2g_D$ is at least 2.3 times larger than the cross section for $g = g_D$; for greater magnetic charges we estimate the energy losses assuming the same dependence for MM in hydrogen and helium [21]

$$\frac{(dE/dx)_{g=ng_D, He}}{(dE/dx)_{g=g_D, He}} = \frac{(dE/dx)_{g=ng_D, H}}{(dE/dx)_{g=g_D, H}} \quad (14)$$

we also neglect the problem of the break down of the dipole approximation when $\sigma > a_0^2$. The results of the procedure are shown in Fig. 4.

The two above approximations lead to values which may be uncertain within a factor of two [20].

The velocity threshold is nearly the same for different magnetic charges, because it depends on the square root of the energy of the levels from which the transitions occur; these levels can be different for different magnetic charges, but the excitation energies of the helium atom are all between 20 and 25 eV; therefore the velocity thresholds are to within 15% the same for different g values. The results are shown in Fig. 3, as curves C ($10^{-4} < \beta < 10^{-3}$).

At *intermediate velocities*, $2 \times 10^{-3} < \beta < 7 \times 10^{-2}$, the usual approach is to consider the medium as a degenerate electron gas; this is not strictly correct for insulators with low Z [24]; moreover this approximation can be valid only at sufficient high densities, that is, in condensed media, as stated in [24]. At low densities, the electrons are not free, but bound in well separated molecules. In the absence of analytical calculations for the energy losses of MMs of intermediate velocities in gases, we assume that the magnetic energy losses are about $(g/2g_D)^2$ times the energy losses of protons [15] of the same speed, which is true in condensed media [10, 24]. The same assumption was

used in ref. [25]. The result is

$$\left(\frac{dE}{dx}\right) = 1.7 \times 10^5 \times (g/2g_D)^2 \text{ MeV g/cm}^2 \quad (15)$$

for $2 \times 10^{-3} < \beta < 10^{-2}$. The results are shown in Fig. 3, as curves B.

For $10^{-3} < \beta < 2 \times 10^{-3}$ and for $10^{-2} < \beta < 0.05$ we use smooth interpolations. In Fig. 3, the dashed lines indicate regions where the calculations are less reliable than those for the solid curves.

The uncertainties in the ionization energy level should not be too important for the calculations of the MACRO acceptance. This should not depend on the ionization level, provided that this level is above a certain value. For $\beta < 5 \times 10^{-3}$ a monopole is detected by the streamer tubes as a slow particle which produces a hit, if the ionization is greater than about $10^{-2} I_{\min}$, where $I_{\min}$ corresponds to the minimum ionizing particle.

For $\beta > 5 \times 10^{-3}$ the monopoles can be easily discriminated from muons because of the high ionization produced (above $100 I_{\min}$ for $g = g_D$ MMs).

As multiply charged MMs loose surely more energy than singly charged ones [21] we do not expect the streamer tube acceptance for $g > g_D$ to be very different from that for $g = g_D$.

3.2 Energy Losses of Dyons in the Streamer Tubes

At *high velocities* ($\beta > 0.05$) the energy losses are computed using the Bethe-Bloch formula for electric charges added to the energy losses from magnetic charges (see previous subsection). The results are shown in Fig. 5, as curves A for $g = g_D$ and $Q = e$ and $Q = 13 e$.

At *intermediate velocities* ($2 \times 10^{-3} < \beta < 10^{-2}$) the electric energy losses for $Q = e$ are discussed in subsection 2.2 (in fact, as explained above, we assume that the electric energy losses of a proton are equal to those of a doubly charged MM of the same β). For $Q = 13 e$ the energy losses are computed again from Eq. 10, first line, except that we omitted the exponential factor which takes into account the energy gap in organic scintillators. The results are shown in Fig. 5 as curves B.

At *low velocities* ($10^{-4} < \beta < 10^{-3}$) the energy losses are due to the Drell effect. We rely on the calculations of ref. [22]. Let us consider a dyon

with $g = g_D$ and $Q = +e$. This positively charged dyon can capture an electron (as slow protons do) if the dyon is sufficiently slow. The capture cross section is of the order of atomic dimensions [27] and the capture occurs almost immediately. Dyons with these velocities arrive at MACRO after several hundred meters of rock; they are likely to have an electron attached (such a system is also called “dyogen”). It may be worth mentioning that, according to ref. [22] for such a system passing through helium or hydrogen, the process with the larger cross section is not the excitation of the helium or hydrogen atoms, but the excitation of dyogen to the first excited level at 6.8 eV above the ground state; this energy is however not sufficient to ionize the n-pentane whose ionization energy is 10.35 eV. The ionization can occur only after the excitation of the helium atoms. The screening effect of atomic electrons can be neglected in computing the excitation cross section of dyogen [22]; it is also possible to neglect the dyogen electron in computing the excitation cross section. This means that the excitation cross section of a helium atom by a dyon (which is also computed in ref. [22]) is equal to the cross section for excitation of a dyon+electron. Using this result we have drawn curve C in Fig. 5.

The dashed lines of Fig. 5, correspond to smooth interpolations.

For dyons of larger electric charge the situation becomes more complex. The dyon of electric charge $Z_1 e$ will have Z_1 electrons, and the resulting electronic structure is in fact known numerically only for spherically symmetric atoms like $Z_1 = 2$ and $Z_1 = 10$ [23]. We have not computed the excitation cross section, but we have only estimated the threshold of the effect. Excitation is greatly reduced if the minimum approach distance is greater than the Bohr radius a_0 , owing to electron screening which sharply reduces the electric potential responsible for inducing the transitions between atomic levels (the magnetic charge has only the effect of changing the levels). The distance of closest approach for zero impact parameter is $2Z_1 Z_2 e^2 / (mc^2 \beta^2)$ where m is the helium mass and Z_2 is the helium charge; for $\beta < (2Z_1 Z_2 e^2 / a_0 m c^2)^{1/2} = 1.7 \times 10^{-4} Z_1^{1/2}$ the excitation cross section sharply drops [22]. For $Z_1 = 13$, the threshold is $\beta \simeq 6 \times 10^{-4}$. Owing to the good sensitivity of streamer tubes (of the order of one hundredth the ionization produced by a slow dyogen) we expect that a dyon can be detected for all velocities above threshold.

4 Energy losses of MMs and Dyons in the CR39 Nuclear Track Detector

The quantity of interest for the CR39 nuclear track detector is the Restricted Energy Loss (REL), that is, the energy deposited within $\sim 100 \text{ \AA}$ from the track. The REL in CR39 has already been computed for MMs of $g = g_D$ and $g = 3g_D$ and for $Q = e$, $g = g_D$ dyons [26-28]. We have checked these calculations and extended them to other cases of interest.

The chemical composition of CR39 is $\text{C}_{12}\text{H}_{18}\text{O}_7$, and the density is 1.31 g/cm^3 .

For computation of the REL only energy transfers to atoms above 12 eV are considered, because it is estimated that 12 eV are necessary to break the molecular bounds [32].

4.1 Energy losses of MMs in CR39

At *high velocities* ($\beta > 0.05$) Eq. 7 applies for the MM total energy losses. The Restricted Energy Losses (REL) are obtained excluding the energy transfers which result in δ -ray production and thus in energy deposited far away from the track. The result is [30]

$$\text{REL} = \begin{cases} \frac{\omega_p^2 g^2}{c^2} \left[\ln \left(\frac{1.123 \beta c \gamma \sqrt{\epsilon-1}}{b \omega_p} \right) - \frac{1}{2} \right] & , \text{ if } \beta < 1/\sqrt{\epsilon} \simeq 0.8 \\ \frac{\omega_p^2 g^2}{c^2} \left[\ln \left(\frac{1.123 c}{b \omega_p} \right) + \frac{1-1/\beta^2}{2(\epsilon-1)} \right] & , \text{ if } \beta > 1/\sqrt{\epsilon} \simeq 0.8 \end{cases} \quad (16)$$

where $\omega_p^2 = \frac{4\pi N_e e^2}{m_e}$, N_e is the electron density, I is the mean ionization potential, m_e is the electron mass, ϵ is given by $\sqrt{\epsilon/(\epsilon-1)} = 0.562 I / \hbar \omega_p$, $b = 1.123 \hbar c / \sqrt{2 m_e c^2 \omega_0}$ is the minimum impact parameter below which production of δ rays (electrons with energy above ω_0) occurs. For the CR39 $\omega_0 \simeq 200 \text{ eV}$, $I \simeq 73 \text{ eV}$, $\epsilon \simeq 1.6$. The results are shown in Fig. 6, curves A.

At *lower velocities* ($\beta < 10^{-2}$) there are two contributions to REL:

1) The contribution due to *ionization* (for $3 \times 10^{-4} < \beta < 10^{-2}$). In this β -range, one has $\text{REL} \simeq (dE/dx)_{\text{ionization}}$. The energy losses can be computed assuming that the medium is a degenerate electron gas; for $3 \times 10^{-4} < \beta < 10^{-3}$ an energy gap of 4 eV is introduced. For $10^{-3} < \beta <$

10^{-2} we applied the formula of Ahlen-Kinoshita [24] for nonconductors

$$\frac{dE}{dx} = \frac{2\pi N_e g^2 e^2 \beta}{m_e c v_F} \left[\ln \frac{2m_e v_F a_0}{\hbar} - 0.5 \right] \quad (17)$$

where $v_F = \frac{\hbar}{m_e} (3\pi^2 N_e)^{\frac{1}{3}} \simeq 2.68 \times 10^8$ cm/s is the Fermi velocity of electrons and a_0 is the Bohr radius. One should also include a contribution to the energy losses coming from the electron magnetic moments; in ref. [24] there is a rough estimate of this contribution which increases the values given by Eq. 17 by a factor of about 4/3.

According to Ritson [31] for $3 \times 10^{-4} < \beta < 10^{-3}$ the ionization energy losses are lower than what predicted by Eq. 17. We assume in this range of β the following parametrization

$$\left(\frac{dE}{dx} \right)_{\text{ionization}} \simeq 2.6 \times 10^6 \left(\frac{g}{g_D} \right)^2 \beta^{1.7} \quad \frac{\text{MeV g}}{\text{cm}^2} \quad (18)$$

2) The contribution due to the *elastic recoil of atoms* (for $3 \times 10^{-5} < \beta < 10^{-2}$). The numerical procedure to compute this contribution can be found in ref. [28, 32]. The elastic recoil is due to the diamagnetic interaction between the MM and the carbon and oxygen atoms of the medium; the contribution of hydrogen atoms is expected to be relatively small and has been neglected. The potential between the atoms and the magnetic charge was first estimated by Price [33] for $g = g_D$ poles; he obtained

$$V(R) = \begin{cases} V_0(g) e^{-4.45R} & \text{for } R < 0.3 \\ \frac{0.097 Z (g/g_D)^2}{R^4} & \text{for } R > 0.3 \end{cases} \quad (19)$$

where V , V_0 are in eV and R in Å. In ref. [32] we have used this expression for $10^{-5} < \beta < 10^{-2}$; $V_0(g)$ was estimated for arbitrary magnetic charges as the energy shift of the $1s$ atomic level when a MM is added at the centre of atom; this approach neglects the other atomic levels and it gives only an estimate of the magnitude of V_0 . Nakamura [28] has taken the expression of Price for $R < 0.3$ Å and used it also for $R > 0.3$ Å; he also assumed a potential with a quadratic dependence on the magnetic charge (g^2).

We use the potential of Nakamura for the calculation of REL as it is the potential used in previous calculations of REL in CR39 [29]. The use of the

method of ref. [32] would only affect a little (around 1-2 %) the acceptance for $\beta < 10^{-4}$. The results are shown in Fig. 6, curves B.

The atomic elastic recoil contribution gives rise to a bump in REL, see Fig. 6, at $\beta \sim 10^{-4}(g/g_D)$. The ionization contribution dominates at β higher than the value at which the minimum REL occurs. For $10^{-2} < \beta < 10^{-1}$ a smooth interpolation has been performed. As shown in Fig. 6, MM's with $g \geq 2g_D$ can be detected by the CR39 detector for $\beta > 3 \times 10^{-5}$.

4.2 Energy Losses of Dyons in CR39

For dyons the ionization energy losses are the sum of the energy losses due to the magnetic charge and the energy losses due to the electric charge of the dyon.

At *high velocities* ($\beta > 0.03$), we use for the electric REL [30]

$$REL_{elec} = \begin{cases} \frac{\omega_p^2 Z_{eff}^2 e^2}{c^2 \beta^2} \left[\ln \left(\frac{1.123 \beta c \gamma \sqrt{\epsilon-1}}{b \omega_p \sqrt{\epsilon}} \right) - \frac{\beta^2}{2} \right] & , \text{ if } \beta < 1/\sqrt{\epsilon} \simeq 0.8 \\ \frac{\omega_p^2 Z_{eff}^2 e^2}{c^2 \beta^2} \left[\ln \left(\frac{1.123 \beta c}{b \omega_p} \right) + \frac{1-\beta^2}{2(\epsilon-1)} \right] & , \text{ if } \beta > 1/\sqrt{\epsilon} \simeq 0.8 \end{cases} \quad (20)$$

with

$$Z_{eff}^2 = \begin{cases} 1 & , \text{ for } Z = 1 \\ Z^2 \left(1 - e^{-\frac{126\beta}{Z^{2/3}}} \right) & , \text{ for } Z > 1 \end{cases} \quad (21)$$

Z_{eff} is the dyon effective electric charge [17]. The symbols have the same meaning as in Eq. 16. The results are shown in Fig. 7, curves A.

At *low velocities* ($3 \times 10^{-5} < \beta < 10^{-2}$) there are two contributions to REL: the ionization and the atomic recoil one.

The *ionization contribution* was computed with Ziegler's fit to the experimental data [15]; this contribution is equal to the electric REL at these velocities.

We computed the *atomic recoil contribution* to REL using the interaction potential between an atom and a dyon which is equal to the sum of the diamagnetic potential [28] and the electric potential [18]; then we applied the same procedure used for MM's.

The results are shown in Fig. 7, curves B. We conclude that dyons can be detected by the CR39 detector for $\beta > 3 \times 10^{-5}$.

5 Total Energy Losses in Scintillators, Streamer Tubes and CR39

In the previous Sections we have computed and discussed the fractions of the energy losses of MMs and dyons to which the considered detectors are sensitive; we did not take into account the energy losses due to elastic collisions with the atoms of the streamer gas which do not produce ionization and therefore are not useful for the detection by the streamer system.

In this Section we compute the total energy losses in Scintillators, Streamer Tubes and CR39. The knowledge of these losses may be useful for a possible search for light MMs or dyons with an array at the Earth surface; in this case, a light particle can loose in a detector a significant fraction of its energy or even stop in it, and the total energy losses are required to estimate those effects.

Let us consider first the **Scintillators** and the **Streamer Tubes**. At *high velocity* ($\beta > 0.05$) the total energy losses of MM in scintillators and streamer tubes are mainly due to ionization; we calculated these using the Bethe-Bloch formula. At *intermediate* β (a few $10^{-3} < \beta < 10^{-2}$) the main contribution to energy losses is again due to ionization, and we used Eq. (17). The results are shown as curves A in Fig. 8 for MMs in scintillators, in Fig. 9 for dyons in scintillators, in Fig. 10 for MMs in streamer tubes, in Fig. 11 for dyons in streamer tubes.

At *low velocity* ($10^{-5} < \beta < 10^{-3}$) the dominant energy loss mechanism is that of elastic collisions with the atoms as a whole. This contribution was computed according to the numeric procedures explained in ref. [32], neglecting the hydrogen atoms (which means that we obtained a lower limit for the energy losses). The potential of ref. [32] was used for computing the energy losses in the streamer tubes and in the scintillators, while the potential of ref. [28] was used for CR39. The results are shown as curves B in Fig. 8 for MMs in scintillators, in Fig. 9 for dyons in scintillators, in Fig. 10 for MMs in streamer tubes, in Fig. 11 for dyons in streamer tubes.

In the transition regions between curves A and B ($\beta \sim 10^{-3}$), the two contributions to the energy losses (elastic collision and ionization) are added.

Notice (Fig. 10 and Fig. 11) that for the streamer tubes the energy losses from elastic collisions with atoms dominate over the energy losses due to the Drell effect, also because the Drell effect is considered only on helium which

is a small fraction, in mass, of the considered streamer tube gas. We do not know the magnitude of the Drell effect for dyons with electric charge $13\ e$; it should be much smaller than the contribution from elastic collisions.

The total energy losses in CR39 can be computed from the procedure of Section 4, with the following modifications:

- substitution of equations 16 and 20 with equation 7 and the Bethe-Bloch formula, respectively;
- disregard the 12 eV cut on the energy of the recoiling atoms.

The results are shown as curves A and B in Fig. 12 for MMs and in Fig. 13 for dyons, respectively.

The interpolations are shown as dashed lines.

6 Conclusions

In this paper we have presented systematic computations of the energy deposited in scintillators, streamer tubes and CR39 nuclear track detectors by magnetic monopoles and dyons in forms useful for their detection. In particular we computed the light yield in scintillators, the ionization in streamer tubes and the REL in nuclear track detectors. The computations were made for magnetic monopoles with different charges ($g = g_D, 2g_D, 3g_D, 6g_D, 9g_D$) and for dyons (or MM-nucleus composites) for a large range of $\beta = v/c$ ($\beta > 10^{-5}$). Also the total energy losses have been computed and discussed.

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Figure 1: Light yield of MMs in the plastic scintillator NE110 ($\rho = 1.032 \text{ g/cm}^3$) and in the MACRO liquid Scintillator ($\rho = 0.86 \text{ g/cm}^3$), as a function of the velocity βc for different magnetic charges g . No significant difference was found between the two scintillators. The Ahlen-Tarlé curve refers to the calculations of ref. [8] which were proved incorrect by the experimental measurements reported in ref. [9]. The light yield from a minimum ionizing muon is shown for comparison. See text for the explanation of regions A, B and C.

Figure 2: Light yield of dyons with $g = g_D$ and $Q = +e$ (or of a M+p composite), and $g = g_D$ and $Q = +13e$ (or of a M+Al composite) in plastic scintillator NE110 (dashed lines) and in the MACRO liquid scintillator (solid lines) as a function of β .

Figure 3: Energy losses produced in the limited streamer tubes filled with 73% He, 27% n-pentane, $\rho = 0.856 \text{ mg/cm}^3$, by MMs as a function of β , relative to the ionization produced by a minimum ionizing particle, $I_{min} = 2.2 \text{ MeV g/cm}^2$. See text for the explanation of regions A, B and C. Notice that the solid curves represent the regions where the calculations are more reliable; the dashed lines are interpolated values.

Figure 4: The cross sections for the Drell effect induced by MMs in helium as a function of β , computed with the procedure described in the text. The validity of the calculations is uncertain for cross sections larger than the squared Bohr radius a_0 , shown as a dashed horizontal line.

Figure 5: Energy losses, relative to the ionization produced by a minimum ionizing particle, $I_{\min} = 2.2 \text{ MeV g/cm}^2$, produced in the limited streamer tubes filled with 73% He, 27% n-pentane, ($\rho = 0.856 \text{ mg/cm}^3$) by dyons with $g = g_D$ and $Q = +e$ (or by a M+p composite) and $g = g_D$ and $Q = +13 e$ (or by a M+Al composite) as a function of β . See text for the explanation of regions A, B and C. The solid curves represent regions where the calculations are more reliable, while the dashed lines are interpolations.

Figure 6: Restricted Energy Losses of MMs as a function of β in the nuclear track detector CR39 ($\rho = 1.31 \text{ g/cm}^3$). The detection thresholds of two types of CR39 used by MACRO experiment [34] (EN3 and L6) are also shown ref. [10,31]. Notice that the solid curves represent β regions where the calculations are more reliable, the dashed lines are interpolations. See text for explanations about curves in regions A and B.

Figure 7: Restricted Energy Losses of dyons with $g = g_D$ and $Q = +e$ (or of a M+p composite) or $g = g_D$ and $Q = +13 e$ (or of a M+Al composite) as a function of β in the nuclear track detector CR39 ($\rho = 1.31 \text{ g/cm}^3$). The detection thresholds of two types of CR39 (EN3 and L6) are also shown. The solid curves represent regions where the calculations are more reliable, the dashed lines are interpolations. See text for explanation of the curves in the regions A and B.

Figure 8: Total energy losses of MMs in the MACRO liquid scintillator, as a function of the velocity βc for various magnetic charges g . The dashed lines indicate interpolations. See text for the explanation of curves in regions A and B.

Figure 9: Total energy losses of dyons with $g = g_D$ and $Q = +e$ (or M+p) and $g = g_D$ and $Q = +13 e$ (or M+Al) in the MACRO liquid scintillator, as function of β . The dashed lines indicate interpolations. See text for the explanation of regions A and B.

Figure 10: Total energy losses in the limited streamer tubes filled with 73% He, 27% n-pentane by MMs as function of β . Notice that the solid curves represent regions where the calculations are more reliable, the dashed represent interpolations. See text for the explanation of regions A and B.

Figure 11: Total energy losses in the limited streamer tubes filled with 73% He, 27% n-pentane by dyons with $g = g_D$ and $Q = +e$ (or M+p) and $g = g_D$ and $Q = +13 e$ (or M+Al) as function of β . Notice that the solid curves represent regions where the calculations are more reliable, the dashed lines represent interpolations. See text for the explanation of regions A and B.

Figure 12: Total energy losses of MMs as function of β in the nuclear track detector CR39. Notice that the solid curves represent regions where the calculations are more reliable, the dashed lines represent interpolations. See text for the explanation of regions A and B.

Figure 13: Total energy losses of dyons with $g = g_D$, $Q = +e$ (or M+p) and $g = g_D$, $Q = +13 e$ (or M+Al) as function of β in the nuclear track detector CR39. Notice that the solid curves represent regions where the calculations are more reliable, the dashed lines are interpolations. See text for the explanation of regions A and B.