Searches for monopoles
DESY Theory Workshop Seminar

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1 Introduction

In this note I will go through some of the various ways in which people have tried to observe or constrain magnetic monopoles. I am no expert on the topic, but hopefully, you will find that the note gives you a useful overview of the various approaches. There are three main avenues through which one can attempt to constrain monopoles. These are:

- Colliders
- Astrophysics
- Direct detection

In this note, we will briefly discuss all of these subjects. However, because the astrophysical constraints lend themselves more to theoretical discussion I have focused more on them.

2 Quick recap: Dirac quantization condition

Recall from the first lecture in our workshop seminar series that the Dirac quantization condition requires the magnetic charge[1] g to be quantized in terms of the fundamental electric charge e:

$$g = n\frac{2\pi}{e}. \tag{1}$$

In natural units we have $2\pi = e^2/2\alpha$ where $\alpha \approx 1/137$ is the fine structure constant. Therefore, we can also write the quantisation condition as

$$g = \frac{ne}{2\alpha} \approx 69n \times e. \tag{2}$$

The minimal charge that a monopole can have is then $g_{\text{min}} \approx 69e \approx 21$. Most of the constraints discussed here assume this charge.

[1] The magnetic charge is normalized somewhat differently here than in the first lecture. Specifically, the conventions differ by a factor of 4π. I stick to the convention of [1], so that the references can be followed with the expressions given here.

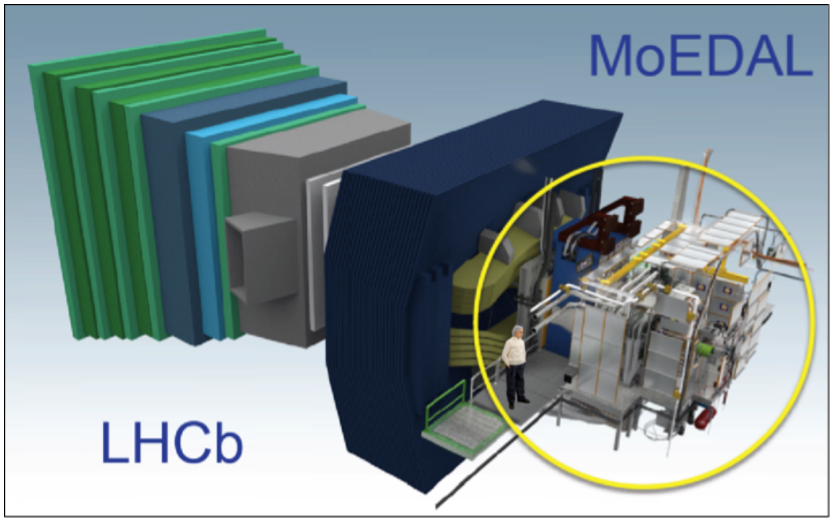

Figure 1: Illustration of the MoEDAL dectector installed at LHCb. Taken from the MoEDAL webpage: moedal.web.cern.ch.

3 Collider constraints

We expect a GUT monopole much too heavy to detect. Specifically, if a GUT monopole has a mass of the order of the GUT scale then it is 10^{12} times too heavy to be accessible at the energies available at the LHC. Nonetheless, if monopoles much lighter than GUT monopoles exist these might be detectable.

Magnetic monopoles are strongly interacting and long-lived. However, the primary LHC experiments might not be ideally configured to search from them. Instead, dedicated detected have been built at the LHC and other colliders to search for light monopoles. The most sensitive such detector is MoEDAL[2, 3], which is located at LHCb. MoEDAL is a largely passive experiment consisting of plastic nuclear track detector sheets placed around LHCb. The sheets are removed from the detector and analysed offline by ultra-fast scanning microscopes. An illustration of the experiment is found in figure 1.

Normally, long-lived highly ionizing particles (HIP) are not sensitively reconstructed by ATLAS. However, when configured with customized triggers this sensitivity is significantly enhanced [4, 5], and ATLAS currently provides the strongest bound on the production cross section of monopoles with masses less than a few TeV.

Interestingly, searches for monopoles were also carried out at HERA and PETRA at DESY. A comparison of such historical searches is found in figure 2 and the most recent results from PDG[6], which includes ATLAS and MoEDAL results, are found in figure 3.

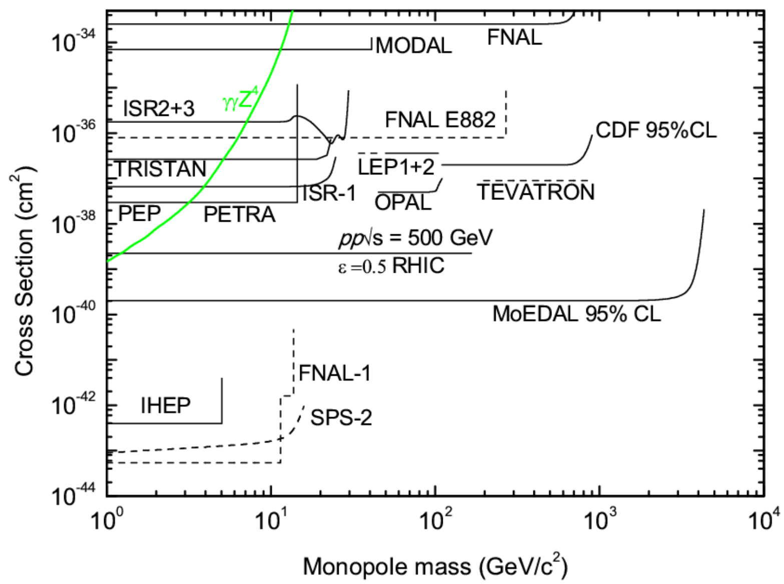

Figure 2: Cross section upper limits on monopole production from past searches at accelerators/colliders. The plot is dated 2011, so the MoEDAL bound is a projection from the planned MoEDAL sensitivity. The plot is taken from [7].

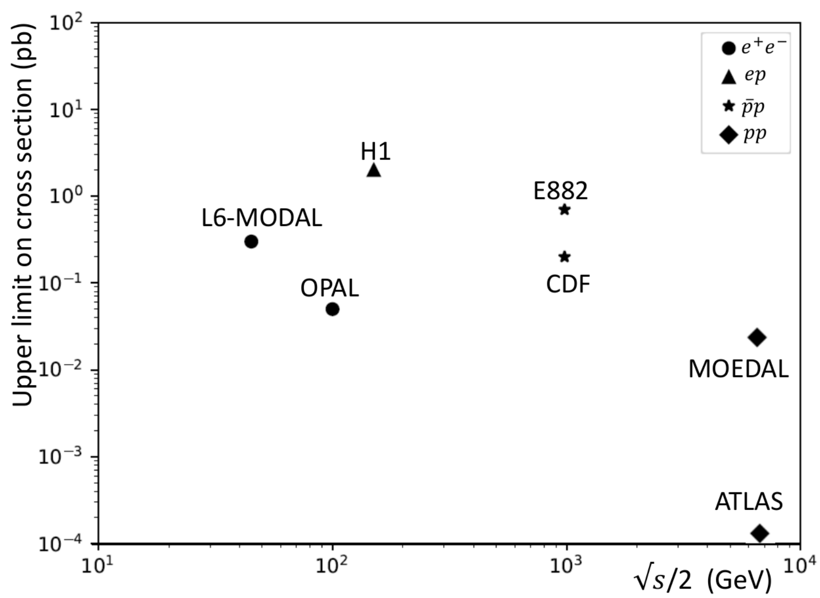

Figure 3: Most recent collider constraints from PDG[6]. Includes up-to-date constraints from MoEDAL and ATLAS.

4 Astrophysical constraints

Although GUT monopoles would be many orders of magnitude too heavy to produce in a collider experiment they would generate astrophysical effects that we can observe. The most significant of these concerns the galactic magnetic fields, which can be used to constrain the presence of free magnetic charges. Such a study was proposed by Parker in 1970 [8] and the constraints derived by Turner, Parker and Bogdan in 1982 [1] are still the current bounds quoted by the PDG.

The constraints are conventionally given on the monopole flux F. This flux is conventionally measured in units of cm^{-2} sec^{-1} sr^{-1}, where sr stands for steradian and is the unit of solid angle.

4.1 The Parker bound

Free magnetic charges can dissipate a magnetic field. This is in complete analogy with the dissipation of electric fields by free electric charges within a conductor, where the field is dissipated unless the field is continuously regenerated by an external energy supply. In both cases, free charges are accelerated by the fields. This transfers energy from the field to the kinetic energy of the said charge. The field is damped in direct proportion to the energy lost unless it is continuously generated at last as fast as the energy is transferred to free charges.

Galactic magnetic fields of approx $B_c \sim 3\mu G$ are observed to exist. These can be assumed to be generated on a time-scale of $t_{\text{gen}} \sim 10^{15}$ sec $\sim 3 \times 10^7$ yr. We will not go into how such fields are generated, but see e.g. [9] for an introduction. If magnetic monopoles exist, these would be accelerated by the fields and thus dissipate the energy. The Parker bound is then derived by asking which flux F of monopoles would lead to a dissipation more rapid the regeneration:

$$\frac{\partial B}{\partial t}_{\text{monopoles}} < \frac{\partial B}{\partial t}_{\text{regenerated}} \tag{3}$$

We here discuss bound as derived in [1] so that we can derive the current bound as quoted by PDG.

Structure of galactic magnetic field: The model for the galactic magnetic field which is proposed in [1] is somewhat analogous to that seen in a regular ferromagnet. The overall magnetic structure is modelled with many magnetic subdomains, which we here will refer to as magnetic cells. These cells all have magnetic fields on the order of $B_c \sim 3\mu G$, but the orientation of the fields are assumed to vary randomly between each cell. These cells have a characteristic scale of $l_c \sim 0.3$ kpc, while the overall structure has a scale on the order of $r_g \sim 10$ kpc. This structure is illustrated in figure 4.

Acceleration: A magnetic monopole placed in a magnetic field behaves very much like an electric charge placed in an electric field. Specifically, a monopole

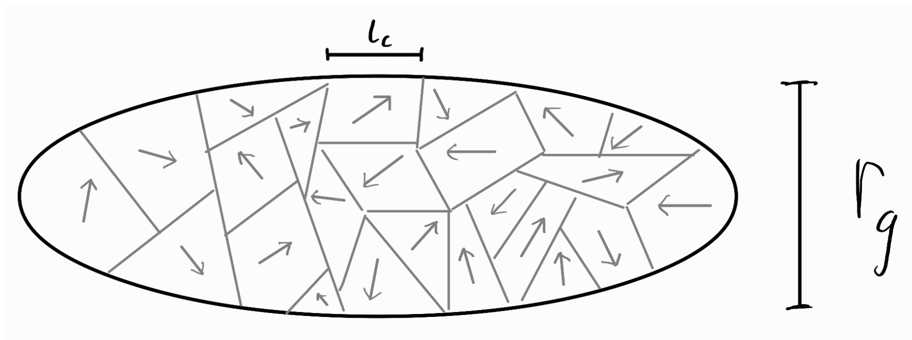

Figure 4: Configuration of the galactic magnetic field as assumed in [1]: A galactic magnetic field of scale $r_g \sim 10$ kpc is is divided into magnetic subdomains. These domains, or cells, are then assumed to have a magnetic field strength of order $B_c \sim 3\mu G$ with an orientation which varies randomly between cells. The cells are assumed to have a characteristic size of $l_c \sim 0.3$ kpc.

of magnetic charge g placed in a field of strength B_c is accelerated as

$$F_{\text{mag}} = gB_c \approx 0.06 \text{ eV} \left(\frac{B_c}{3\mu G}\right) \tag{4}$$

If we ignore any initial velocity that the monopole might have had, then after having traversed a cell of size l_c the monopole has gained the kinetic energy of

$$E_{\text{kin}} = gB_c l_c \approx 0.6 \times 10^{20} \text{ eV} \left(\frac{l_c}{0.3\text{kpc}}\right)\left(\frac{B_c}{3\mu G}\right) \tag{5}$$

The magnetic field of the cell has given the monopole a velocity of

$$v_{\text{mag}} \approx 10^{-3} c \left(\frac{l_c}{0.3\text{kpc}}\right)^{1/2} \left(\frac{B_c}{3\mu G}\right)^{1/2} \left(\frac{10^{17} \text{ GeV}}{M}\right)^{1/2}, \tag{6}$$

where we assumed that the particle started from rest. This characteristic velocity should be compared to the virial velocity which is associated with the gravitational potential. This is

$$v_{\text{vir}} \sim 10^{-3} c. \tag{7}$$

We, therefore, have two regimes that depend on the monopole mass M:

$$M \gg 10^{17} \implies v_{\text{vir}} \gg v_{\text{mag}} \implies \text{Gravity dominates}$$
$$M \ll 10^{17} \implies v_{\text{mag}} \gg v_{\text{vir}} \implies \text{Magnetic kick dominates}$$

These regimes can be interpreted as follows: In the high mass regime ($> 10^{17}$ GeV) the kinetic energy gained by the monopole is small compared to that implied by virial motion of the monopole. Therefore, the kick given by a magnetic

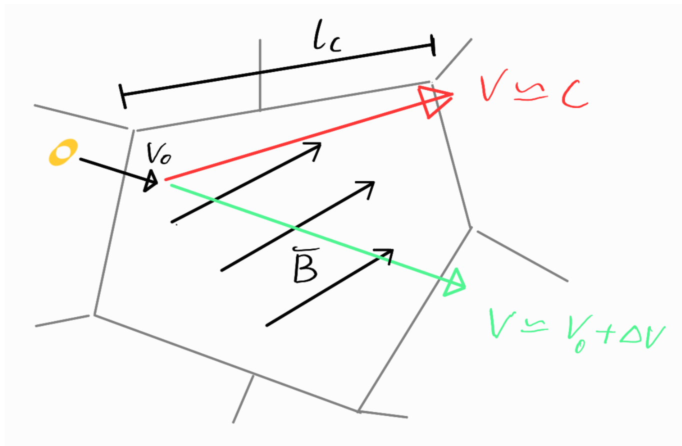

Figure 5: Illustration of the acceleration of a monopole (yellow) across a magnetic cell of size l_c. Red: In the low mass regime the monopole is efficiently accelerated by the cell. Green: In the high mass regime the monopole receives only a perturbation of the initial velocity.

cell results in a small perturbation of the monopole velocity. The monopole can thereby maintain a low velocity of order $v_{\rm vir} \sim 10^{-3}c$ and thus not immediately get ejected from the galaxy[2]. In contrast, in the "low" mass regime ($< 10^{17}$ GeV) the monopole is accelerated well beyond $v_{\rm vir}$. It is therefore rapidly accelerated across many cells until ejected from the galaxy. See figure 5.

Magnetic kick dominates In the low-mass regime, where the magnetic kick dominates, we can describe the history of a single monopole entering the galaxy as a random walk in which the monopole dissipates energy according to eq. 5 in each step. If the monopole has to cover a distance of r_g to escape, and each step is of order l_c, then by crossing the galaxy a single monopole dissipates a total energy of

$$E_{\rm cross} \approx \sqrt{\frac{r_g}{l_c}} g B_c l_c \tag{8}$$

This should be compared to the energy of the magnetic field in the same region:

$$E_{\rm mag} \approx \frac{B^2}{2} \times \frac{4}{3}\pi r_g^3. \tag{9}$$

Instead of a single monopole we now consider a flux of monopoles entering the galaxy. This flux measures the number of monopoles pr. area pr. solid angle pr

[2] More precisely, for a monopole cloud to remain gravitationally bound on the timescale of the age of the universe, the monopole mass has to be higher than 10^{19} GeV. This also makes monopoles poor dark matter candidates. See ref. [1] for more discussion on this point.

time. The total amount of energy dissipated by a flux F is then

$$\frac{\partial E}{\partial t}_{\text{monopoles}} \approx F \times (\pi \text{ sr }) \times (4\pi r_g^2) \times E_{\text{cross}}. \tag{10}$$

By demanding

$$\frac{\partial E}{\partial t}_{\text{monopoles}} \lesssim \frac{E_{\text{mag}}}{t_{\text{gen}}}, \tag{11}$$

we then arrive at a bound on F:

$$F \lesssim \frac{1}{6\pi}\sqrt{\frac{r}{l_c}}\frac{B}{g}\frac{1}{t_{\text{gen}}}\frac{1}{\text{sr}}, \tag{12}$$

which corresponds to

$$\begin{aligned} F \lesssim & 10^{-15} \text{ cm}^{-2} \text{ sr}^{-1} \text{ sec}^{-1} \\ & \times \left(\frac{B}{3\mu G}\right)\left(\frac{r_g}{10 \text{ kpc}}\right)^{1/2}\left(\frac{l_c}{0.3 \text{ kpc}}\right)^{1/2}\left(\frac{10^{15} \text{ sec}}{t_{\text{gen}}}\right). \end{aligned} \tag{13}$$

A flux exceeding this bound would have dissipated the galactic magnetic fields faster than they could be regenerated and it is therefore excluded by observation.

Gravity dominates In the high mass regime, the kick is only a small perturbation of the monopole velocity. Therefore, no random walk takes place and we instead investigate a single cell. If a monopole traverses such a cell of size l_c with v_{vir}, then it is accelerated for a time of $\Delta t \approx l_c/v_{\text{vir}}$. The change in velocity is then

$$\Delta v \approx \frac{gB}{M}\frac{l_c}{v_{\text{vir}}}. \tag{14}$$

This small change in the velocity perturbs the kinetic energy to $E = M(\vec{v}_{\text{vir}} + \Delta\vec{v})^2/2 = E_0 + \Delta V$ where

$$\Delta E = M\vec{v}\cdot\Delta\vec{v} + \frac{1}{2}M(\Delta v)^2. \tag{15}$$

If the incident monopoles are isotropic or there is an exact balance between monopoles and anti-monopoles, then the first term vanishes. Assuming that either case holds true, we make the approximation

$$\Delta E \approx \frac{1}{2}\frac{g^2 B_c^2}{M}\frac{l_c^2}{v_{\text{vir}}^2}. \tag{16}$$

This energy is extracted from the magnetic field of the cell, which has a total energy of

$$E_{\text{mag,cell}} \approx \frac{B^2}{2} \times \frac{4}{3}\pi l_c^3. \tag{17}$$

As before, we can then consider the total amount of energy dissipated from this cell by a flux F:

$$\frac{\partial E}{\partial t}_{\text{monopoles}} \approx F \times (\pi \text{ sr }) \times (4\pi l_c^2) \times \Delta E. \tag{18}$$

Demanding again

$$\frac{\partial E}{\partial t}_{\text{monopoles}} \lesssim \frac{E_{\text{mag,c}}}{t_{\text{gen}}}, \tag{19}$$

we arrive at

$$F \lesssim \frac{1}{3\pi} \frac{M v_{\text{vir}}^2}{g^2 l_c t_{\text{gen}}} \frac{1}{\text{sr}}, \tag{20}$$

which corresponds to

$$\begin{aligned} F \lesssim & 10^{-13} \text{ cm}^{-2} \text{ sr}^{-1} \text{ sec}^{-1} \\ & \times \left(\frac{M}{10^{19} \text{ GeV}}\right) \left(\frac{v_{\text{vir}}}{10^{-3} c}\right)^{1/2} \left(\frac{0.3 \text{ kpc}}{l_c}\right) \left(\frac{10^{15} \text{ sec}}{t_{\text{gen}}}\right). \end{aligned} \tag{21}$$

The Parker bound: If the astrophysical parameters, i.e. B_c, l_c, v_{vir}, t_{gen}, and r_g are assumed to be valid then the Parker bound constrains the flux of monopoles to less than

$$F < \begin{cases} 10^{-15} \text{ cm}^{-2} \text{ sr}^{-1} \text{ sec}^{-1} \left(\frac{M}{10^{17} \text{ GeV}}\right) & \text{if } M \gtrsim 10^{17} \\ 10^{-15} \text{ cm}^{-2} \text{ sr}^{-1} \text{ sec}^{-1} & \text{if } M \lesssim 10^{17} \end{cases} \tag{22}$$

Note that these bounds were derived with the minimal magnetic charge allowed by the Dirac quantization condition. The bounds become stronger if more strongly charged monopoles are considered.

4.2 Other astrophysical constraints

There are several other astrophysical effects that are used to constrain monopoles. We will not go into them in detail, but we list them here so that interested readers can study them in more detail:

Extended Parker bound The Parker bound derived above is related to the survival of the presently observed magnetic fields. However, if one extends the argument to the survival of the seed fields which are assumed to have preceded the present-day magnetic fields, then much stronger bounds can be derived. This was done by Adams et al.[10] who found that

$$F < \left[\frac{M}{10^{17 \text{ GeV}}} + 3 \times 10^{-6}\right] 10^{-16} \text{ cm}^{-2} \text{ sr}^{-1} \text{ sec}^{-1}. \tag{23}$$

This bound is less reliable in the sense that it relies on much more speculative astrophysical assumptions. However, if these astrophysical assumptions can be trusted, then one gains a bound several orders magnitude stronger than the original Parker bound.

Catalyzed baryon number violation If GUT monopoles that catalyze baryon number violation exist, then these could enhance the luminosity of astrophysical objects by being captured. Such constraints are model-dependent and depend on the catalysis cross section, but the bounds tend to lie in the range

$$F < 10^{-19} \text{ to } 10^{-29}. \tag{24}$$

As is evident, such bounds can be quite strong. However, they only apply to monopoles with suitable catalysis cross sections. See the PDG review for references on this topic [6].

5 Direct detection

5.1 Monopoles bound in matter

A magnetic monopole will bind to a ferromagnetic material, so monopoles might be hidden inside samples of such materials. If present, such embedded monopoles might be detected by superconductive coils coupled to sensitive Superconducting Quantum Interference Devices (SQUID) readouts. Specifically, a monopole of charge g acting on a superconducting coil with N turns and inductance L will induce a change of current of

$$\Delta I \approx 4\pi N \frac{g}{L}. \tag{25}$$

A magnetic dipole causes no net change in the current, so such searches should be able to pick embedded monopoles. Nevertheless, no such monopoles have ever been detected despite testing of samples of various materials [11, 12].

The Earth's crust has not always been ferromagnetic because all material on the earth has at some point been heated above the curie temperature. Therefore, magnetic monopoles might have been "dropped" from terrestrial samples of ferromagnetic material and fallen deeper into the planet. To compensate for such losses, searches on moon rock and meteorites have been carried out. Also with negative results.

From tests of a variety of samples of terrestrial and extraterrestrial origin Jeon and Longo [12] found an upper bound of

$$\frac{\text{monopoles}}{\text{nucleons}} < 10^{-29}. \tag{26}$$

That is, the samples contained less than 1 monopole for every 10^{29} nucleons. See figure 6 for a diagram of the detector.

5.2 Cosmic rays

A flux of monopoles might also be detected directly. For this purpose, a variety of detectors is used. These include: Scintillators, gas chambers, nuclear track detectors and limited stream tubes.

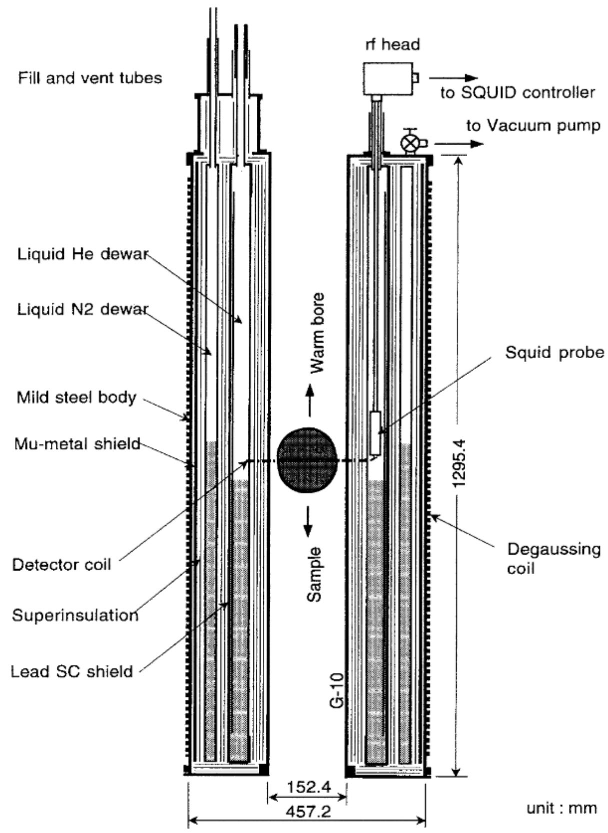

Figure 6: Diagram of the monopole detector used in [12]. The diagram is section through the center-line and is taken from the PRL version of the article.

The most sensitive bound is currently set by MACRO [13], which is located at the Gran Sasso underground laboratory. The experiment uses a combination of liquid scintillator, limited stream tubes, and NTDs. The results were released in 2002. MACRO constrains roughly

$$F \lesssim \text{few} \times 10^{-16}\ \text{cm}^{-2}\ \text{sr}^{-1}\ \text{sec}^{-1}. \tag{27}$$

This bound outcompetes the Parker bound for all but the slowest monopoles. See figure 7 for a comparison.

If a monopole in question can catalyse nucleon decay then it is also possible to search for evidence of such processes. As before, these constraints are model-dependent and they lie in the range

$$F \lesssim 10^{-14} \text{ to } 10^{-14}\ \text{cm}^{-2}\ \text{sr}^{-1}\ \text{sec}^{-1}. \tag{28}$$

The strongest of these bounds is given by Super-Kamiokande, which searched for neutrinos from induced proton decay in the sun[14].

6 Conclusion and further reading

Hopefully, this note has given an overview of the different ways in which magnetic monopoles may be constrained. If you wish to learn more, the primary sources used here are the following reviews:

- PDG review on magnetic monopoles [6]. (General overview)
- Introduction to magnetic monopoles [15] (General overview)
- Searches for Magnetic Monopoles and...beyond [7] (Collider constraints)
- Magnetic monopoles and the survival of galactic magnetic fields [1] (Parker)

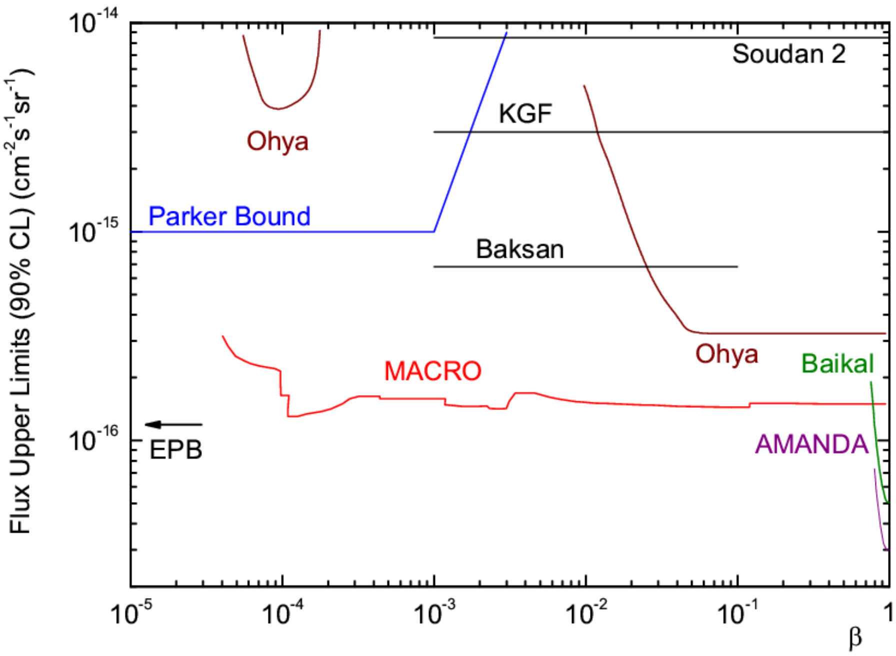

Figure 7: The 90% CL upper limits vs $\beta = v/c$ for a flux of cosmic GUT monopoles with the minimal magnetic charge allowed by the Dirac quantization condition. The bound from the direct detection experiment MACRO [13] dominates the Parker bound for all but the slowest monopoles. The plot is taken from [7].

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