MAGNETIC MONOPOLES

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Outline

- Motivation – why do we care?
- Theoretical history
- Properties
  - How to Detect
  - Where to Look
- Some Previous Searches
- Current State
- Future Research

Motivation

- All known magnets are bipolar, have north and south pole
- Even when split, get two more magnetic dipoles
- Not the case for electricity – can have electric monopoles
- Why have we seen electric monopoles but only magnetic dipoles?
- Is there a fundamental magnetic charge?

Motivation

- Symmetry in Maxwell's Equations

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

$$\boldsymbol{\nabla} \cdot \mathbf{E} = \frac{1}{\epsilon_0}\rho_e$$

$$\boldsymbol{\nabla} \cdot \mathbf{B} = \mu_0 \rho_m$$

$$\boldsymbol{\nabla} \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial \mathbf{t}} = -\mu_0 \mathbf{J}_\mathbf{m}$$

$$\boldsymbol{\nabla} \times \mathbf{B} - \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial \mathbf{t}} = \mu_0 \mathbf{J}_\mathbf{e}$$

Motivation

- All known magnets are bipolar, have north and south pole
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- Not the case for electricity – can have electric monopoles
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- Symmetry of Maxwell's equations

Dirac's Monopole

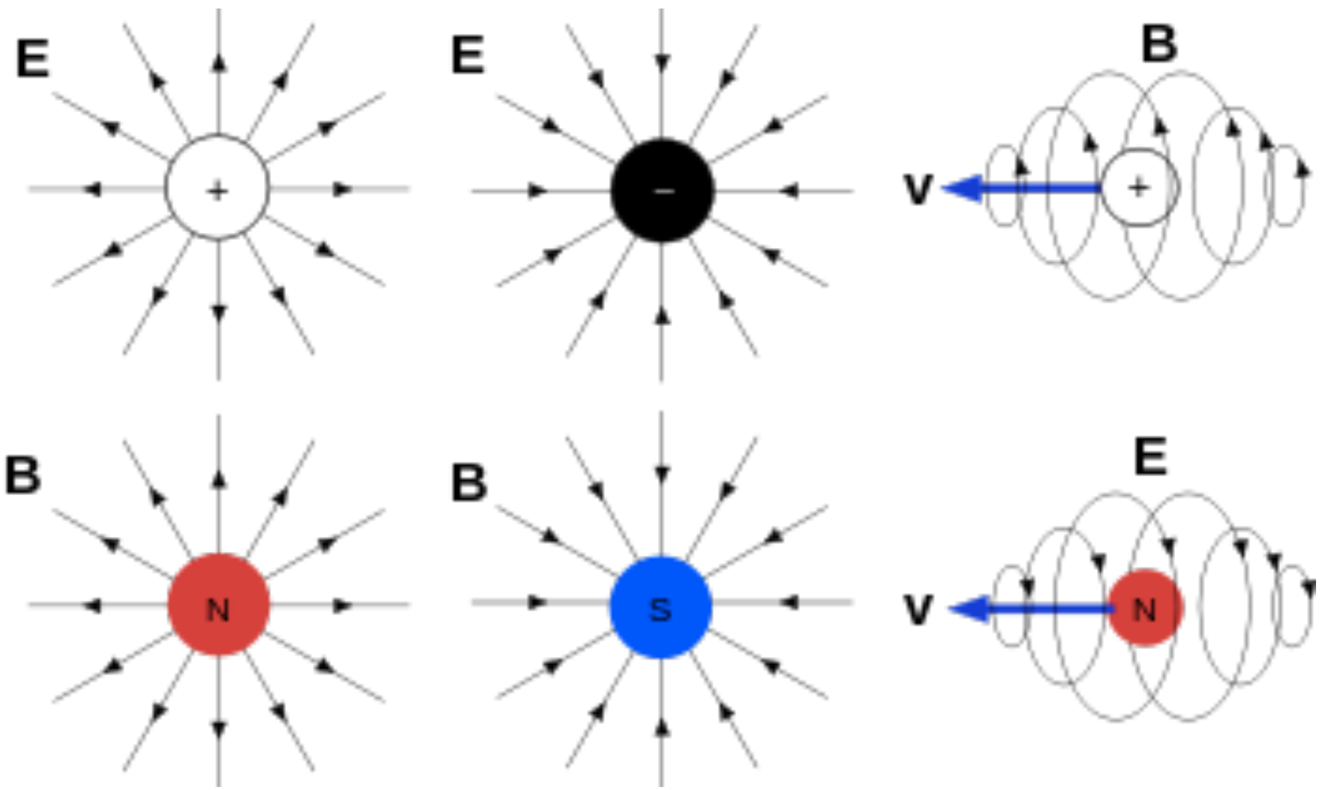
- Paper published in 1931 by Paul Dirac
- Quantum theory did not prohibit magnetic monopoles
- Existence would explain quantization of electric charge:

$$g_D = \frac{c\hbar}{2e} = \frac{e}{2\alpha_E} =\approx 137e/2,$$

Other monopoles

- Polyakov and t'Hooft (1974) – magnetic monopoles follow from general ideas of a grand unified theory
  - Predicted independently
  - A GUT necessarily contains magnetic monopoles
  - Properties of an MM in a given GUT are calculable and unambiguous

Properties of Magnetic Monopoles



Properties of Magnetic Monopoles

- Magnetic charge:

$$\frac{ge}{\hbar c} = \frac{1}{2} \Rightarrow \frac{g}{e} = \frac{1}{2\alpha_e} \approx 68.5,$$

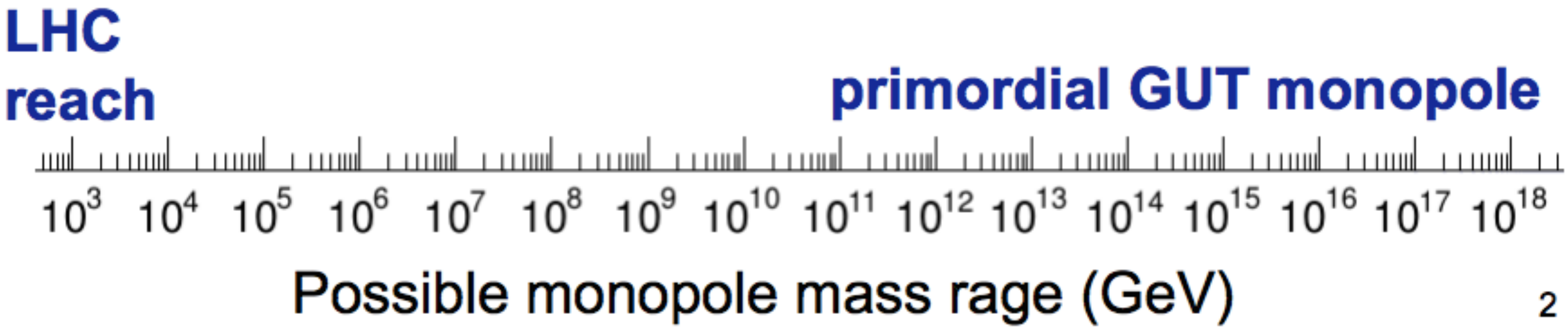
- Coupling constant – analogous to fine structure constant

$$\alpha_m = \frac{(g\beta)^2}{\hbar c} = \frac{1}{4\alpha_e}\beta^2,$$

- Energy acquired in a magnetic field, $W = ng_D Bl$
- Follow a non-helical path in a magnetic field
- Highly ionizing – interact with matter like an ion with charge 68.5e

Properties of Magnetic Monopoles

- No specific mass predicted
- Can estimate "classical monopole" mass using radius of electron: 2.4 GeV
- Super String monopoles: 10^3 GeV
- GUT monopoles: 10^{17} GeV



Where to look for monopoles

- Bound monopoles
- Monopoles produced in accelerators
- Cosmic ray monopoles

- No theory predicts any level of abundance

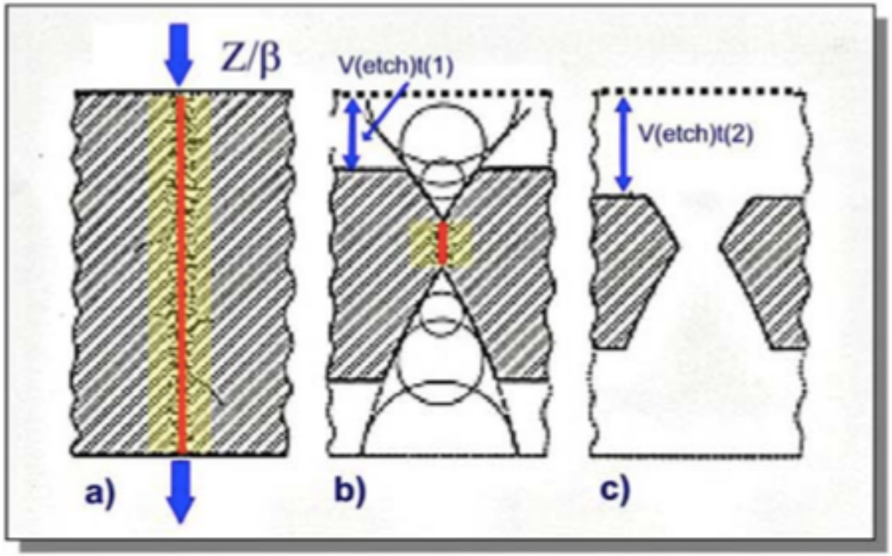
How to detect a monopole

- Induction Detector
  - MM induce an emf and a current in the ring
  - SQUID – sensitive to extremely subtle magnetic fields, magnetic monopole of any mass or velocity

- Ionization Detector
  - Works well for MMs with $\beta \sim 10^{-4}$

How to detect a monopole

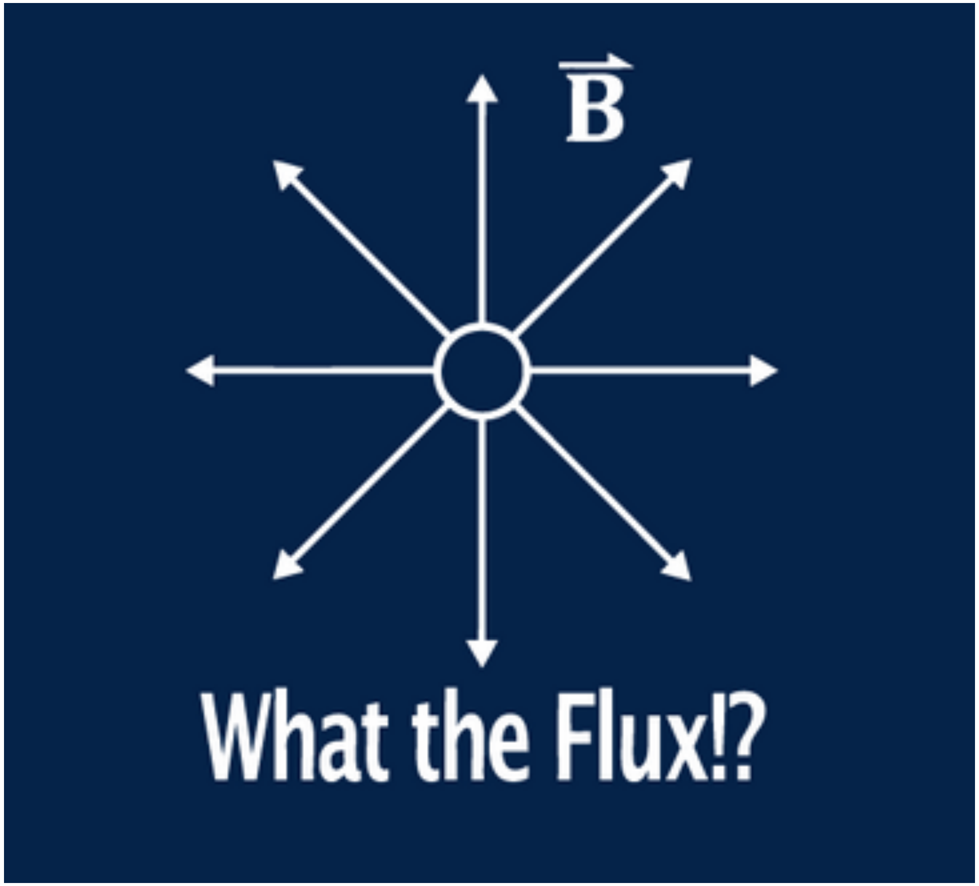
- Nuclear Track Detectors
  - Highly ionizing particle leaves damage zone as it passes through
  - Plastic is etched away, depth of cone is dependent on velocity



- Cherenkov Detectors

- Scintillation Counters

Previous Searches



Searches in material

- 1969, Paul Buford Price, GE labs in NY
  - Searched in samples of deep-ocean sludge
  - Found nothing

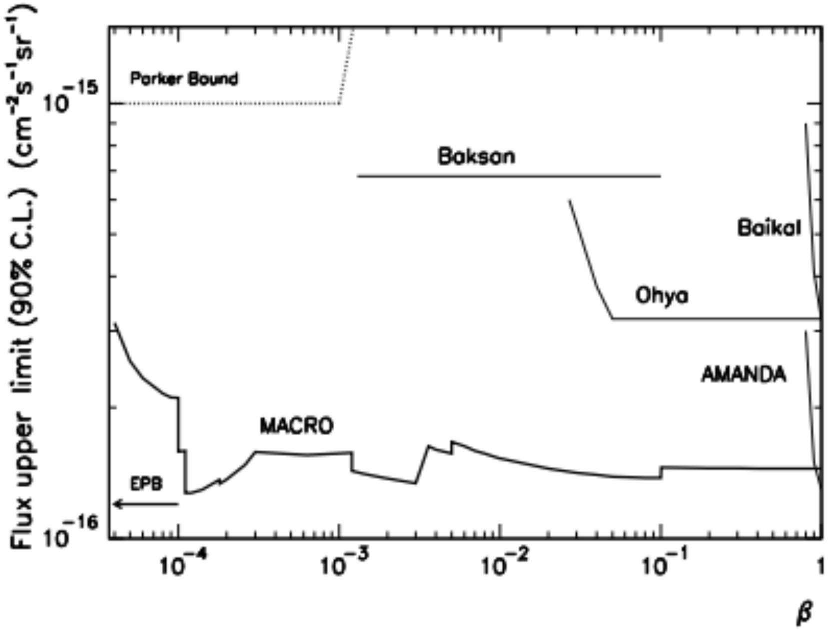
- 1970, Luis Alvarez, UC Berkeley
  - Searched in moon rock from Apollo missions
  - Passed through loop of superconducting wire
  - Found nothing

Searches in cosmic rays

- 1970s, Paul Burford Price again, UC Berkeley
  - Balloon experiments to search in cosmic rays
  - 1975 – thought he found one, was challenged by Alvarez
  - Couldn't reproduce data
- 1982, Blas Cabrera, Stanford University
  - "Valentine's Day Monopole"
  - Set up superconducting induction coil, passing cosmic ray should induce a jump in current
  - Feb. 14 detected one very obvious jump in current
  - Could not reproduce data
  - Decided it was a rare "release of mechanical stress"

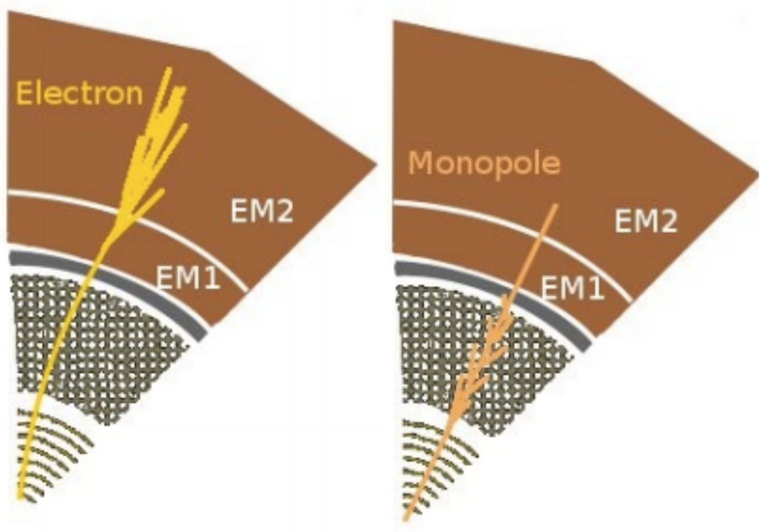
Searches in cosmic rays

- MACRO
  - Monopole Astrophysics and Cosmic Ray Observatory
  - Searched for GUT MMs with
  - Liquid scintillators, streamer tubes, NTDs
  - No candidates detected
    - Global limit was computed by combining limits from each analysis.



Searches in accelerators

- CERN – ATLAS Detector
  - 7 TeV pp collisions
  - Relevant components: TRT and LAr calorimeter
  - Model-independent 95% CL upper cross-section limit: 2 fb for MM with mas between 200 and 1500 GeV
  - 95% CL lower mass limit of 870 GeV

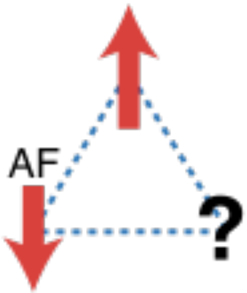


Searches in accelerators (summary)

Accele-Rator	Reaction	Beam Energy Gev	√s GeV	Mass limit GeV	Cross Section cm^2	MM Charge	TECN	Year
CERN	pp	63	63	<20	1.e-37	<24	CNTR	1978
SLAC	e+e-	29	29	<30	4.e-38	<3	PLAS	1982
CERN	pp	52	52	<20	8.e-36		CNTR	1982
CERN	e+e-	34	34	10	4.e-38	<6	PLAS	1983
CERN	pp	540	540		1.e-31	1,3	PLAS	1983
SLAC	e+e-	29	29		3.e-38	<3	PLAS	1984
FNAL	pap	1800	1800	<800	3.e-38	>=1	PLAS	1987
CLEO	e+e-	10.6	10.6	<4	9.e-37	<0.15	CLEO	1987
CERN	e+e-	50-52	50-52	<24	8.e-37	1	PLAS	1988
DESY	e+e-	35	35	<17	1.e-38	<1	CNTR	1988
KEK	e+e-	50-61	50-61	<29	1.e-37	1	PLAS	1989
FNAL	pp	1800	1800	<850	2.e-34	>=0.5	PLAS	1990
CERN	e+e-	88-94	88-94	<45	3.e-37	1	PLAS	1992
CERN	e+e-	88-94	88-94				PLAS	1993
CERN	PbA	160A	17.9	<8.1	1.9e-33	>=2	PLAS	1997
AGS	AuAu	11A	4.87	<3.3	0.65e-33	>=2	PLAS	1997
FNAL	pap	1800	1800	260-420	7.8e-36	2-6	INDU	2000
FNAL	pap	1800	1800	265-410	0.2e-36	1-6	INDU	2004
HERA	e+p	300	300		0.5e-37	1-6	INDU	2005
FNAL	pap	1800	1800	369	0.2e-36	>=1	CNTR	2006

Current State: Spin Ice

- Spin ice – geometrically frustrated magnetic system
  - Complex structure of atoms in a lattice leads to many distinct ground states.



- Magnetic monopoles observed as an emergent phenomena

- http://www.nature.com/nature/journal/v461/n7266/full/nature08500.html

Future Plans

- Higher energies probed at accelerators
  - MoEDAL at CERN
    - Monopole and Exotics Detector At the LHC
    - NTD – look for monopoles, dyons, doubly charged Higgs

- More searches in cosmic rays

- Mass lower limits and cross sections providing more narrow regions to search in

Summary

- If found, magnetic monopoles would
  - provide an explanation for quantization of electric charge
  - symmetrize Maxwell’s equations
  - provide direction in search for unified theory
- Many searches have been done but none have been successful yet
- Macroscopic emergent phenomena can help us understand properties and may provide direction for later experiments
- We might not be looking for the right things
  - Dyons?

Sources

- http://users.physik.fu-berlin.de/~kleinert/files/dirac1931.pdf (Dirac's 1931 paper)
- http://www.theory.caltech.edu/~preskill/pubs/preskill-1984-monopoles.pdf
- http://pdg.lbl.gov/2004/listings/s028.pdf
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