INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION

INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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SCHOOL ON
NON-ACCELERATOR PHYSICS
25 April - 6 May 1988

MAGNETIC MONOPOLE PHYSICS AND EXPERIMENTS

by

James Stone
University of Boston
U.S.A.

Magnetic Monopole Physics and Experiments

J. Stone
ICTP School on Non-Accelerator Physics
April-May 1988

Program

Background and History

GUTs motivation

Astrophysical Flux Limits

Detection Techniques and Experiments

- Accelerators*
- Induction
- Catalysis of Nucleon Decay
- Track Etch*
- Stable Matter Searches*
- Ionization / Excitation
  - MACRO

* Time permitting.

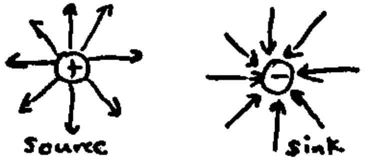
Electricity and Magnetism prior to 1865

Electric Charges were point particles with ⊕ and ⊖

Coulomb's Law: $\vec{F} = \frac{1}{4\pi\epsilon_0} \frac{Q_1 Q_2}{r^2} \hat{r}$

- repulsive and attractive depending on $Q_1 Q_2$
- conservative force ⇒ Define field $\vec{E} = \frac{\vec{F}}{q} = -\nabla V$

Electric Field Lines: for isolated charges



$\vec{F} = q\vec{E}$

Electric Currents are moving charges: $I = \frac{dQ}{dt}$

Gauss' Law: $\oint_{\text{closed surface}} \vec{E}\cdot d\vec{s} = \epsilon_0 Q_{\text{enclosed by surface}}$ calculate $\vec{E}$ from charge distribution

Current density ; resistivity/conductivity of materials ; Ohm's Law

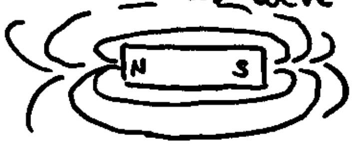
⇒ Electricity

Magnetism Known several hundred years earlier.

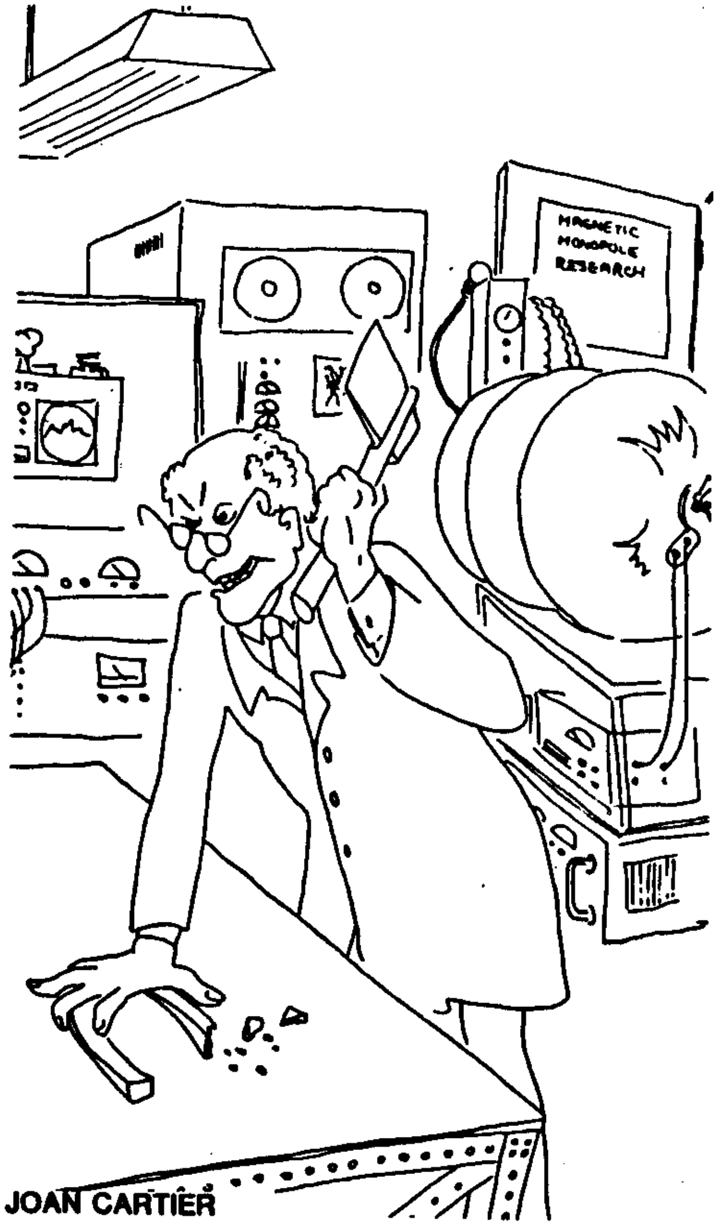
Certain materials showed natural magnetism

Magnetite , Iron Co, Ni, Gd, O_2 Ferromagnetic Paramagnetic Diamagnetic

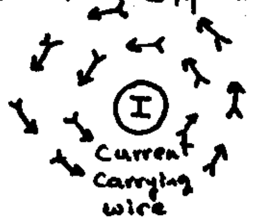
All sources were dipoles!



No isolated magnetic poles seen!



Oersted's Experiment:



$B \propto \frac{I}{R}$

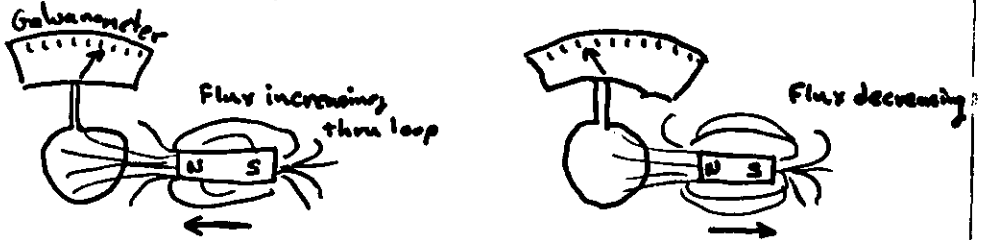
First connection between electricity and magnetism.

Ampere's Law: $\oint_{\text{closed path}} \vec{B}\cdot d\vec{l} = \mu_0 I_{\text{enclosed by path}}$

Long straight wire

$B = \frac{\mu_0 I}{2\pi r}$

Faraday: If currents produce magnetic fields, do magnetic fields produce currents?



Induced current depended on change in magnetic flux.

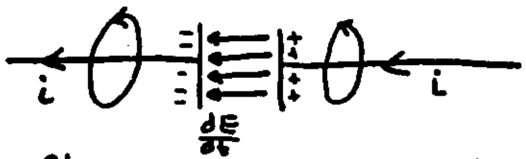
Faraday's Law: $\mathcal{E}mf = -n\frac{d\Phi_B}{dt}$ Flux $= \Phi_B = \int \vec{B}\cdot d\vec{A}$

Induced emf in wire caused electrons to move.

Ohm's Law $\Rightarrow$ induced current.

Theoretical contribution...

Maxwell observed a discontinuity with capacitors



Changing E-field in capacitor as charge deposited

$\Rightarrow$ displacement current: changing electric field ($\frac{d\Phi_E}{dt}$) produced a magnetic field.
1st measured in 1929

All elements for the 1st unification theory

Electromagnetism - Maxwell's Equations:

$\vec{\nabla}\cdot\vec{D} = 4\pi\rho$

$\vec{\nabla}\cdot\vec{B} = \phi$ (no monopoles)

$\vec{\nabla}\times\vec{H} - \frac{1}{c}\frac{\partial\vec{D}}{\partial t} = \frac{4\pi\vec{j}}{c}$

$-\vec{\nabla}\times\vec{E} - \frac{1}{c}\frac{\partial\vec{B}}{\partial t} = \phi$ (no magnetic current)

$\Rightarrow c = \frac{1}{\sqrt{\epsilon_0\mu_0}}$

Propagation of EM radiation

↳ special relativity

Symmetrical Form of Maxwell's Equations (1898, Heaviside)

Need to include magnetic monopoles.

$\vec{\nabla}\cdot\vec{D} = 4\pi\rho$

$\vec{\nabla}\cdot\vec{B} = 4\pi\sigma$, σ = monopole charge density

$\vec{\nabla}\times\vec{H} - \frac{1}{c}\frac{\partial\vec{D}}{\partial t} = \frac{4\pi\vec{j}}{c}$

$-\vec{\nabla}\times\vec{E} - \frac{1}{c}\frac{\partial\vec{B}}{\partial t} = \frac{4\pi}{c}\vec{g}$, $\vec{g}$ = magnetic current density

↳ left hand rule (magnetic charges violate parity)

Hence, monopoles symmetrized Maxwell's Equations.

1931 Dirac introduced vector potential $\vec{B} = \vec{\nabla} \times \vec{A}$ in order to calculate the "Coulomb" field of a monopole

$$\vec{A} = \frac{g}{r} \frac{\vec{r} \times \hat{n}}{\vec{r}(\vec{r} - \vec{r} \cdot \hat{n})}$$ 1st gauge theory?

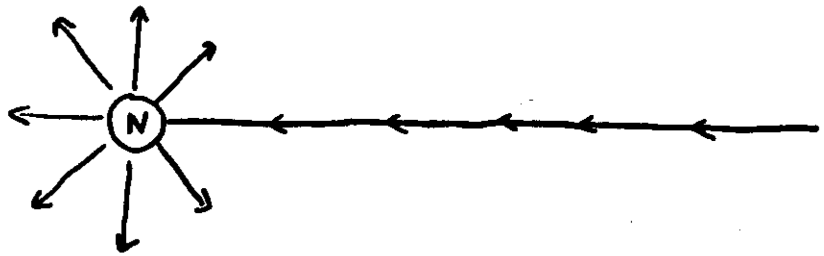
$$\vec{B} = \vec{\nabla} \times \vec{A} \Rightarrow \vec{B} = \frac{g}{r^2} \hat{r}$$

But in Maxwell's equation: $\vec{\nabla} \cdot \vec{B} = \vec{\nabla} \cdot (\vec{\nabla} \times \vec{A}) = \phi$!

$\Rightarrow$ there can be no magnetic charge in Maxwell's formalism if we insist that $\vec{B} = \vec{\nabla} \times \vec{A}$.

Also, there is a divergence in $\vec{A}$ if $\vec{r}$ points along $\hat{n}$.

$\Rightarrow$ Origin of the Dirac String: 1st string theory??



Hence, all flux which originates on the magnetic charge, returns to it along the Dirac String.

∴ there is no magnetic charge as a source!

In spite of the difficulties, Dirac's formulation initiated monopole physics.

Nice Features: - minimum monopole charge $= \left(\frac{137}{2}\right) e = g$

- String on such a charge resembles a tube of quantized flux in a superconductor
  magnitude = 2 fluxons = $2\phi_0 = \frac{hc}{e}$.
- introduced a definite relationship between electric and magnetic charges

Dirac Quantization Condition: $\frac{eg}{\hbar c} = \frac{n}{2}$ $n = 1, 2, 3, \cdots$

Important Consequences:

1) Magnetic monopoles carry very large charge
   $g = 68.5e$ (smallest value)

* 2) The existence of a single magnetic charge of this magnitude could account for the quantization of electric charge in units of e.

Dirac gave no prediction of the monopole mass!

.... experiments

Accelerator Searches for Dirac Monopoles

Hypothesis: Low mass monopoles are produced by reactions such as,

$p + p \rightarrow p + p + g + \bar{g}$

$p + \bar{p} \rightarrow g + \bar{g}$ - relativistic

$e^{+} + e^{-} \rightarrow g + \bar{g}$ - highly ionizing

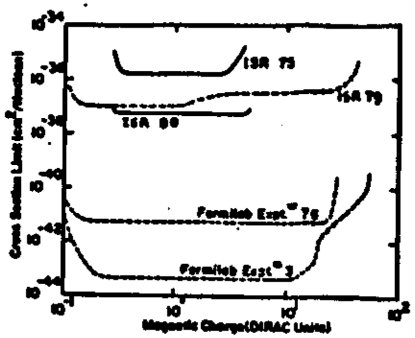
General Experimental Techniques:

I. Surround intersection regions with C.R.39 and/or Kapton foils, (min. ionizing particles below thresh). Heavily ionizing relativistic monopoles leave defects in the plastic sheets which can be detected by chemical etching.

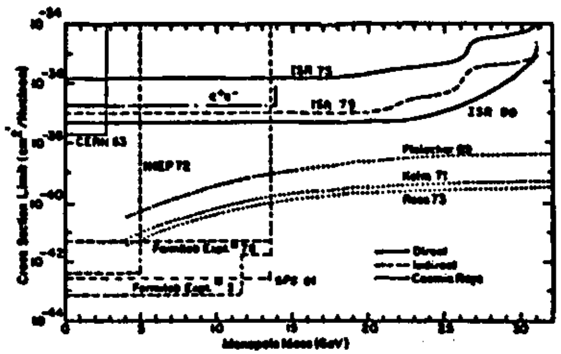
II. Expose ferromagnetic collectors (eg. W-Fe powder) to a proton beam in beam dump where monopoles would stop and become trapped. Remove collectors and pass thru superconducting coils or expose them to intense pulsed magnetic fields to extract the monopoles and accelerate them thru nuclear emulsions.

Summary of Accelerator Results

No monopoles were found, ∴ limits were set on production cross-section vs. monopole charge & mass.



Limit from SPS $p\bar{p}$ collider (not shown) extends up to monopole mass = 150 GeV.



Future Searches:

LEP

FNAL $p\bar{p}$

SSC

Ehrenhaft Monopole   Jan. 16, 1944

"All the News That's Fit to Print."

NEWS INDEX, PAGE 46, THIS SECTION

The New York Times.

LATE CITY EDITION
Clearing with little change in temperature today; fresh winds.

Section 1

Copyright, 1944, by The New York Times Company.

VOL. XCIII...No. 31,463. Entered as Second-Class Matter, Postoffice, New York, N. Y.

NEW YORK, SUNDAY, JANUARY 16, 1944.

TEN CENTS

WALLACE TELLS CIO VICTORY AIM ALONE GUIDES PRESIDENT

Statement at Parley Here Is Construed as Apology for Labor-Draft Proposal

STIRRING DISCORD SCORED

Vice President Attacks 'Some' Business Men, Lauds Others —Farm Lobby Disowned

The text of Mr. Wallace's address appears on Page 44.

Under the impetus of an enthusiastic welcome by 400 Congress of Industrial Organizations leaders at a luncheon session of the CIO Political Action Committee at the Park Central Hotel yesterday, Vice President Henry A. Wallace departed from his prepared text and made what was construed as an apology or "explanation" for President Roosevelt's labor draft proposal and other recent actions that have not been to the liking of the CIO.

"Many things," he declared, "which some of us have not been able to understand, have been explained by the fact that the President is keeping his mind on these two things, winning the war and the peace, to the exclusion of anything else."

Mr. Wallace in his prepared address had just said that through all the attacks on Mr. Roosevelt by those seeking to stir up discord on the home front—"and some of them have been slanderous"—the President "has kept his eye on just one objective—how best to win an early and complete victory, how best to attain a secure peace."

Silent at Mention of President

Despite the fact that a good part of Mr. Wallace's speech was filled with the highest praise of the President for his leadership on both the war and home fronts, the CIO leaders present sat in silence at every reference to the

Proof Offered of Existence Of Pure Magnetic Current

Discovery by Prof. Felix Ehrenhaft, if Confirmed, Expected to Rank With Faraday Finding of Dynamo Principle

By WILLIAM L. LAURENCE

Prof. Felix Ehrenhaft, noted Vienna physicist, who fled after the Nazi occupation of Austria, presented yesterday before the American Physical Society, meeting at Columbia University, a set of his latest experiments, carried out in his laboratory in New York, which he said provided for the first time experimental proof of the existence of pure magnetic current. This means, he declared, that "not only electric currents but also magnetic currents flow through the universe."

The presentation of the experiments, illustrated with lantern slides, created a sensation among the prominent physicists present. They said that if the experiments described by Professor Ehrenhaft could be corroborated by others they would mark one of the greatest revolutions in modern science, to be ranked with the discovery of the principle of the dynamo by Michael Faraday 113 years ago.

Just as Faraday's discovery marked the ushering in of the age of electricity, it was pointed out, so this discovery of Professor Ehrenhaft, assuming the correctness of his results, would mean the ushering in of a new era in technology based on currents of magnetism. It would mean, one leading physicist said, that we would double the possibilities for building machines—for every electrical machine now in existence we would be able to build a machine utilizing magnetic instead of electric current.

Hitherto the concept of electromagnetism has been based on the belief, formulated originally by Peregrinus about 700 years ago, that magnetism has direction but no motion, and that only electricity can move. Professor Ehrenhaft's experiments prove for the first time, he said, that there exist single magnetic charges, either north or south, and that magnetism flows just as does electricity.

"The experiments show," Profes-

Continued on Page Forty-five

STETTINIUS ASKS FULL COOPERATION WITH SOVIET RUSSIA

In Broadcast He Calls Any Other Course in War or Peace 'Tragic Blundering'

BIG DEPARTMENT SHIFTS

Far-Reaching Plans of Reorganization Are Announced by Secretary Hull

Text of the State Department radio program is on Page 30.

Special to The New York Times.

WASHINGTON, Jan. 15—Anything other than complete cooperation with Soviet Russia after the war would be "tragic blundering" on the part of the United States, said Edward R. Stettinius Jr., Under-Secretary of State, during an hour's broadcast tonight over the National Broadcasting Company's network entitled "The State Department Speaks."

Participating with Mr. Stettinius in the event were G. Howland Shaw, Assistant Secretary of State, and Robert D. Murphy, Ambassador at Large.

"I have worked closely with the Soviet officials here for over three years and I have nothing but admiration for the bravery, resourcefulness and determination of the people of the Soviet Union," Mr. Stettinius declared.

"I feel we have everything to gain and nothing to lose from a continuing and close cooperation between the Soviet Union and the United States both now and after the war. Anything else would be nothing less than tragic blundering for both of us."

Shaping War and Peace Role

In the course of his address Mr. Stettinius [illegible] the broad reorganization of the State Department announced tonight by Secretary Hull.

"Like many businessmen, the State [illegible]

RAF BOMBERS SMASH BRUNSWICK, DROP 2,240 TONS IN 23 MINUTES; FRENCH IN 5TH ARMY TAKE TOWN

NEW SOVIET DRIVE

Foe Reports a Russian Push in the Leningrad-Lake Ilmen Sector

PRIPET GAINS CONTINUE

Heaviest Fighting Still Taking Place on Vinnitsa Front as Red Army Holds Firm

By The United Press.

LONDON, Sunday, Jan. 16—Soviet troops hurled back powerful German counter-attacks on two sectors of the front south of Kiev and swept westward across the Pripet Marshes yesterday as Berlin reported that the Russians had opened a new offensive in the Leningrad and Lake Ilmen areas.

The German High Command communiqué, broadcast from Berlin, asserted that powerful Red Army forces had attacked on the long dormant Leningrad and Lake Ilmen fronts, as well as around Nevel, in a three-pronged drive to break the German siege lines guarding the Baltic States. That report of Soviet assaults against the northern anchor of the crumbling German lines in Russia was not confirmed by Moscow.

Moscow's broadcast war bulletin, one of the shortest in weeks, announced that the Germans, for the fourth successive day, had been hurled back east of Vinnitsa in the southwestern Ukraine, where the Nazis were fighting to keep the Russians from [illegible] the Odessa-Warsaw railroad lifeline to the Dnieper bend. The bulletin also reported that the Nazis had counter-attacked eighty-five miles

Acquafondata and 3 Peaks Captured in Advance in Italy

French Troops Meet Fiercest Resistance on San Pietro Ridge as Americans Battle for Mt. Trocchio—Adriatic Area Quiet

By MILTON BRACKER

By Wireless to The New York Times.

ALGIERS, Jan. 15—Gaining momentum despite the peak-studded and ridge-spined terrain, where the Germans are fighting back furiously, French units of Lieut. Gen. Mark W. Clark's Fifth Army have captured Acquafondata and three more heights and extended their gains in the three-day offensive to almost five miles, it was officially announced today.

The French rolled back three more German drives on the eastern slopes of the San Pietro ridge at the north end of the front. These made five such drives in forty-eight hours. The French have also by-passed Vittorio, which they have surrounded on three sides, and are within four and a half miles of the Cassino-Atina road at a point some three miles above Cassino.

In the area around the Via Casilina, American troops were finding the barrier of Mount Trocchio as tough as expected. At no point were they less than three miles from their primary objective. Patrol activity was incessant, but the southern gateway to Cassino remained firmly barred.

The progress of the French in the upper half of the Fifth Army's assault front is all the more remarkable when the latest official line is studied. In effect, the French forces, which include Moroccan goumiers and some American units specifically assigned to them, have given the Germans one blow after another over a rocky area comparable with the worst of the country around the Cassino-Maggiore masses.

With the American forces around Cervaro, the French have now carved out a rough isosceles triangle with its apex at Alfedena and its base between Cervaro and Concacasale, each seventeen miles from Alfedena and six miles from each other. The western side of this triangle is indented by a rather peculiar salient at Viticuso.

Continued on Page Twenty-seven

Peru Charges a Revolt Plot By Germans and Japanese

By The Associated Press.

LIMA, Peru, Jan. 15—The Peruvian Government announced today that a number of conspirators, including Germans and Japanese, plotting a New Year's pro-Nazi coup, had been detained and would be deported, while others had been notified to leave the country. The Government

700 PLANES STRIKE

British Deliver Record Concentration at Reich Industrial Center

MOSQUITOS HIT AT BERLIN

Magdeburg Also Attacked in Double Feint—French Coast Battered Night and Day

By DAVID ANDERSON

By Cable to The New York Times.

LONDON, Jan. 15—A burning ring set off by British pathfinder planes appeared in the sky over Brunswick, ancient German town that is now the site of Messerschmitt factories, a little after 7 o'clock last night. In the course of the next twenty-three minutes Brunswick was hit by a bombing attack more intense than any yet inflicted upon the enemy.

Flowing over the city went a mass of heavy bombers of the Royal Air Force estimated here to number 700 or more.

At the peak of their assault 130 tons of high explosives and incendiaries a minute poured down on Brunswick—within three minutes at that time there fell on this German city punishment equivalent to the worst absorbed by London in any twenty-four hours.

RAF Tactics Again Pays Off

It was not simply a case of rugged force crushing Nazi resistance, because the RAF employed a [illegible] that has proved profitable time and again in recent months.

At the same hour Brunswick was blasted sharp attacks were delivered at Berlin and Magdeburg by fast-flying Mosquito bombers, with

MORE COAL COMING TO THE NORTHEAST

Ickes Also Requests West Virginia Producers to Hold Remainder for Emergencies

Special to The New York Times.

WASHINGTON, Jan. 15—Harold L. Ickes, Solid Fuels Administrator, today directed high volatile coal producers in the northern West Virginia fields to fill major orders from all-rail retail dealers in the northeastern States and to make the remainder available to him for emergency distribution there.

DEMOCRATS MOVE TO KILL P.R. VOTING

City Organizations Inspire a Move at Albany Along Two Legislative Lines

Special to The New York Times.

ALBANY, Jan. 15—The Democratic party organizations of New York City moved today to abolish proportional representation as a method of electing city Councilmen. Following the last election, when two Communists and one man accused of being one were elected to the Council of seventeen members, the Democratic legislative

"All the News That's Fit to Print"

The New York Times

LATE CITY EDITION

VOL. CXXIV . No. 42,937 — NEW YORK, FRIDAY, AUGUST 15, 1975

August 1 1975

INTEREST RATES ON M.A.C. BONDS SET AT NEW HIGH

Underwriters Increase Them Because Sales Falter and City Needs Cash

PAYROLL MUST BE MET

Intricate Deal Is Culminated to Close $275-Million Offering This Morning

Bronfman Asks Abductors For More Proof Son Lives

Appeal Dashes Optimism Raised by Tape That Included Son's Voice—Statement Urges Kidnappers 'Follow Through'

ISRAEL REPORTED WILLING TO RETURN OILFIELD TO EGYPT

U.S. Is Said to Give Pledge on Petroleum Assistance as Part of a Sinai Pact

Mujib Reported Overthrown and Killed In a Coup by the Bangladesh Military

Ahmad, a Long-time Aide and Member of Cabinet, Is the New President

KISSINGER GIVES LISBON ANTI-REDS STRONG BACKING

Says U.S. Will Side With Those Who Want to Subvert Revolution

DECLARATION OF POLICY

Pressure Reported Growing in Portugal for Removal of Pro-Communist Premier

Basic Unit of Magnetism Believed to Be Detected

By WALTER SULLIVAN

2D BERGMAN AIDE ADMITS HIS GUILT

Accountant Pleads in U.S. Court and Discloses He Is Helping Prosecution

MANILA REPORTS MINDANAO TRUCE

Key Moslem Insurgent Unit Accepts Terms After Five Years of Bloodshed

By ALICE VILLADOLID

Lisbon Resumes Control Of Angola Administration

Death of 2 Doctors Poses a Fitness Issue

Jersey Told to End Medicaid Drug Cost

Price

Monopole

Physicists Believe They Have Detected the Basic Unit of Magnetism

— 12 —

The Weather

The Washington Post

FINAL

98th Year .... No. 253

FRIDAY, AUGUST 15, 1975

Portugal Retakes Angola Control; Nationalists Out

Socialists Ask Ouster Of Goncalves

By Miguel Acoca

LISBON, Aug. 15 (Friday)—The Portuguese government resumed administrative control of Angola yesterday, abrogating the agreement under which the southwest African territory was scheduled to become independent in November.

Ford Will Appeal Oil Tariff Ruling

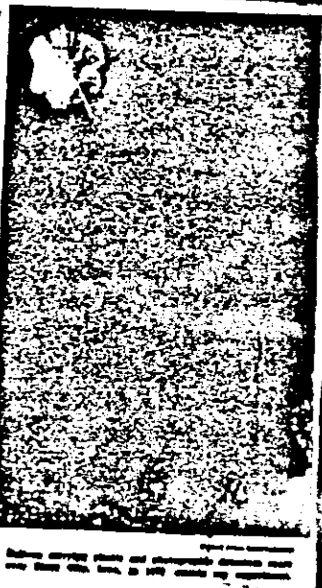
Army Seizes Power

Mujibur Is Slain in Bangladesh Coup

MUJIBUR RAHMAN

Kissinger Warns Soviet On Portugal

Magnetic Particle With Single Pole Is Believed Found



Revolver Will Be Refired

Test Ordered on Sirhan Gun

Call Us, Bronfmans Urge Kidnapers

Magnetic Monopole Trace Found

DISCOVERY, From A1

B. Price
Monopole

"All the News That's Fit to Print"

The New York Times

VOL. CXXXI. . No. 45,297 — NEW YORK, WEDNESDAY, APRIL 28, 1982

Page 11

UNIT OF MAGNETISM SAID TO BE TESTED

Monopole Is Reportedly Found in an Elaborate Experiment at Stanford University

By WALTER SULLIVAN

May 1, 1982
Cabrera Monopole

The Washington Post

FINAL

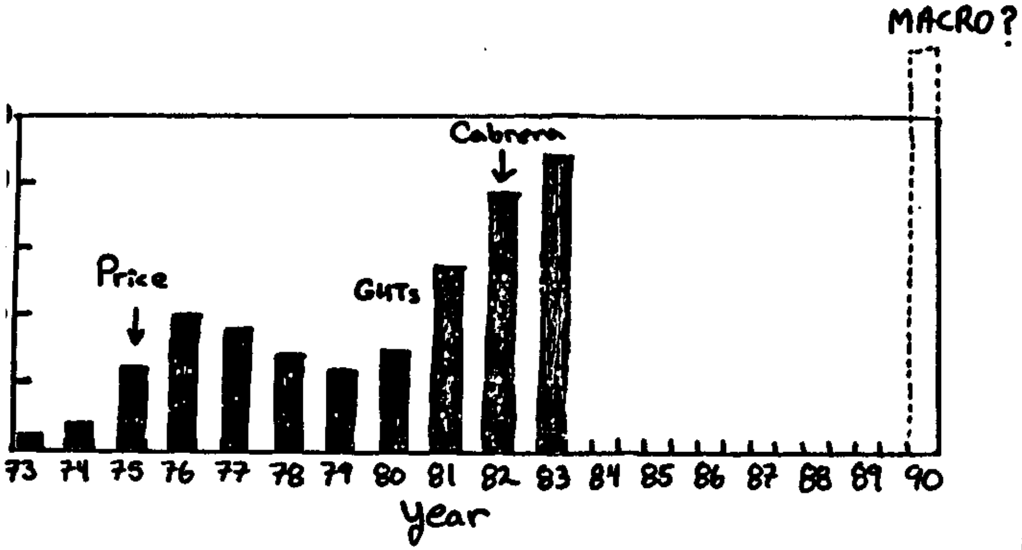
SATURDAY, MAY 1, 1982

Basic Particle of Magnetism Possibly Found by Physicist

By Philip J. Hilts

Interest in Monopole Physics as measured by the number of published papers vs. year.

Original version: John Preskill in "MONOPOLE '83"
Updated by: David Fryberger, SLAC-PUB-3535



John Preskill: "... it is not certain that nobody has ever seen one. What seems certain is that nobody has ever seen two."

Grand Unification Theories renewed theoretical and experimental interest in monopole physics.

1974 General proof by 't Hooft and Polyakov showed that any unifying semi-simple non-Abelian gauge group which breaks down to a U(1) factor necessarily contains magnetic monopoles.

$$G \rightarrow SU(3) \times SU(2) \times U(1)$$

In GUT's, the monopole mass is predicted to be on the order of the unification scale.

$\therefore$ e.g. $SU(5)$ $\quad M_m \sim 10^{16}$ GeV

Such massive monopoles can not be produced at accelerators, but could have been created in the early universe during phase transition.

Hence, grand unified monopoles could still be around today as a component of cosmic radiation or dark matter.

Properties: $M_m \sim 10^{16}$ GeV

$\beta \sim 10^{-4} \rightarrow 10^{-2}$

Highly penetrating (enormous K.E.)

Lightly ionizing (low velocity)

Low Flux (astrophysical constraints)

Monopoles may or may not ....

- have electric charge (dyons)
- be attached to protons or nuclei
- catalyze nucleon decay
- form $M\bar{M}$ bound states (monopolonium)

Detection of Monopoles:

- superconducting induction coils + SQUIDS — magnetic charge
- nucleon decay detectors — catalysis
- ionization / excitation
  - Scintillators (light yield at low velocities)
  - gaseous detectors (He) (Zeeman level crossing)
  - track-etch materials (mica, CR-39, LEXAN)
- trapping in old ferromagnetic materials
- acoustic detection of dE/dx loss in metal
- small band gap devices
  - Silicon
  - IR phosphors
  - Superconducting colloids

Maximum achievable size of detectors:

- depends on $ and technique used.

4π Collection aperature of detector important due to astrophysical constraints.

Area ~ Football Field

Astrophysical Limits on Monopole Density and Flux

A bound on the monopole density can be obtained by requiring that the monopole mass density be less than or equal to the critical density which just "closes" the universe.

$$\rho_c \sim 2 \times 10^{-29}\ \mathrm{gm/cm^3}$$

Then, if $M_m \sim 10^{16}$ GeV,

$$\rho_M \lesssim 10^{-21}\ \mathrm{monopoles/cm^3}$$

The monopole flux can be obtained from

$$\Phi \leq \rho_M \frac{\bar{v}}{4\pi} = \rho_M \frac{\bar{\beta} c}{4\pi}$$

$$\Phi \lesssim \frac{(10^{-21})(3\times 10^{10})}{4\pi}\bar{\beta}$$

$$\Phi \lesssim (2.4\times 10^{-12})\bar{\beta}\ \mathrm{cm^{-2}s^{-1}sr^{-1}}$$

For an average monopole velocity $= 10^{-3}c$, this gives an upper bound on the monopole flux,

$$\Phi \lesssim 2.4\times 10^{-15}\ \mathrm{cm^{-2}s^{-1}sr^{-1}}$$

Monopole Flux Limit based on survival of the Galactic magetic field.

Parker Bound

E. Parker
Parker, Turner, Bogden

Interstellar fields of 2-5μG have been measured. (Polarization of starlight)

Generally, the field lines follow the spiral galactic structure.

Fields are believed to be generated by a "dynamo" action due to the differential rotation of the galaxy. Regeneration time via this mechanism is $\sim 2 \times 10^8$ years.

Monopoles circulating in the galaxy would be accelerated and drain power from the magnetic field.

Assuming a monopole mass $M_m \sim 10^{16}$ GeV and a large-scale magnetic field $\sim 3\mu G$, Parker estimates the maximum monopole flux in our galaxy consistent with the power available via the dynamo effect to maintain a persistent magnetic field of $3\mu G$.

$$\Phi \lesssim 10^{-15} cm^{-2} s^{-1} sr^{-1}$$

$M_m \sim 10^{16}$ GeV
$\beta \sim 3 \times 10^{-3}$

"Parker Bound" is mass and velocity dependent.

Parker Bound vs. M_m

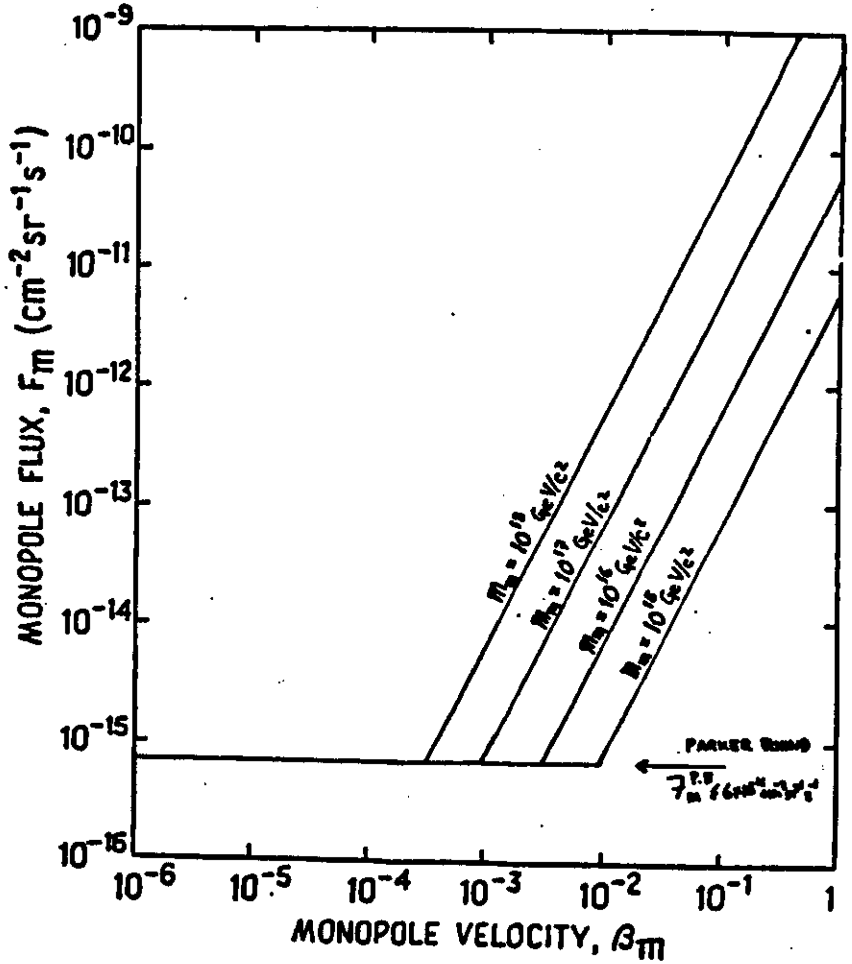
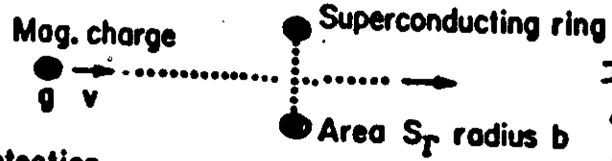


Figure 1.

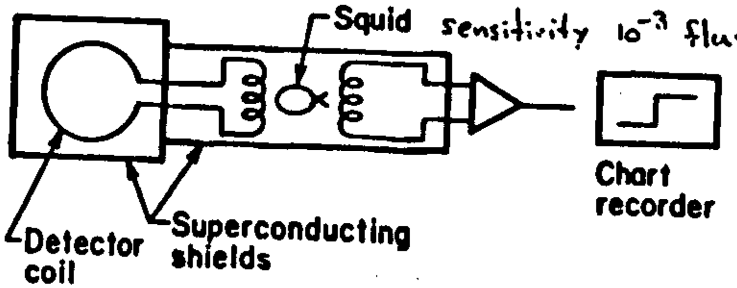
Monopole Detection by Induction

Basic Technique



Induce persistent current in loop
2 fluxons/turn

Detection



sensitivity 10^{-3} fluxons

- Must shield coil and SQUID from external magnetic fields.

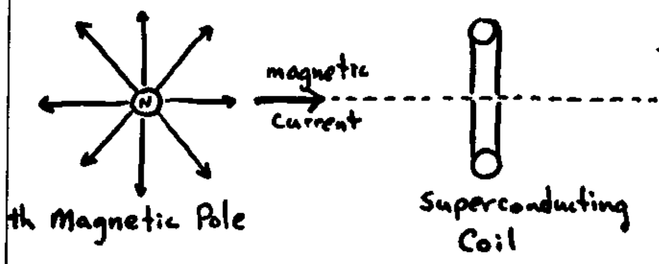
Meisner Effect in S.C. Pb & Nb Shields } Shielding factors
Nested Mu-metal & soft iron } of 10^8 achieved

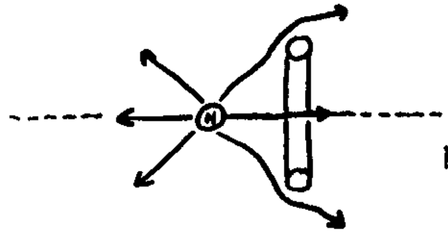
- Coil Configurations:
  - Simple loops
  - twisted loops
  - planar gradiometers

Monopole Passing thru Superconducting - Loop

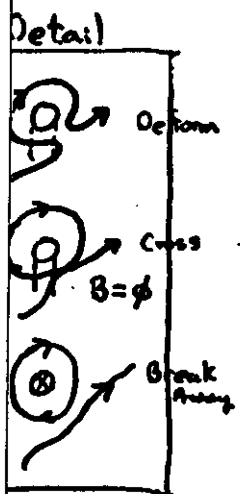
Symmetrized Maxwell Eqn.

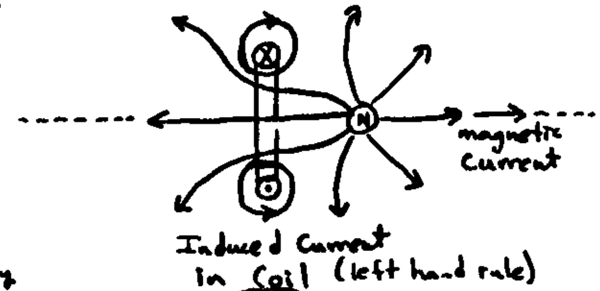
$$-\vec{\nabla}\times\vec{E}-\frac{1}{c}\frac{\partial B}{\partial t}=\frac{4\pi}{c}\vec{g}$$

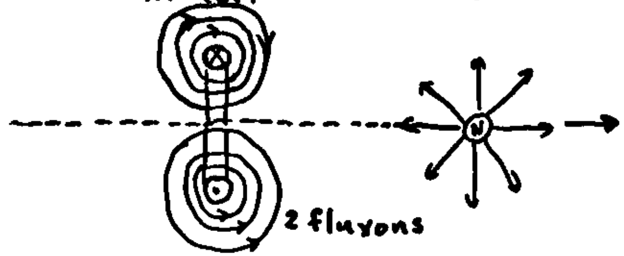




As monopole gets closer to loop, field lines deform to avoid loop.
Meissner Effect: Superconductor repel magnetic fields.







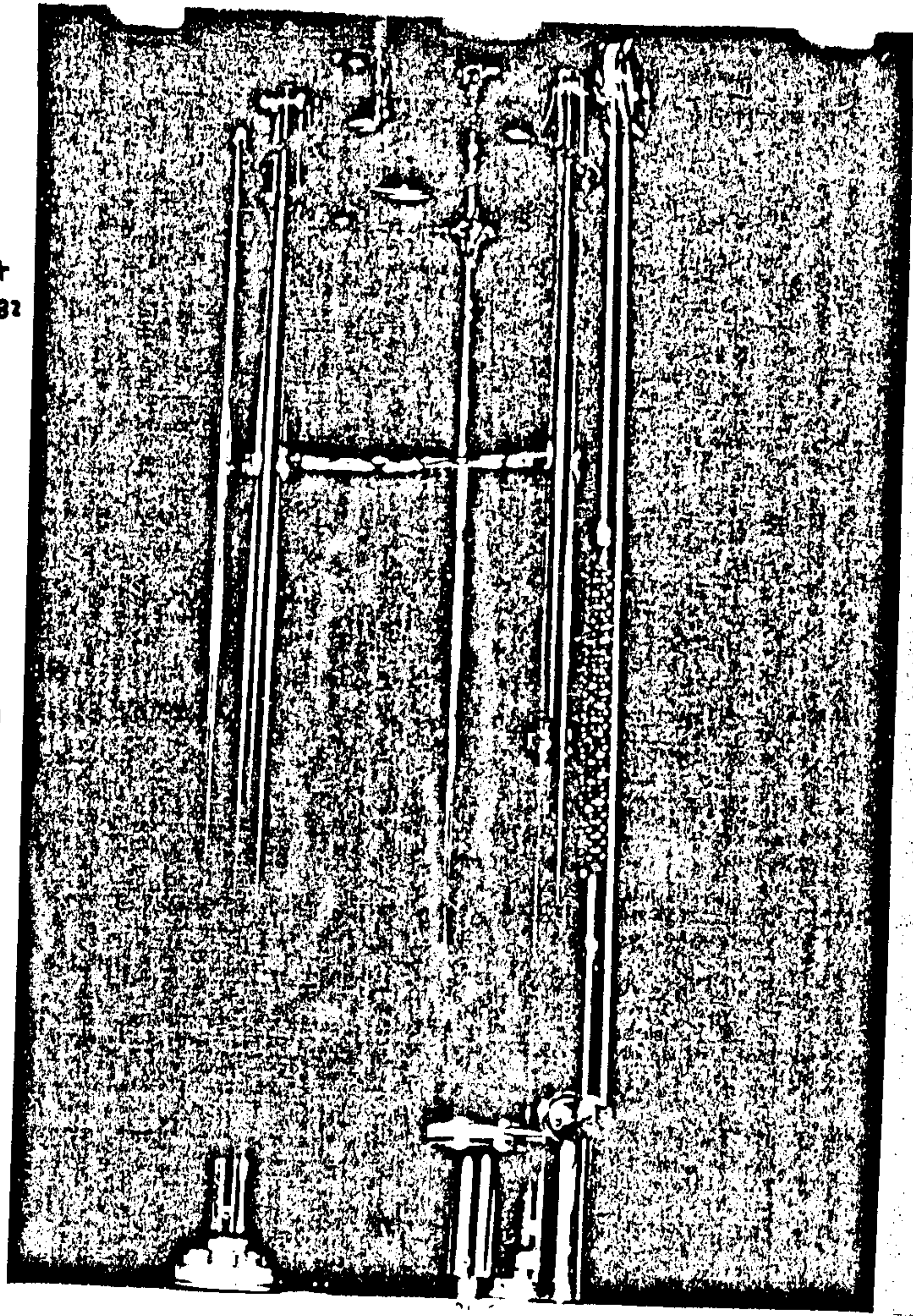
Monopole leaves but loop remains with a residual current to maintain flux that linked to the coil.

$$\Delta I=\frac{4\pi n g}{L}$$

small currents ⇒ SQUID required.

The Induction Experiments

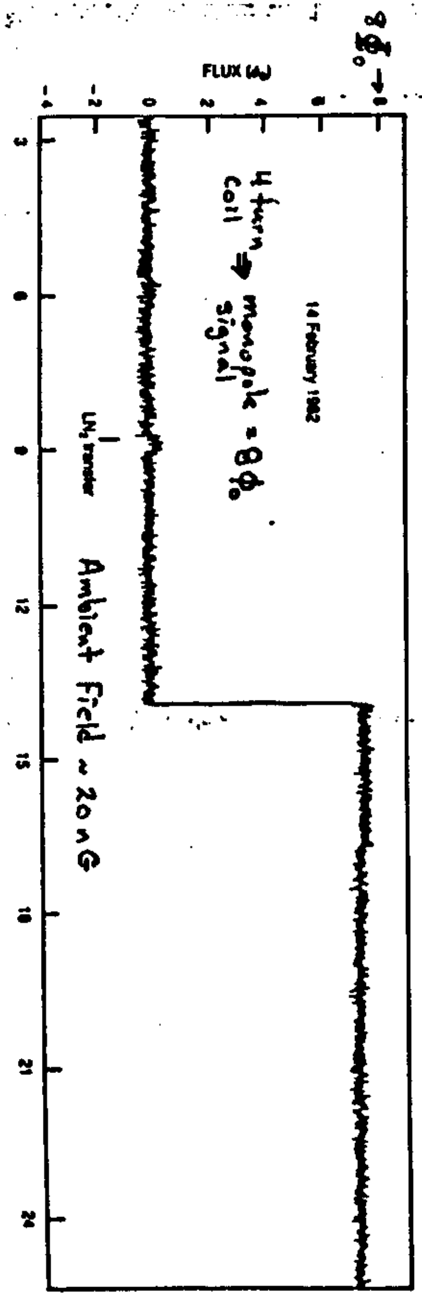
Group	# Loops	Loop Area cm²	Ave. Area over 4π cm²	Arrangement
Stanford I	1	20	10	4 turns Simple Loop — 1 event 14. Feb. '82
Stanford II	3	79	71 Coinc. 405 Near miss 476 Total Coinc.	3 ⊥ loops 2 turns each
IBM I	2	100	25 coinc.	Planar Gradiometers 4 cm apart, parallel
IBM II	6	1125	1000 Coinc.	Planar Gradiometers Rectangular Box
-F-M	2	2800	2100 700 coinc.	Twisted loops (macramé) 21.6 cm apart, parallel
be U.	1	50	25	3 turns Simple loop
perial lege	3	600	300 Coinc.	Circle + 2 D's
NY	2	400	?	Planar Gradiometers



Stanford-I Detector

Observed Event 14. Feb. 1982

151 days of data ⇒ Monopole Flux = $6.1 \times 10^{-10}\ cm^{-2} sr^{-1} s^{-1}$

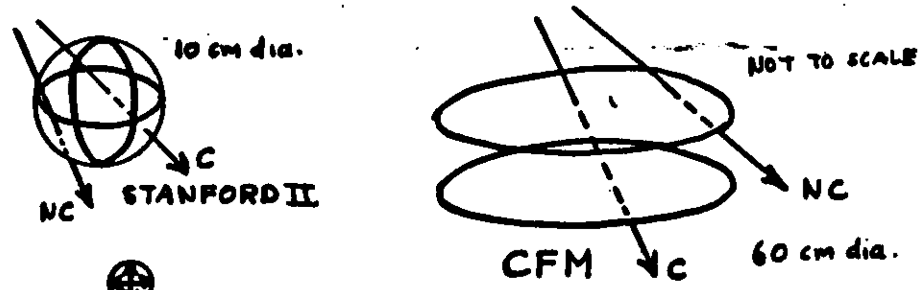


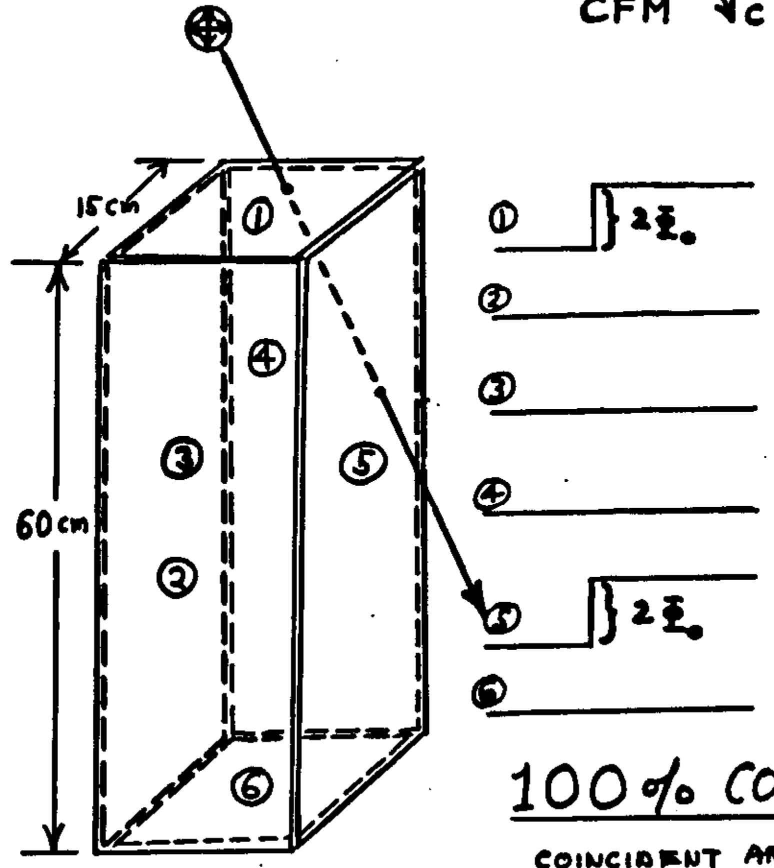
Candidate monopole event found by Blas Cabrera of Stanford University. If a single Dirac magnetic charge passes through the detection loop, one would expect an $8\Phi_0$ change in the flux through the superconducting circuit.

PRL 48, 1378 (1982)

No coincidence.
Laboratory unoccupied.
No seismic disturbance.
No monitoring of parameters which could cause offset.

COINCIDENCE DETECTION





TWO AND ONLY TWO DETECTORS MUST FIRE

IBM
6 INDEP. DETECTORS
CLOSED BOX

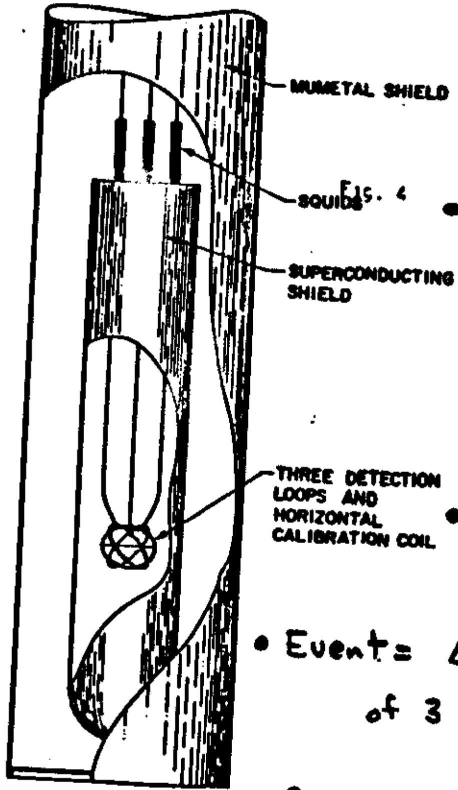
100% COINCIDENCE

COINCIDENT AREA FOR 4π-sr ISOTROPIC FLUX = 1000 cm²

($\frac{1}{4}$ TOTAL SURFACE AREA)

IBM 4/56

Stanford-II Detector.



Characteristics

- Ultralow ambient field (~20nG) via expanded Pb foils.
- 3 orthogonal niobium loops, 10cm ϕ, 2 turns
- Event = $\Delta I > 0.1\,\Phi_0/L$ in 2 of 3 loops in coincidence
- Precise calibration of monopole signal via calibration coil.
- Instrumented with monitors: magnetometer, accelerometer, AC, sound alarm, etc.
- High bandwidth data acquisition for coincident events.

oincidence Loop Area

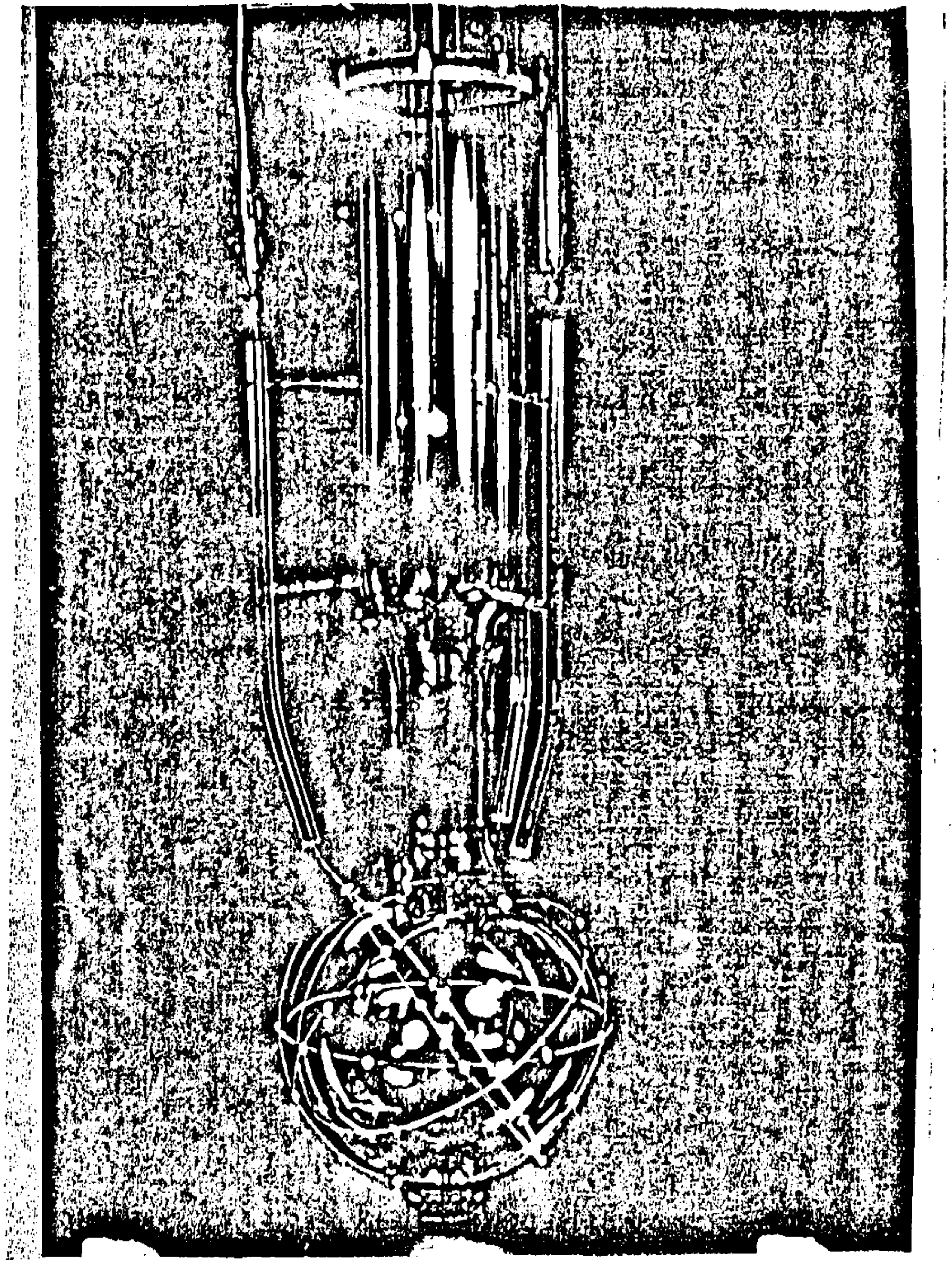
70.5 cm²

icidence Shield Area

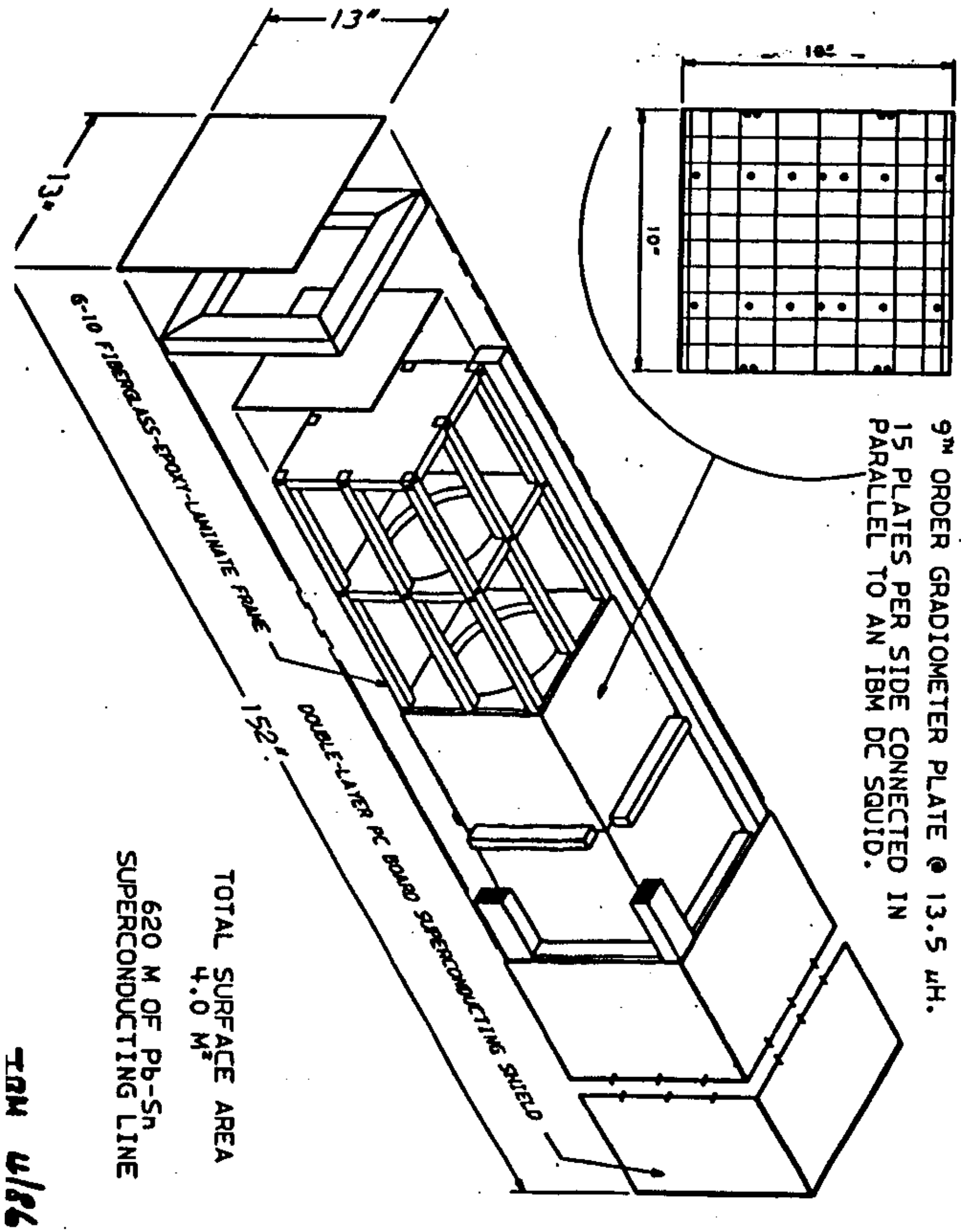
405 cm²

Total

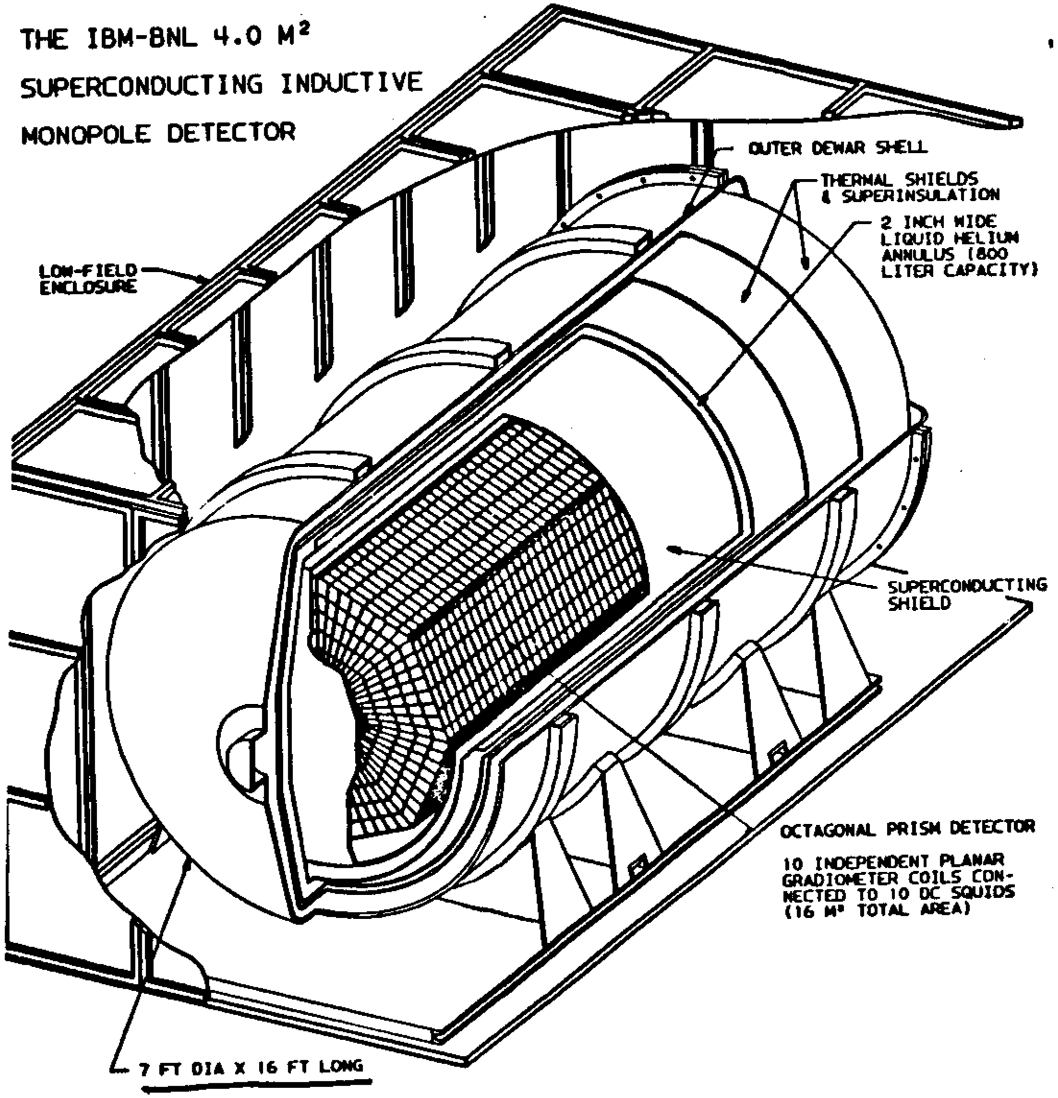
475.5 cm²



IBM-BNL 1.0 M² FULLY COINCIDENT INDUCTION DETECTOR

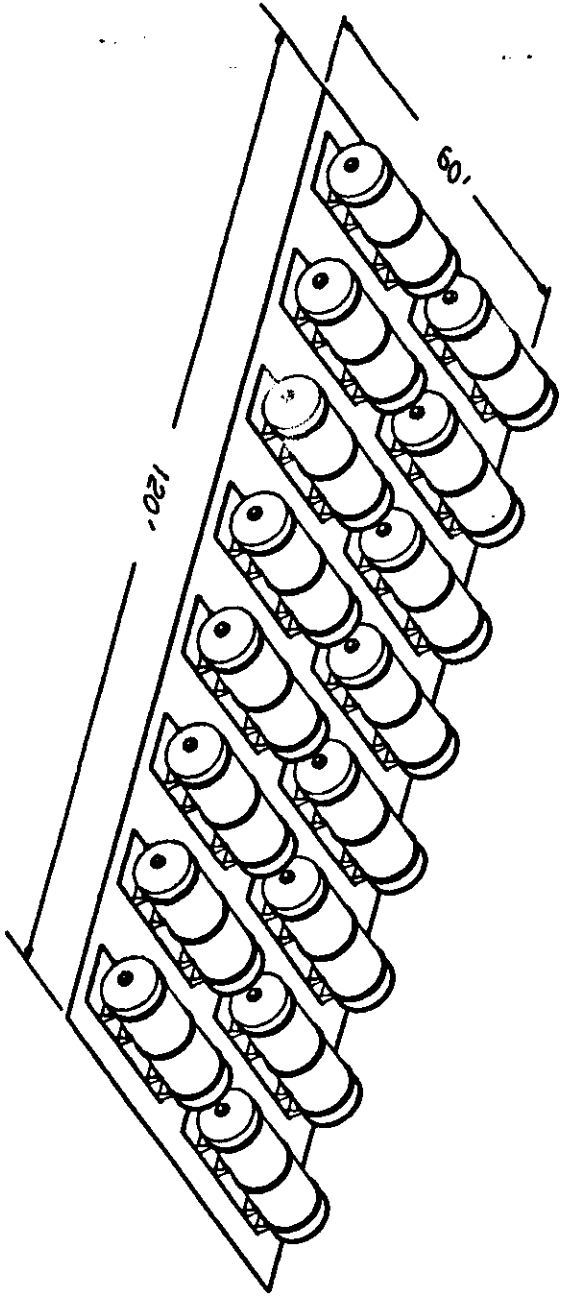


THE IBM-BNL 4.0 M² SUPERCONDUCTING INDUCTIVE MONOPOLE DETECTOR



IBM 4/86

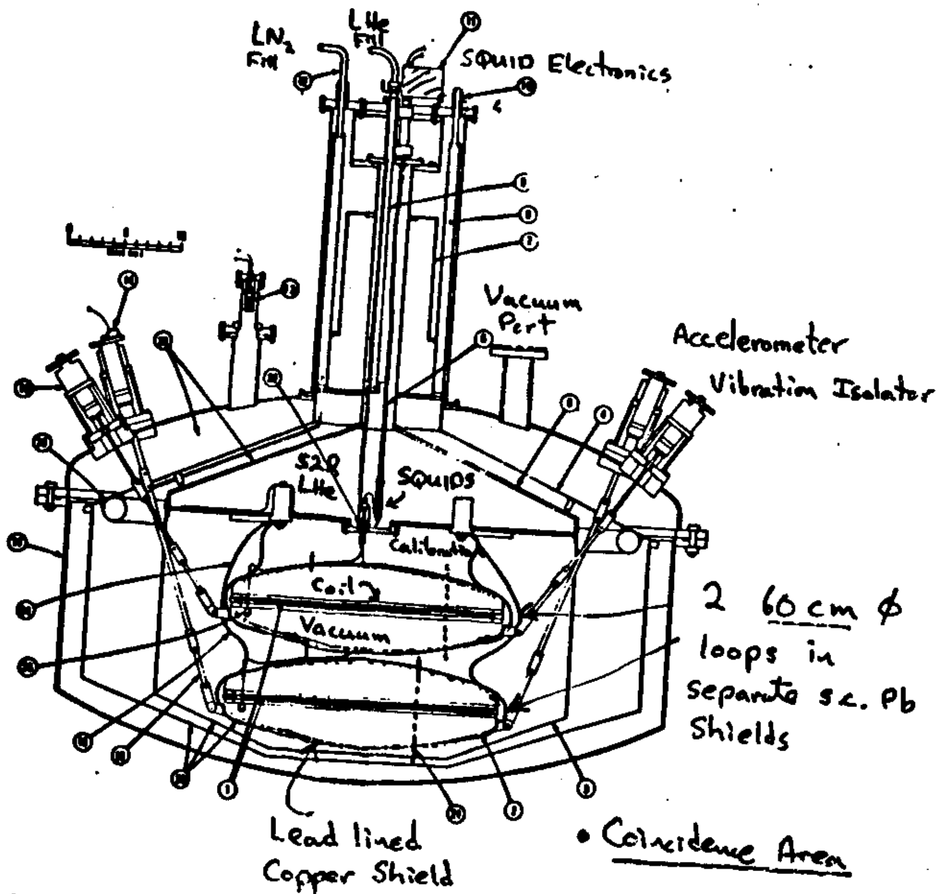
IBM-BNL MONOPOLE DETECTOR ARRAY



16 DEWARS 7' DIA X 25 ' LONG
16 DETECTORS @ 6.6M² = 105.6 M² TOTAL AREA
16 X 18 = 288 SQUIDS

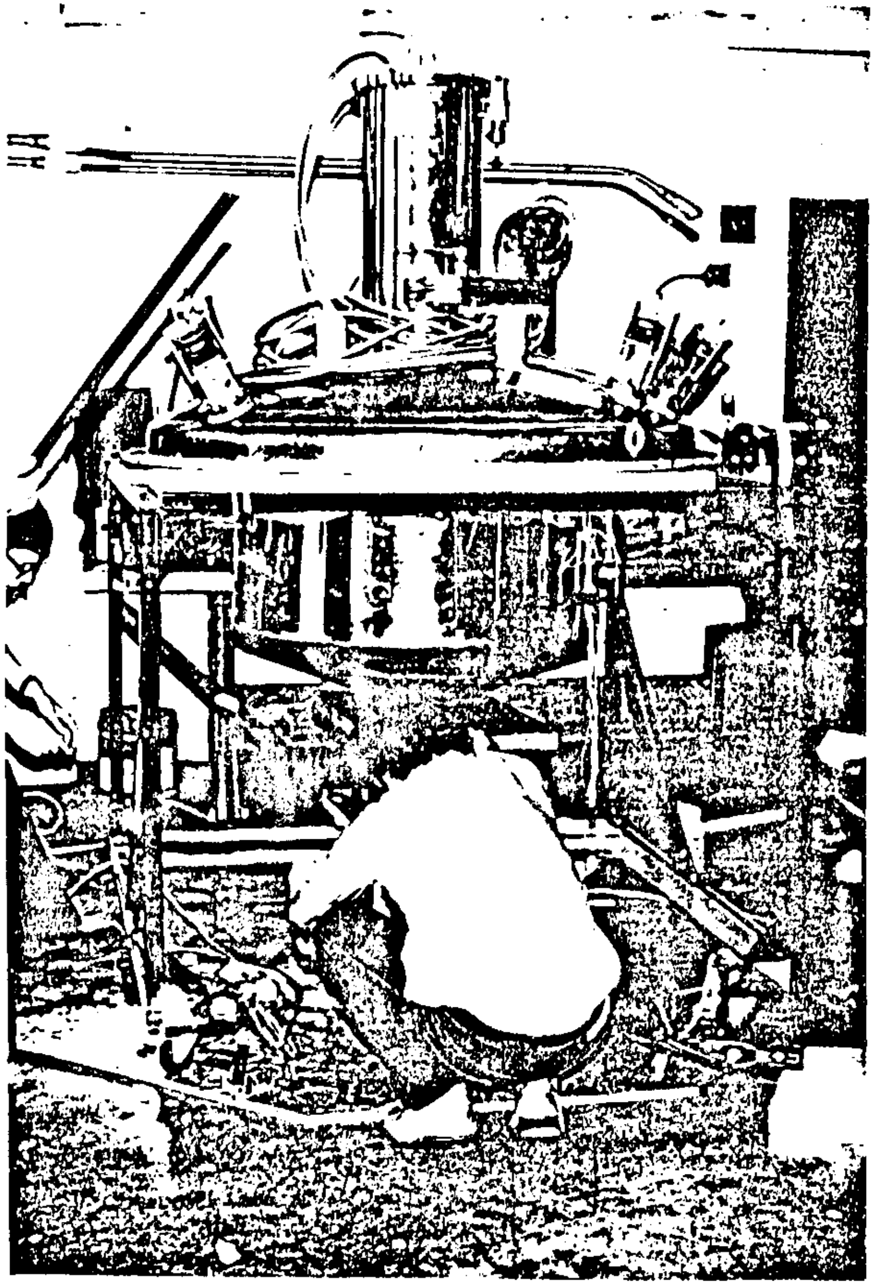
ESTIMATED LHe CONSUMPTION = 50 LITERS PER HOUR
→ He LIQUIFIER AND GAS RECOVERY SYSTEM

Chicago-FNAL-Michigan Detector

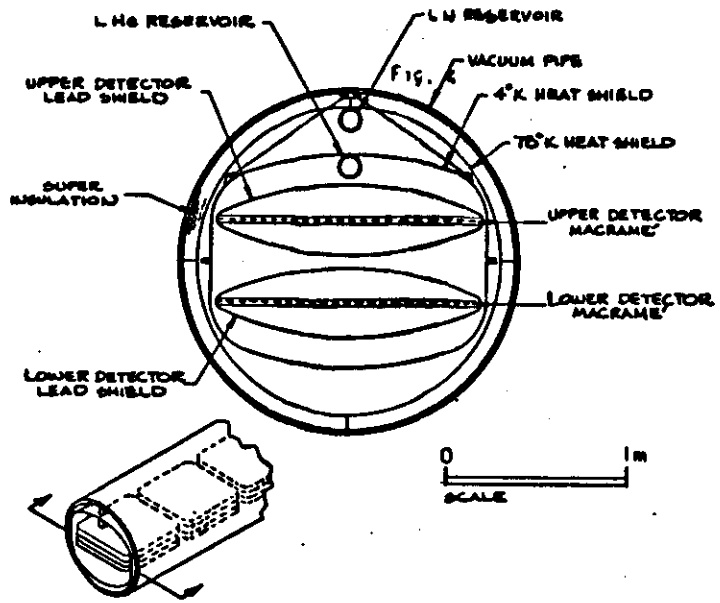


Other Characteristics:

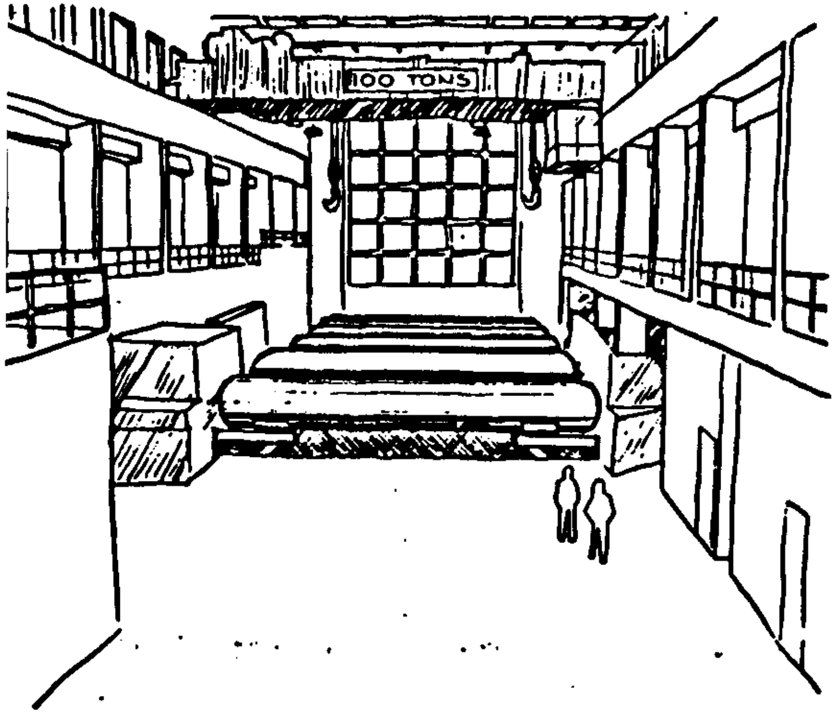
- Coils made of standard p.c. board with plated thru holes; mechanically rigid.
- S.C. transformer is used to match large coil L (25 μH) to SQUID.
- Calibration of monopole signal by thin solenoids penetrating the pick up coils and shields.



C-F-M Concept



$17\,m^2$ CRYOSTAT AND DETECTOR MODULE



THE DETECTOR INSTALLED IN THE FERMI INSTITUTE ACCELERATOR BUILDING at the University of Chicago

Summary of S.C. Induction Detector Results

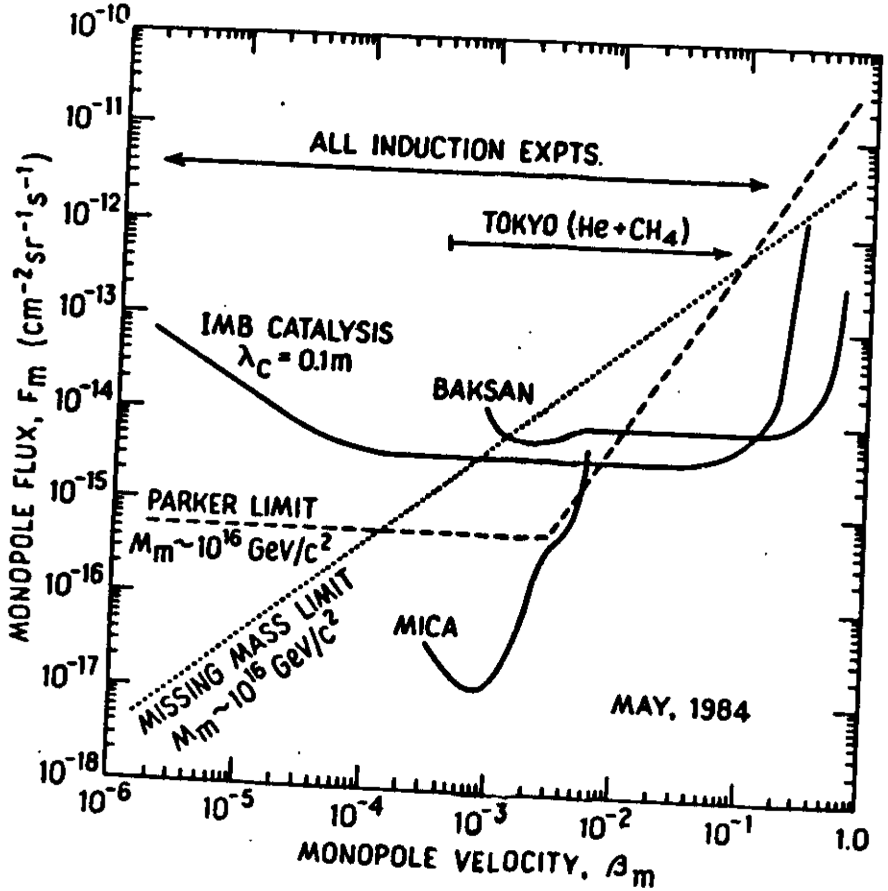
Experiment	Ave. Area over 4π (cm²)	Live Time	Flux Limit 90% C.L. $cm^{-2}sr^{-1}s^{-1}$	Exposure normalized to Stanford I
Stanford I	10 cm²	151 days	1.4×10^{-9}	1
Stanford II	476 Coinc.	214	2.1×10^{-11}	67
IBM I	25 Coinc.	165	5.1×10^{-10}	2.7
IBM II	1000 Coinc.	7	3.0×10^{-10}	4.7
CFM	1400	22	6.9×10^{-11}	21
Imperial College	300 Coinc.	—	—	—
Kobe University	25	42	2.0×10^{-9}	0.7

Total = 97.1 × original Stanford I

∴ Global Flux Limit, 90% C.L.

$F_m < 1.4\times10^{-11}\ cm^{-2}sr^{-1}s^{-1}$

1988 $F_m < .8\times10^{-12}\ cm^{-2}sr^{-1}s^{-1}$



Summary of monopole flux limits versus monopole velocity. The solid curves are the most restrictive experimental limits from each of the various techniques discussed in this paper. The broken curves are limits derived from astrophysics.

Experimental Limits based on Monopole Catalysis of Nucleon Decay

Data from Nucleon Decay Experiments

- Irvine - Michigan - Brookhaven - USA
- Kamioka - Japan
- Soudan I - Minnesota
- NUSEX - Mont Blanc
- Lake Baikal - USSR
- Kolar Gold Field - India

(10)

Magnetic Monopole "Catalysis" of Nucleon Decay

Superheavy magnetic monopoles are a natural consequence of Grand Unified Theories which break to a U(1) gauge group.

$M_m \sim 10^{16}$ GeV   't Hooft (1974), Polyakov

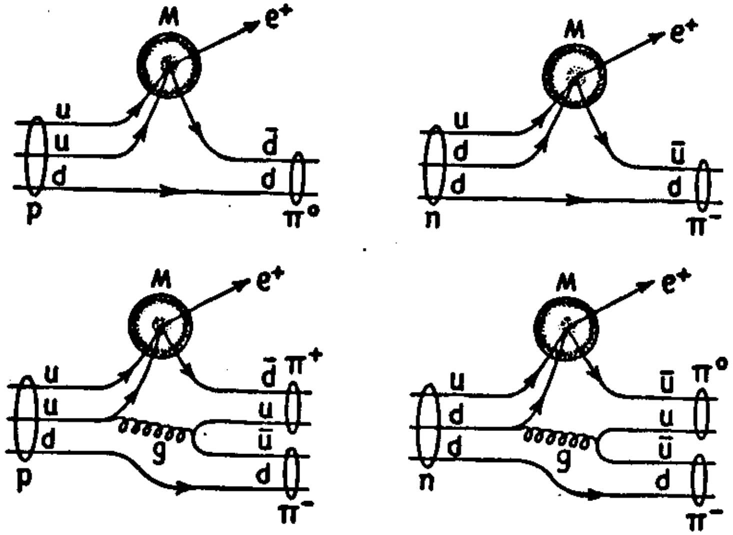
Monopoles in proximity to hadronic matter may "catalyze" baryon number violating processes.

$$M + p,n \rightarrow M + e^+ + \text{mesons}$$

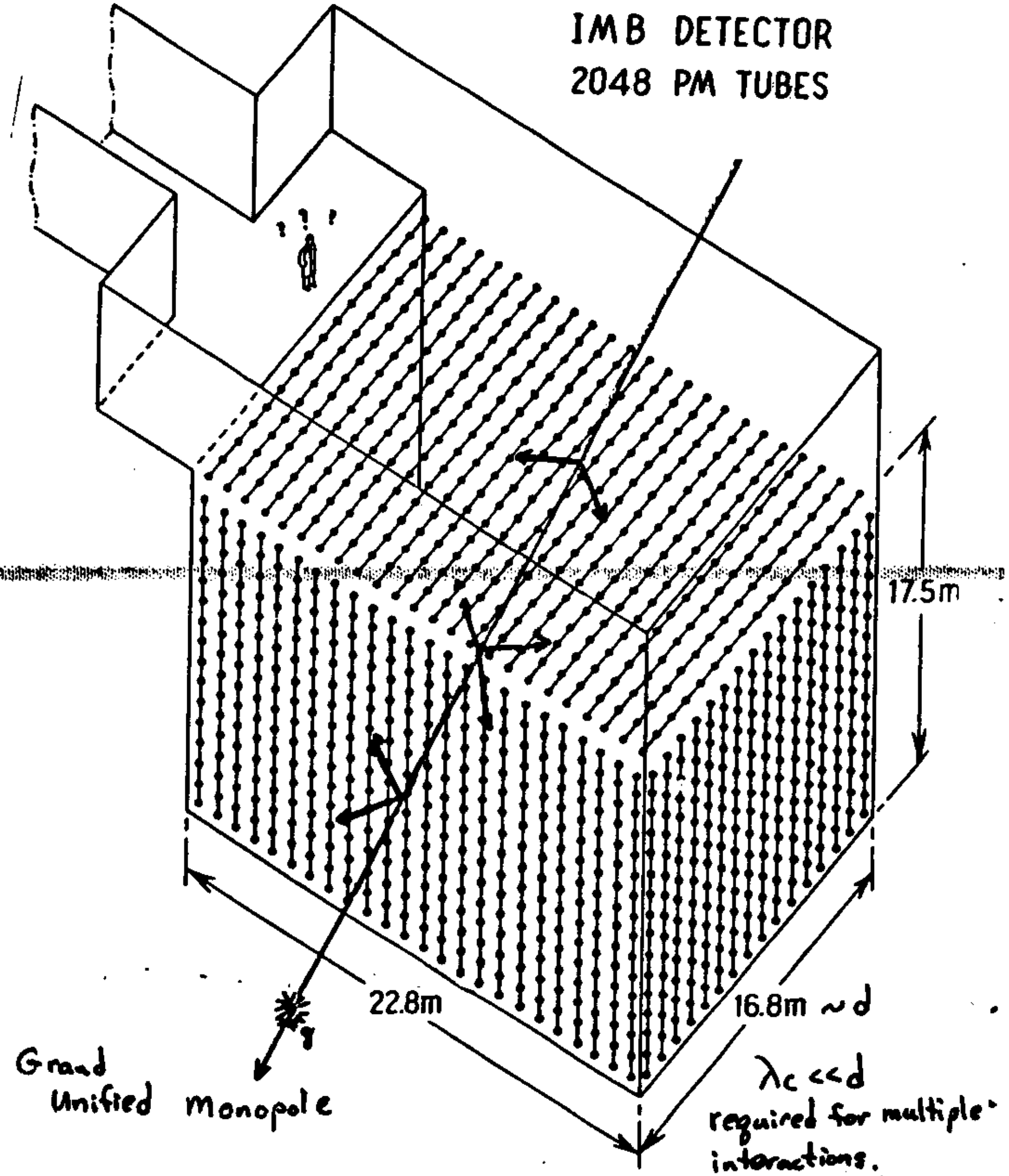
$\sigma_c \sim \frac{1}{M_X^2}$ Dokos & Tomaras (1980)

Catalysis Cross Sections are predicted to be ~ strong interactions (millibarns)!

, Indpt. of m_X.   Rubakov, Callan (1982)

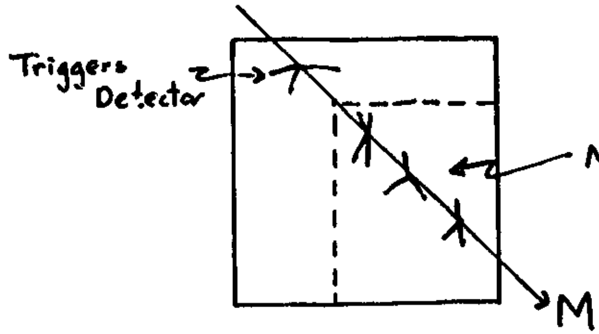


Signal in a Proton Decay Detector



Electronics Deadtime:

Most proton decay detectors are live for 5-10 μsec (long enough to observe $\mu \to e\nu\bar{\nu}$ following an event trigger) and then are dead for 3 - 800 msec to read out the data.



Monopoles are slow, eg. $\beta_m \sim 10^{-3}$.

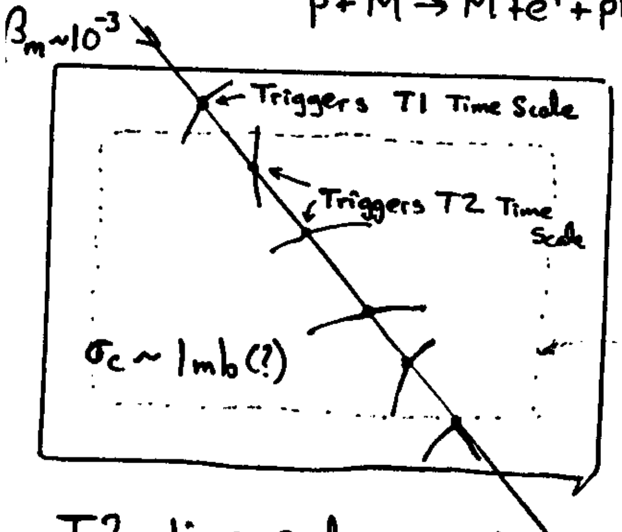
If, L = 3m, Δt = 10 μsec ; L = 30m, Δt = 100 μsec

Range of β_m and λ_c limited by deadtime.

IMB detector now has electronics extending the livetime sensitivity for multiple interactions to 10 msec. (Ring buffers, etc)

Monopole Catalysis in the IMB Detector

$p + M \rightarrow M + e^+ + \text{pions}$



Multiple Proton Decays possible.

Require at least one event in F.V. to lower background.

T2 time scale up to 7.5μsec

∴ Look for Second event in T2.

Require: NT2 ≥ 50 in 300 ns coincidence
NT1 ≥ 30 in 50 ns

Observe: 4.7 ± 0.3 events/day in T2
Scanning yields only muon events.

From the cosmic muon rate of 2.7/second through the detector, we expect the random coincidence rate in T2 to be ~4.7/day.

No candidate events have been found. (Scanning)

To illustrate

Event Rate:

$$N_{obs.} = F_m \cdot A \cdot \Omega \cdot \Delta t \cdot \epsilon(\text{geom.}, \beta_m, \lambda_c) \cdot \epsilon_{trig}$$

F_m = monopole flux

A = effective cross-sectional area of detector

Ω = solid angle $\approx 4\pi$

Δt = detector live time

* $\epsilon(\text{geom.}, \beta_m, \lambda_c)$ = efficiency for =1, ≥2 interactions

$\epsilon_{geom.}$ ⇒ geometrical cuts, fiducial volume, etc.

ϵ_{β_m} ⇒ time window of electronics ~5-10μsec

ϵ_{λ_c} ⇒ probability for =1, ≥2 interactions to occur within time window

* $\epsilon_{trig.}$ = trigger efficiency of detector for various nucleon decay modes.

e.g. $M + n \rightarrow M + 3\nu$ $\epsilon_{trig} = \phi$

$M + p \rightarrow M + e^+ \pi^0$ $\epsilon_{trig} \sim 100\%$

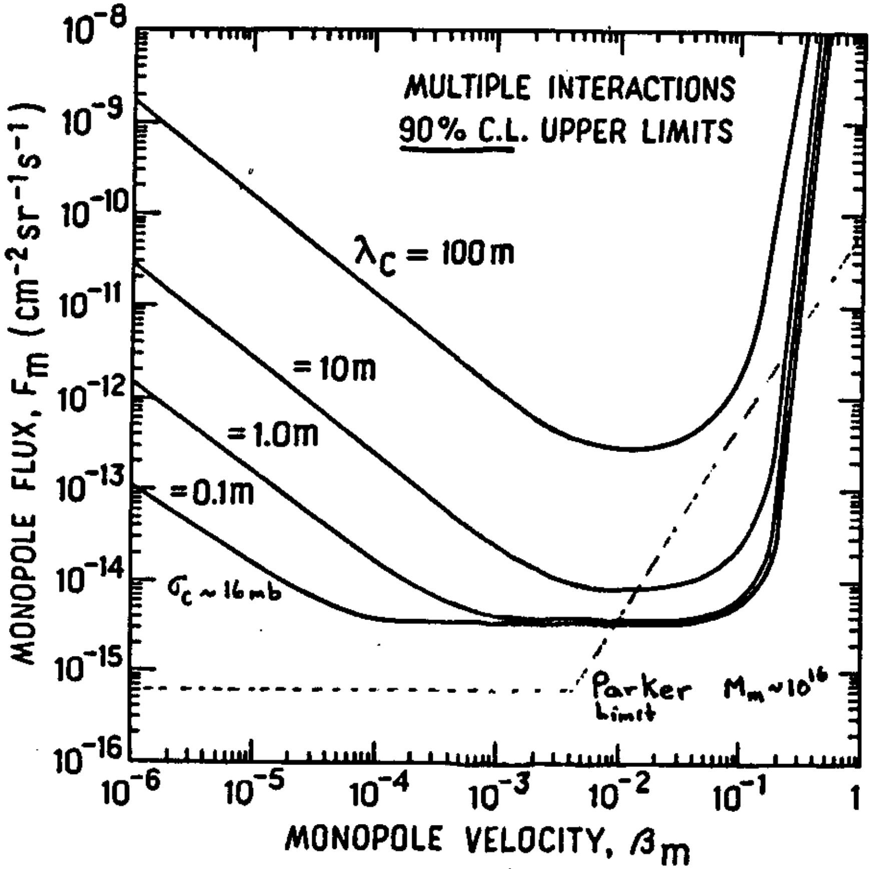
.IMB

$\epsilon_{trig} = 0.9 \pm .1$ for e^+ + mesons

$\epsilon_{trig} \gtrsim .75$ for all modes

IMB 300 Days Live Time

≥ 2 Catalysis Interactions



T2

For $\lambda_c = 1$ m $F_m < 2.4 \times 10^{-15}$ $cm^{-2} s^{-1} sr^{-1}$ $10^{-3} \leq \beta_m \leq 10^{-1}$

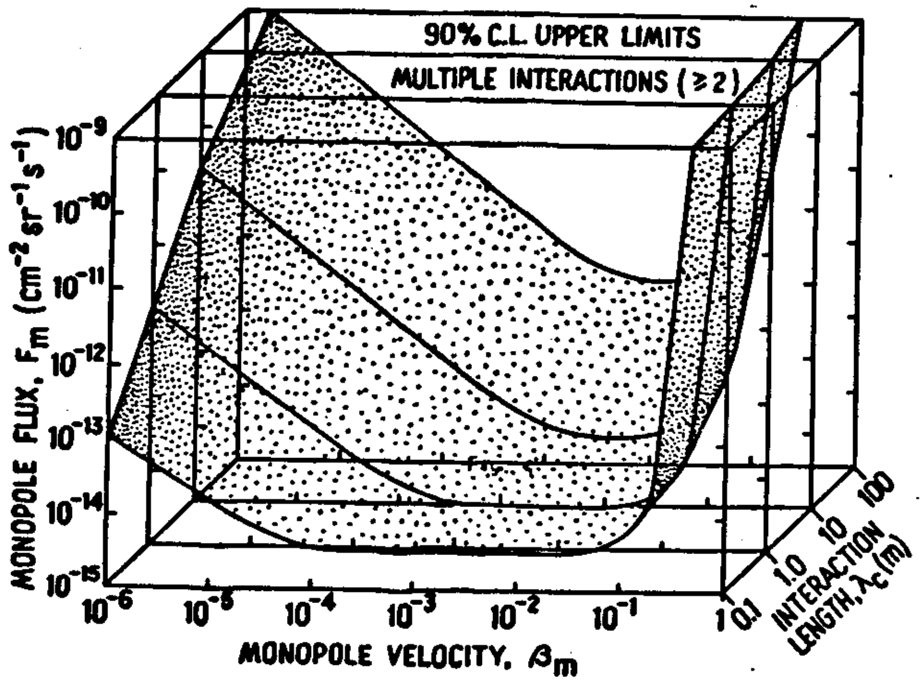
For $\lambda_c = 0.1$ m $F_m < 2.1 \times 10^{-15}$ $cm^{-2} s^{-1} sr^{-1}$

Parker Limit $F_m < 6 \times 10^{-16}$ $cm^{-2} s^{-1} sr^{-1}$

IMB Monopole Catalysis Flux Limit

F_m vs. β_m vs. λ_c

"Surface"



Summary of Experimental Limits

Detector	Live Time (days)	Interaction Length, λ_c (meters)	Velocity Range β	Monopole Flux Limit ($cm^{-2}sr^{-1}s^{-1}$) $\equiv 1$ Interaction	≥ 2 Interactions
KGF	561	$\lambda_c = 4m$	—	2×10^{-13}	—
	561	$\sigma_c \geq 10mb$	$\beta_m \geq 10^{-3}$	—	2×10^{-14}
Soudan I	285	$10^{-2} \leq \sigma_0 \leq 10^{2}$	$\beta_m \geq 10^{-3}$	—	1.5×10^{-13}
NUSEX	317	$\lambda_c \sim 4m$	$\beta_m > 10^{-4}$	6.1×10^{-13}	—
	317	$\lambda_c \leq 1m$	$\beta_m \geq 10^{-4}$	—	2.3×10^{-14}
Kamioka	135	$\lambda_c \leq 1.7m$	$10^{-4} \leq \beta_m \leq 10^{-3}$	—	7.6×10^{-15}
	135	$\lambda_c \leq 17m$	$10^{-5} \leq \beta_m \leq 10^{-3}$	—	6.4×10^{-15}
IMB	200	$\lambda_c \sim 16.7m$	—	1.7×10^{-12}	
	300	$\lambda_c \leq 10m$	$5\times10^{-3} \leq \beta_m < 6\times10^{-2}$	—	2.4×10^{-15}
	300	$\lambda_c \leq .1m$	$10^{-3} \leq \beta_m \leq 10^{-1}$	—	2.1×10^{-15}
Lake Baikal	50	$\sigma_c \geq 10^{-21} cm^2$	$\beta_m \leq 10^{-4}$	—	7×10^{-15}

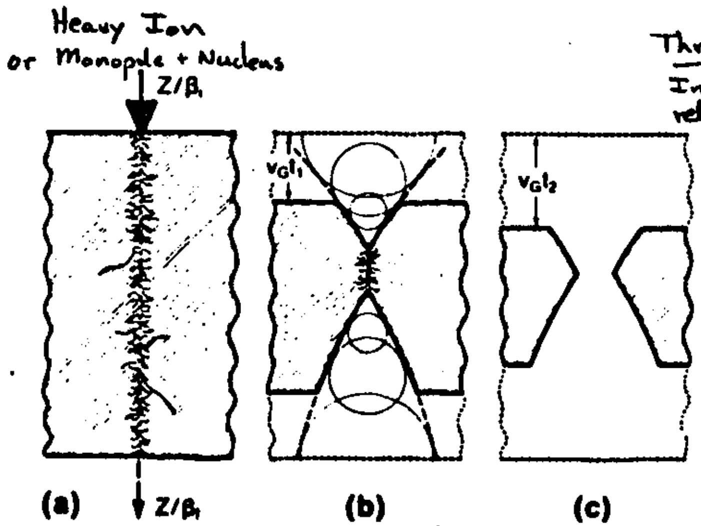
Detector Parameters

	Soudan I	KGF	NUSEX	Kamioka	IMB
Depth (mwe)	1800	7000	5200	2700	1500
Material	Taconite Cement	Iron	Iron	H_2O	H_2O
Ave. Density $\frac{gm}{cm^3}$	1.9	1.5	3.5	1.0	1.0
Mass Total	31	140	150	3000	8000
(tonnes) Fiducial	16	100	100	1000	3300
Dimensions (m)	3x3x2	4x4x6	$(3.5)^3$	15.5ϕx16	23x17x18
⟨A⟩ Eff. Area (m^2)	10	32	18	220	550
⟨L⟩ Ave. Path Length (m)	1.7	3.1	2.3	10.3	12.8
Elect. Live Time (μsec)	6.5	7.0	5.0	88	8.0
Elect. Dead Time (m sec)	800	20	20	3.0	3.0

Track Etch Detector Technique ---

- Low velocity, massive particles (ions, monopoles) passing thru plastics or crystals can cause damage (lattice defects) along their path by nuclear and electronic collisions. (a)

·g.
R-39
.exan
elinex



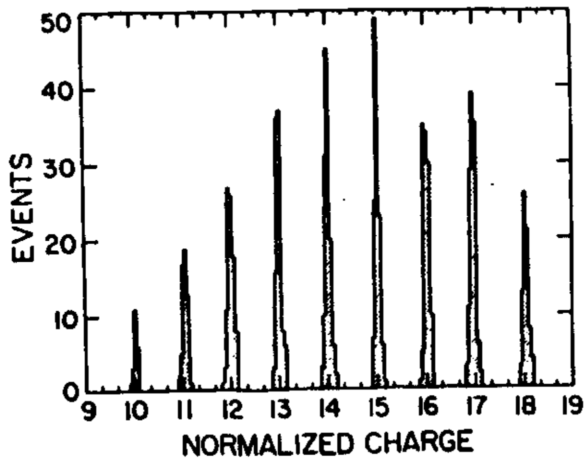
Threshold Devices
Insensitive to relativistic min. ionizing particle.

Pit geometry depends on Z/β + etch rate.

- Latent tracks can be located in one layer by etching (HF) for extended periods and detecting hole (c) with ammonia or by scanning with a microscope.

- Etch other layers for shorter periods and measure geometry of pit to determine ionization rate of particle that produced the track. (b)

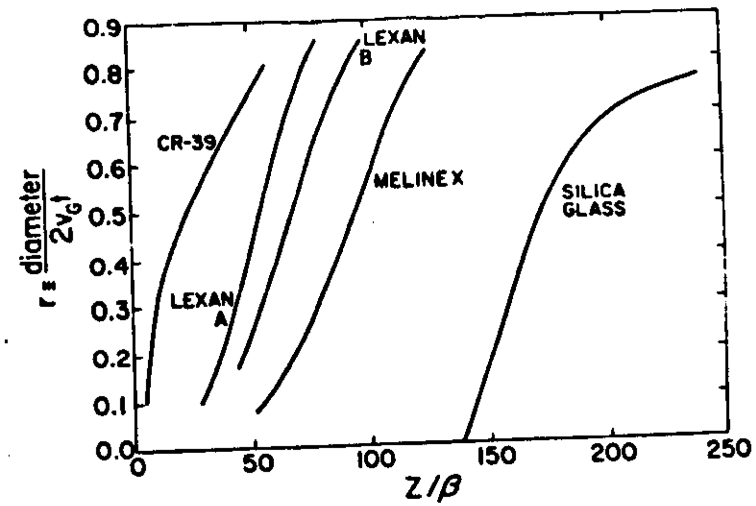
Technique yields extraordinary charge resolution.

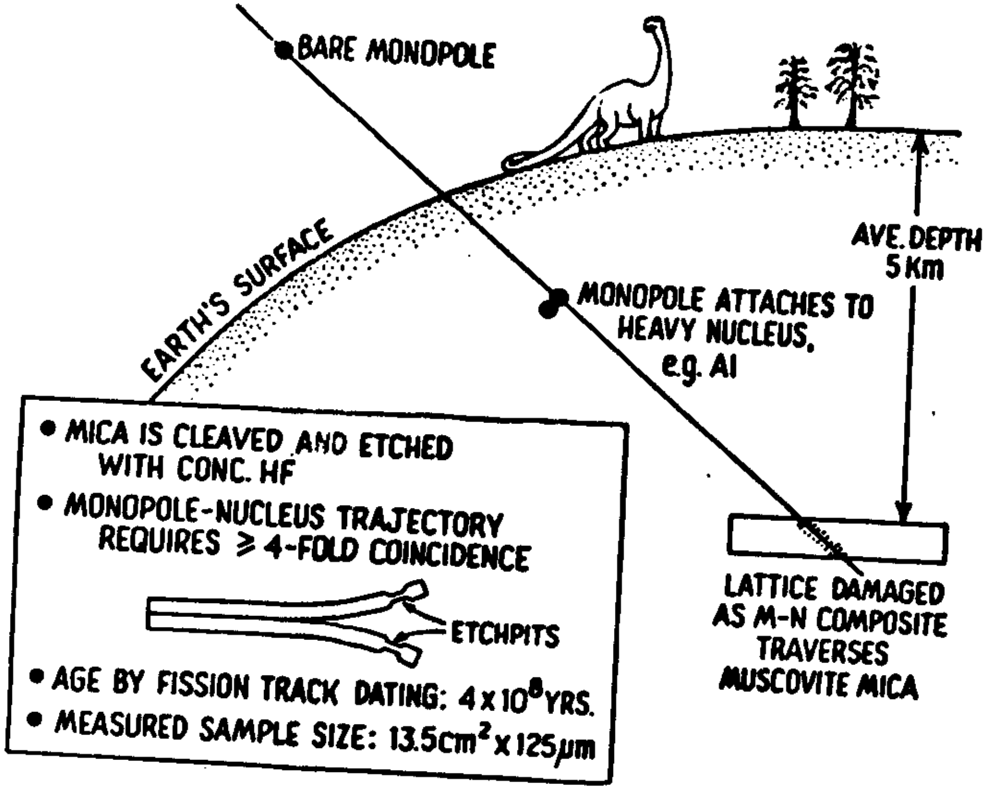


$\sigma_Z = 0.06e$

$9 \leq Z \leq 30$

Calibration using ion accelerators:



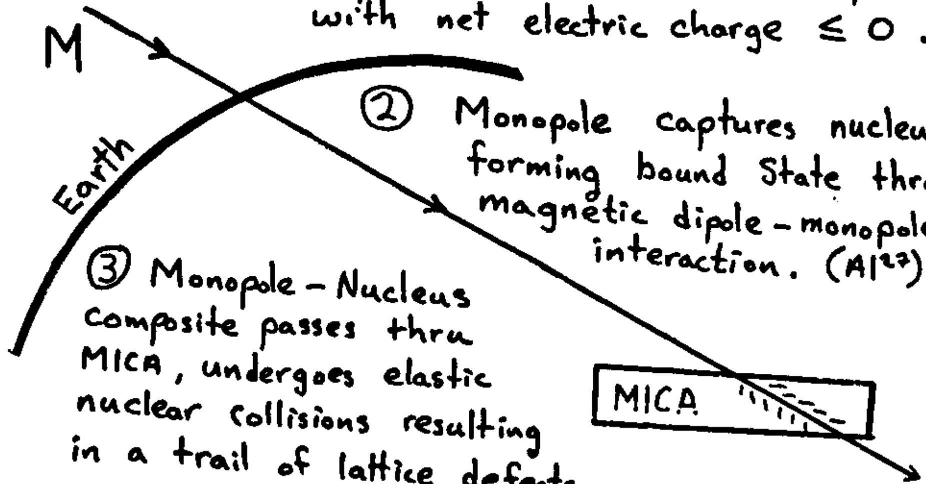


Scenario of the Berkeley Mica Experiment.

Monopole Search Using Ancient MICA

S.P. Ahlen – Indiana ; R.L. Fleicher – General Electric Co.
P.B. Price , S.L. Guo – UC Berkeley

Scenario: ① Monopole enters Earth's atmosphere with net electric charge ≤ 0.

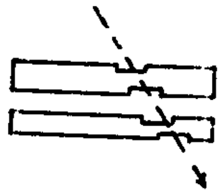


② Monopole captures nucleus forming bound State thru magnetic dipole – monopole interaction. (Al^{27})

③ Monopole – Nucleus composite passes thru MICA, undergoes elastic nuclear collisions resulting in a trail of lattice defects.

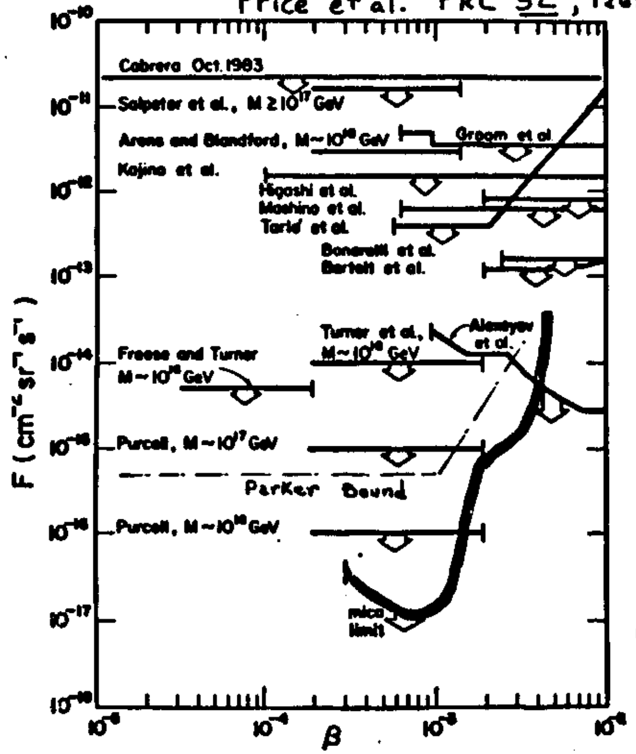
④ As long as MICA is not heated, track survives Etching in Hydroflouric acid enlarges track to macroscopic dimensions.

4-fold coincidences have low background due to fission tracks



MICA Result

Price et al. PRL 52, 1265 (1984)



Age of MICA:
$\sim 4 \times 10^8$ years

Average Depth:
5 Km

Total Size of MICA Sample:
$1000\ cm^2 \times 1\ cm$

Amount Analyzed:
$13.5\ cm^2 \times 125\ \mu m$

Calibrated with $\beta \sim 10^{-3}$ ions

2 Ways the MICA Result can be Evaded:

1. If monopole catalysis of nucleon decay occurs strongly, the monopole-nucleus bound states could be short lived.
2. If monopole carries positive electric charge (proton attached), Coulomb repulsion would prevent the monopole from capturing a nucleus.

Trapping of Monopoles by Ferromagnets

Because of it's magnetic field a monopole feels an attractive "image force" near ferromagnetic and paramagnetic material.

Goto, Kolm, and Ford (for $M_m \sim 10^{16}\ GeV/c^2$)

Iron : $F_{image} \approx 10\ eV/\text{Å}$

Binding Energy ~ 740 eV

Magnetite: $F_{image} \approx 3.4\ eV/\text{Å}$

Binding Energy ~ 250 eV

At earth's surface: $F_{gravity} \sim 10^{-2}\ eV/\text{Å}$ for $M_m \sim 10^{16}\ GeV/c^2$

∴ Superheavy monopoles can be trapped by ferromagnets.

Possible Sources of Monopoles Trapped in Matter

Earth's Crust

Slow monopoles passing through the earth will lose energy by inducing eddy currents in the core. Monopoles which oscillate back and forth with their turning points near the surface may become trapped in ferromagnetic materials near the earth's surface.

Possible Sources: Iron ore deposits, magnetic sands, core samples

Collection Times: ~ $6-25 \times 10^6$ years for magnetic sands

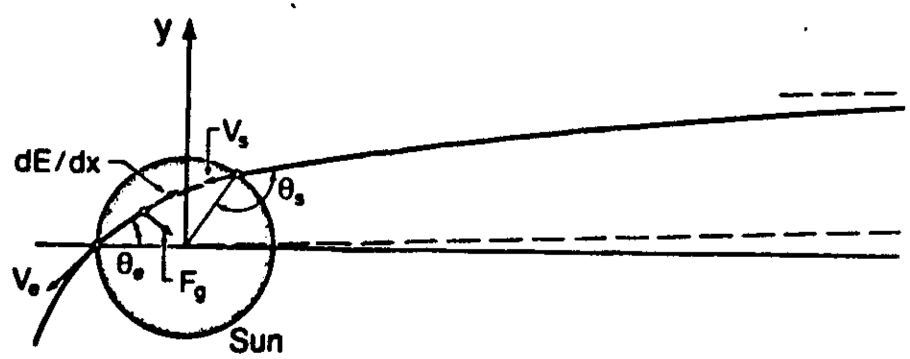
~ 2×10^9 years for sedimentary iron ore

Meteorites

Monopoles could have been trapped in asteroids or planets at the time of accretion from solar nebula, or could have been collected over a long time as these bodies moved thru space. Some meteorites reaching the earth's surface can retain trapped superheavy monopoles depending on the maximum deceleration.

Possible Sources: Small Antarctic meteorites which landed in deep snow.

Collection Time: ~ 4×10^9 years



Experiment:

SQUID Fluxmeter Search for Monopoles in 400 kg of Old Iron Ore

Kobe University, Japan
T. Ebisu and T. Watanabe

Location: Kobe, Japan

Technique: Heat samples of magnetic sand (Fe_3O_4) and maghemite (Fe_2O_3) through Curie temperature. Detect monopoles which diffuse downward by gravity and penetrate a Niobium coil - SQUID magnetometer.

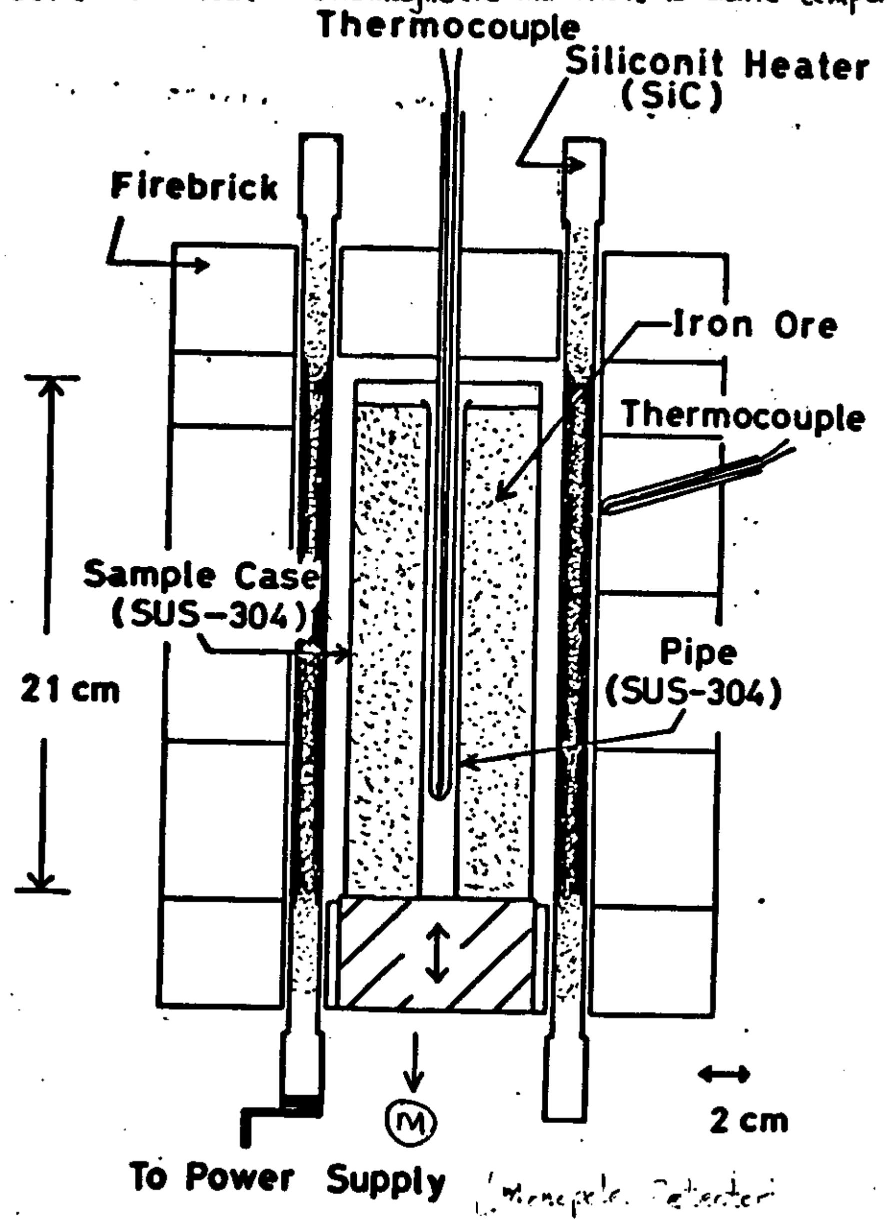
Detector: Superconducting Niobium coil, 8 cm ϕ, 3 turns
s.c. Pb shielding
Furnace to heat samples

Present Status: Taking data, preprint exists
Data reported on 400 Kg

Results: $N_m/N_n < 10^{-29}$

Kobe Detector

Device to heat ferromagnetic materials to Curie temperature



Meteorites

Two General Types

Iron ~ 94% Fe + 6% Ni + <1% other (Kamacite)
Crystalline structure suggests cooling occurred in larger bodies, eg. asteroids.

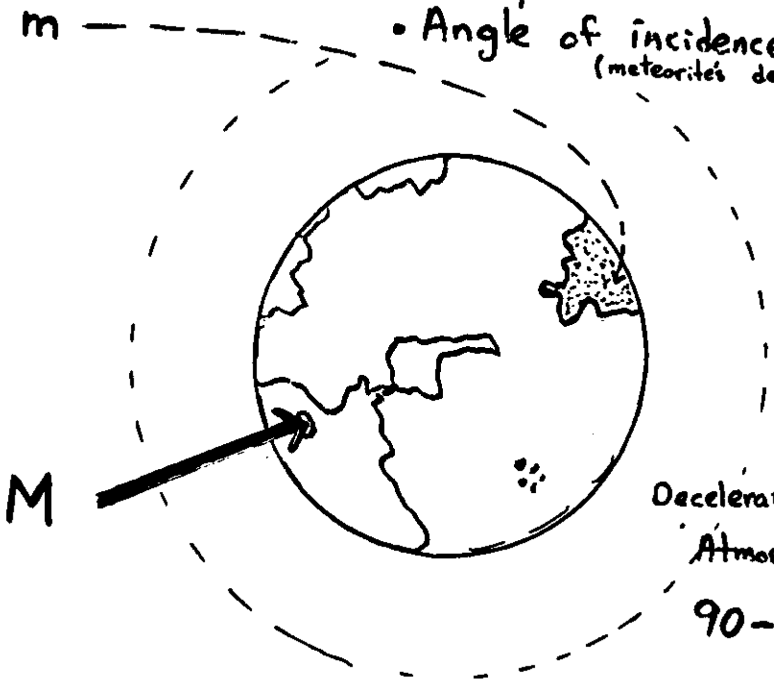
Stony ≈ 5% Fe in mm size grains (chondrites)
Believed not to have remelted since accretion in asteroids ~ 5×10^9 years ago

∴ Monopoles could have been trapped at time nebula accreted to asteroids and planets

or Asteroids and meteors could have collected over ~ 4 billion years in their journey through space.

Do Monopoles Remain in Meteorites During Their Fall to Earth?

Depends on:
- Monopole mass
- Angle of incidence (meteorite's deceleration)



Deceleration in Earth's Atmosphere: 90–1000 g

Decelerations on impact with ground depends on surface; minimized in deep snow.

⇒ **Antarctic Meteorites**

What monopole mass can remain trapped in a meteorite impacting the Earth?

- Assume maximum deceleration = 1000g
- Use Goto et al. for image force on magnetite

$$F_{image} \sim 5\ eV/\mathring{A}$$

Containment requires:

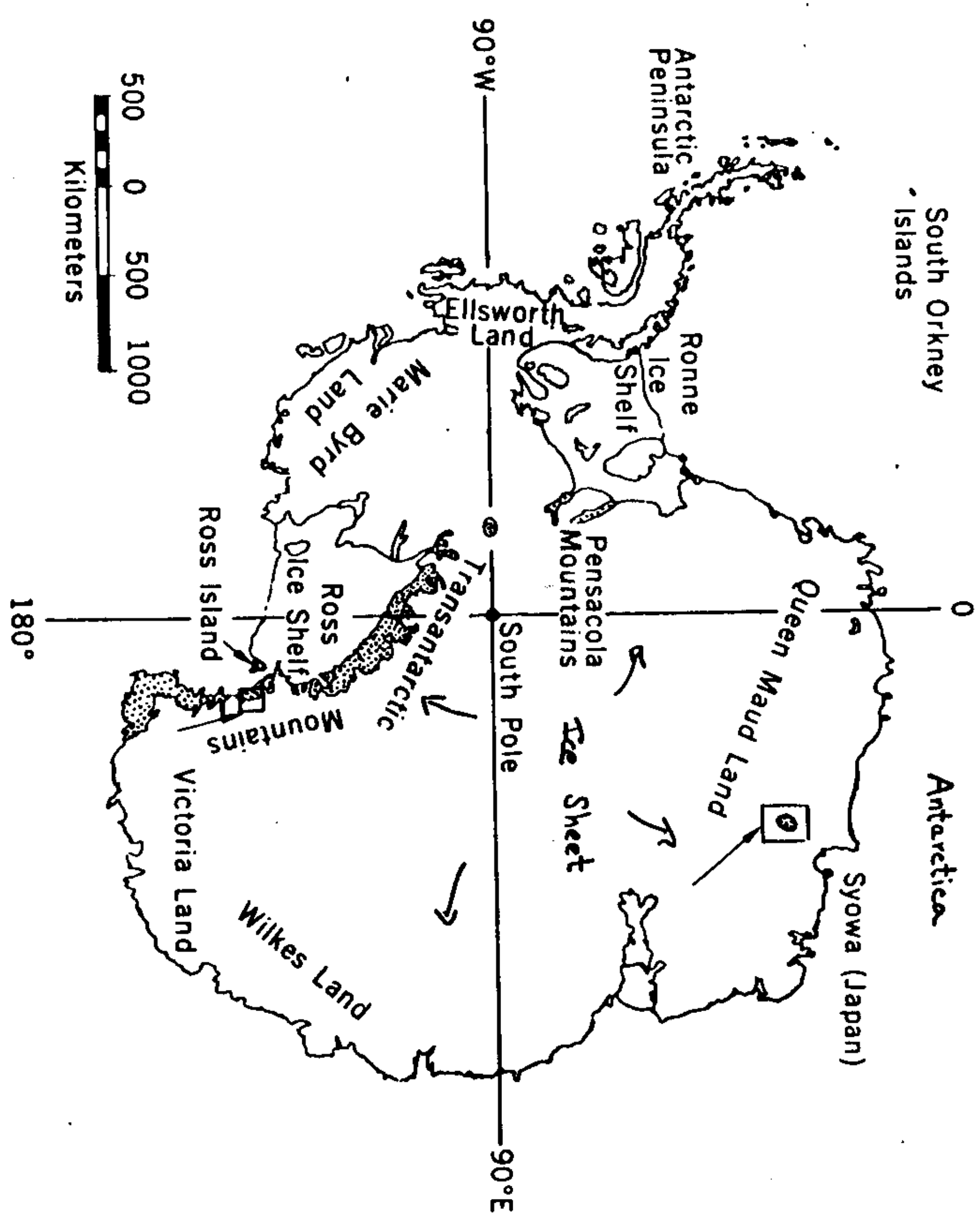
$$1000\ Mg = 5\ eV/\mathring{A}$$

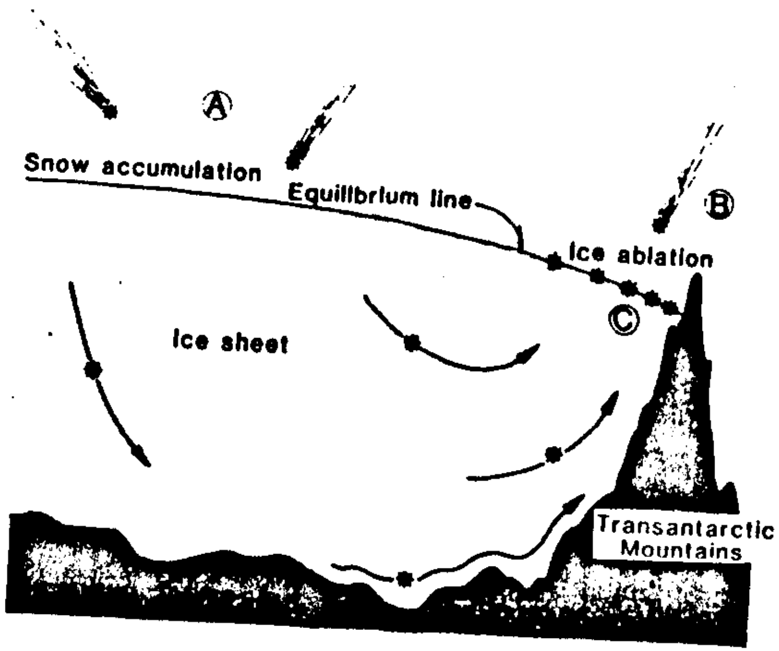
$$M < 5 \times 10^{14}\ GeV/c^2 \quad \text{(worst case)}$$

- Lower impact decelerations (say 200g) could contain higher mass monopoles, eg. $M_m \sim 10^{16}$
- Lower mass monopoles are more easily contained

⟹ Select meteorites which landed in deep snow.

Antarctic Meteorites




A
Snow accumulation
Equilibrium line
B
Ice ablation
C
Ice sheet
Transantarctic
Mountains

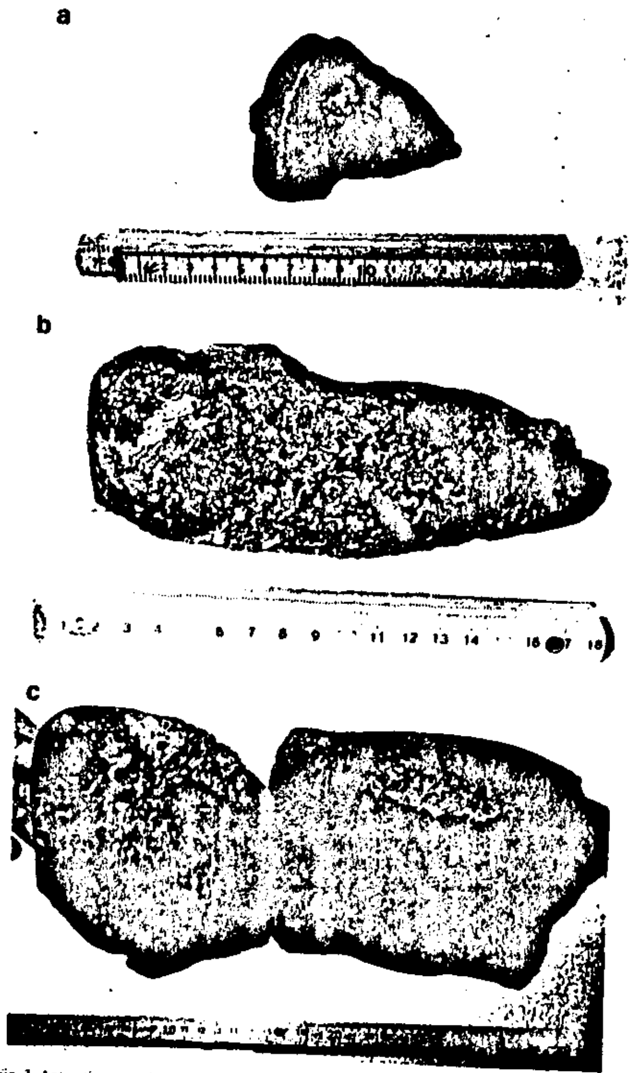
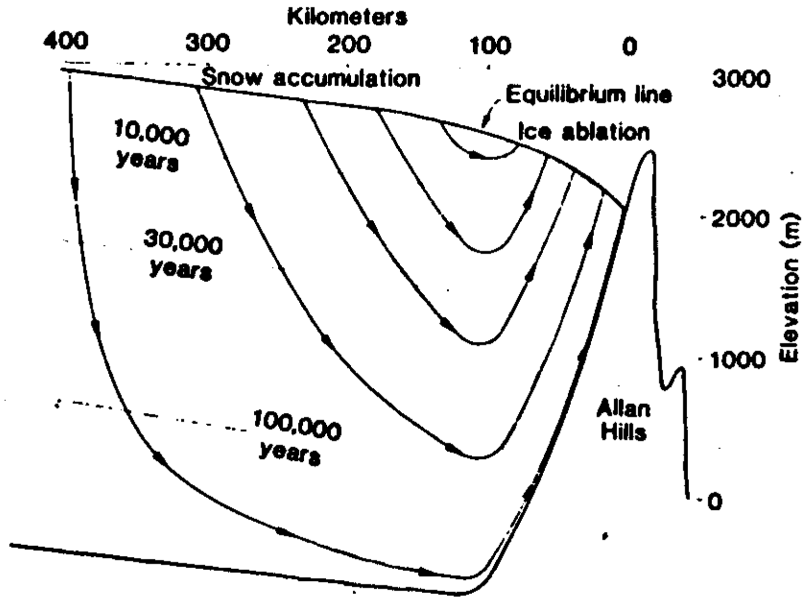


Fig. 3. Antarctic meteorites: (a) iron (Allan Hills No. 2), (b) achondrite (Allan Hills No. 5), and (c) chondrite (Allan Hills No. 3), which was found in three pieces at about 10-m intervals along a straight line. The scales are in centimeters.



Availability of Antarctic Meteorites:

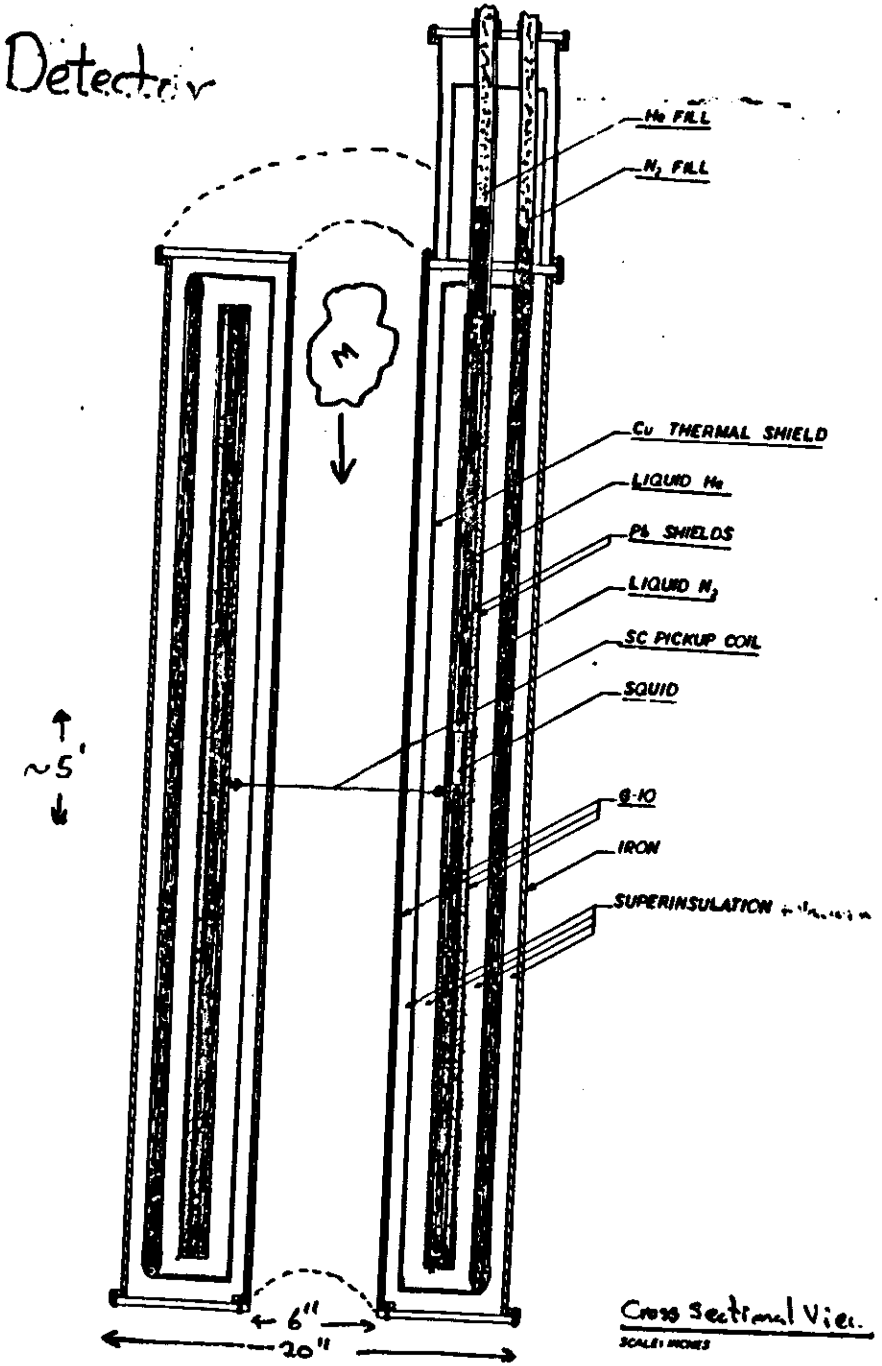
> 6000 have been collected by American & Japanese expeditions.

Collections Kept at:

- NASA's Lunar Science Institute, Houston
- National Institute for Polar Research, Tokyo

Samples are readily available if measurements are non-destructive.

Detector



Cross Sectional View

SCALE: INCHES

Monopole Detection by Ionization / Excitation Techniques

- Scintillators
- Gaseous Detectors
- Track etch

Summary of Results from Ionization/Excitation Experiments

LABORATORY	LOCATION	DETECTOR	AΩ (M^2 SR)	dE/dx (MINIMUM)	β-RANGE	FLUX UPPER LIMIT (CM^{-2} S^{-1} SR^{-1}) Oct.'83	May'84
1. BNL	BUILDING	PROPORTIONAL	1.9	2.0	3×10^{-4} - 1.2×10^{-3}	3.4×10^{-11}	✓
2. BOLOGNA	BUILDING	SCINTILLATORS	10-36	10-25	10^{-3} - 0.6	3.4×10^{-13}	✓
3. TOKYO	BUILDING	SCINTILLATORS	1.1	1.2	10^{-3} - 10^{-1}	1.5×10^{-11}	✓
	BUILDING	SCINTILLATORS	1.4	0.025	2×10^{-4} - 5×10^{-3}	1.5×10^{-11}	✓
	KAMIOKA MINE	SCINTILLATORS	22.0	0.2	6×10^{-4} - 1	1.5×10^{-12}	++
4. UTAH-STANFORD	MAYFLOWER MINE	SCINTILLATORS	2.7	0.12	1.4×10^{-4} - 3×10^{-2}	8.1×10^{-12}	✓
5. MINNESOTA-ARGONNE	SOUDAN MINE	PROPORTIONAL	71.6	0.5	4×10^{-4} - 3×10^{-2}	4.1×10^{-13}	✓
6. USSR	BAKSAN MINE	SCINTILLATORS	1800.0	0.25	4×10^{-7} (4) - 5×10^{-2}	1.5×10^{-14}	8×10^{-15}
7. INDIA-JAPAN	KOLAR MINE	PROPORTIONAL	318.0	2.5	2×10^{-3} - 0.9	3.5×10^{-14}	—
8. MONT BLANC	TUNNEL	STREAMER TUBES	12.0	0.02	3×10^{-4} - 0.5	1.9×10^{-12}	6.4×10^{-13}
9. BNL-BROWN-KEK	NEUTRINO BEAM	DRIFT + SCINT.	14.5	0.3	10^{-3} - 0.2	5.2×10^{-12}	✓
10. TOKYO	BUILDING	SCINT. + GAS	24.7	-	> 2×10^{-4}	1.6×10^{-12}	✓
11. BERKELEY-INDIANA	BUILDING	SCINTILLATOR	17.5	1.2	6×10^{-4} - 2.1×10^{-3}	4.1×10^{-13}	✓
12. BERKELEY	SURFACE	CR39	150.0	S/β>30	0.02 - 1	1.5×10^{-13}	✓
13. KITAMI	BUILDING	NITROCELLULOSE	1000.0	S/β>60	0.04 - 1	5.2×10^{-15}	✓
14. Berkeley	(Track Etch)	MICA				3×10^{-17}	
15. Texas A&M	mine	Scintillator	300 $m^2 sr$		4×10^{-4} – 10^{-1}		
16. Homestake	mine	Scintillator	1300 $m^2 sr$		$>6\times10^{-4}$		
17. Fréjus	Tunnel	Geiger Tubes	1000 $m^2 sr$		$10^{-4}<\beta<10^{-1}$		

Acceptance

Comparison

Experiment	Counters	Acceptance	Tracking	Expandable
Homestake	192 ($2.4\ m^2$)	$\sim 1300\ m^2\ sr$	No	No
Baksan	3200 ($0.5\ m^2$)	$\sim 1800\ m^2\ sr$	No	No
MACRO	572 ($6\ m^2$)	$\sim 12300\ m^2\ sr$	Yes	Yes

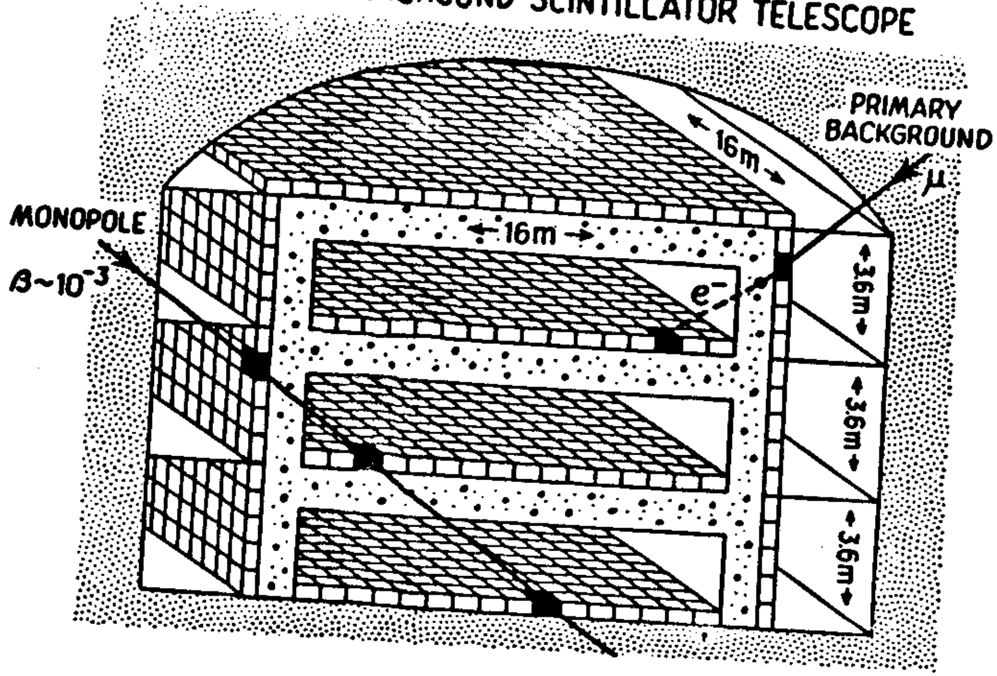
Sensitivity:

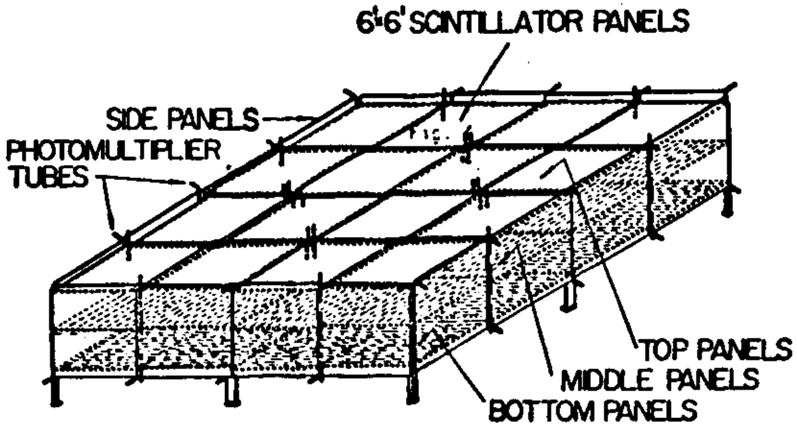
MACRO = 4 ev/y at Parker Limit

90% CL Sensitivity

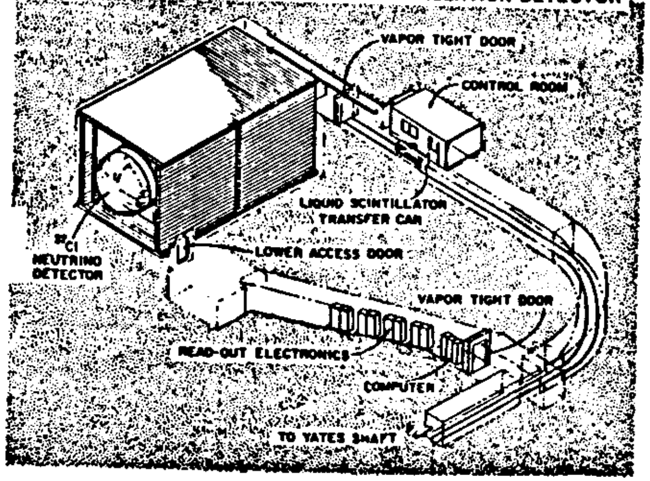
5y = 0.1 x Parker Limit

BAKSAN UNDERGROUND SCINTILLATOR TELESCOPE

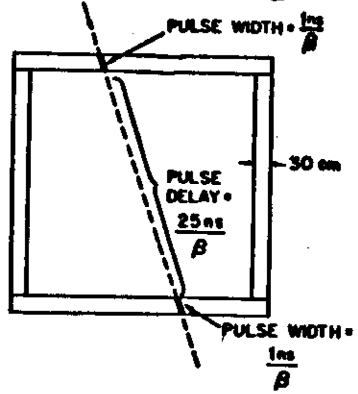




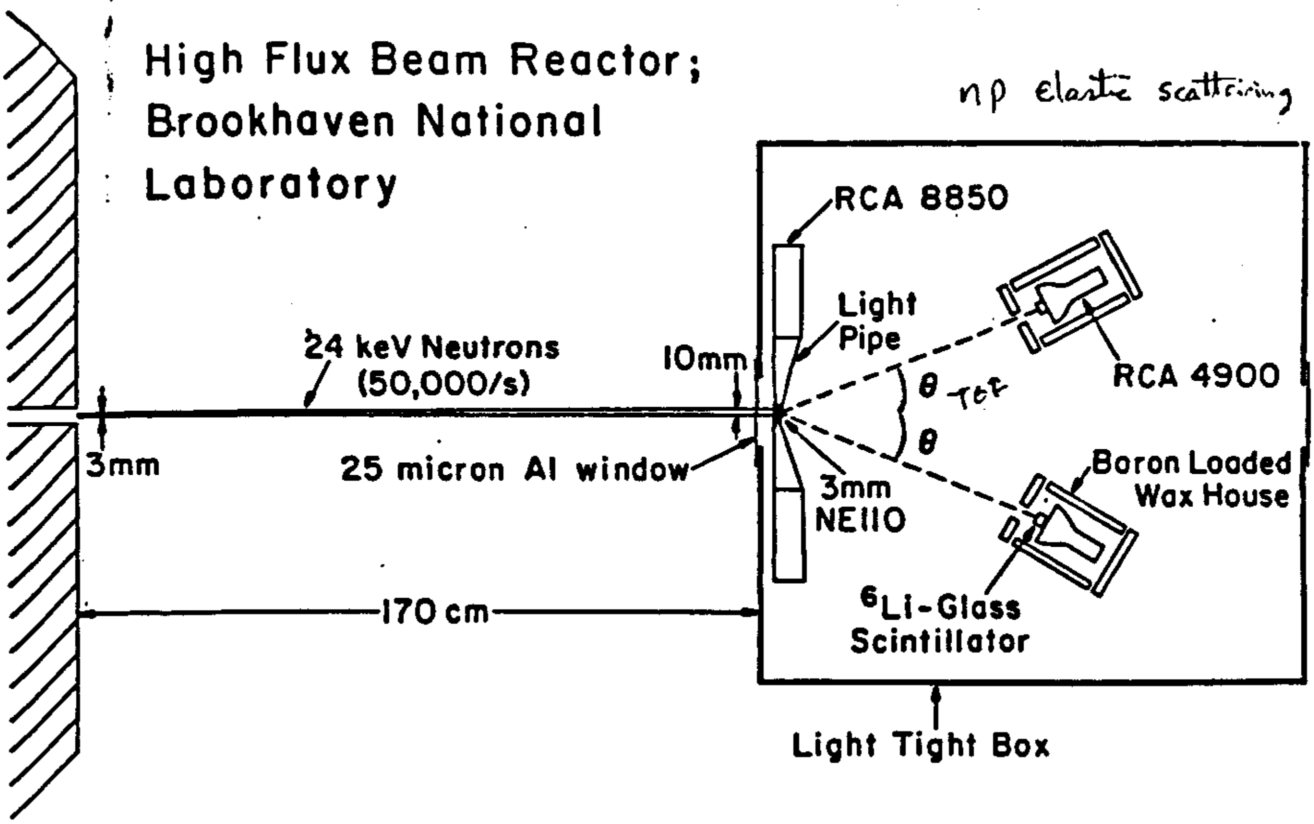
HOMESTAKE LARGE AREA LIQUID SCINTILLATION DETECTOR

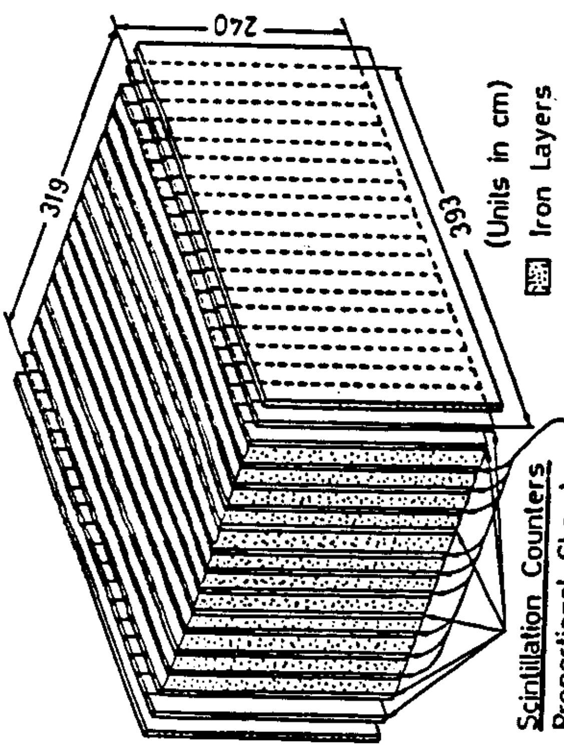


MONOPOLE PULSE TIMING IN THE HOMESTAKE DETECTOR



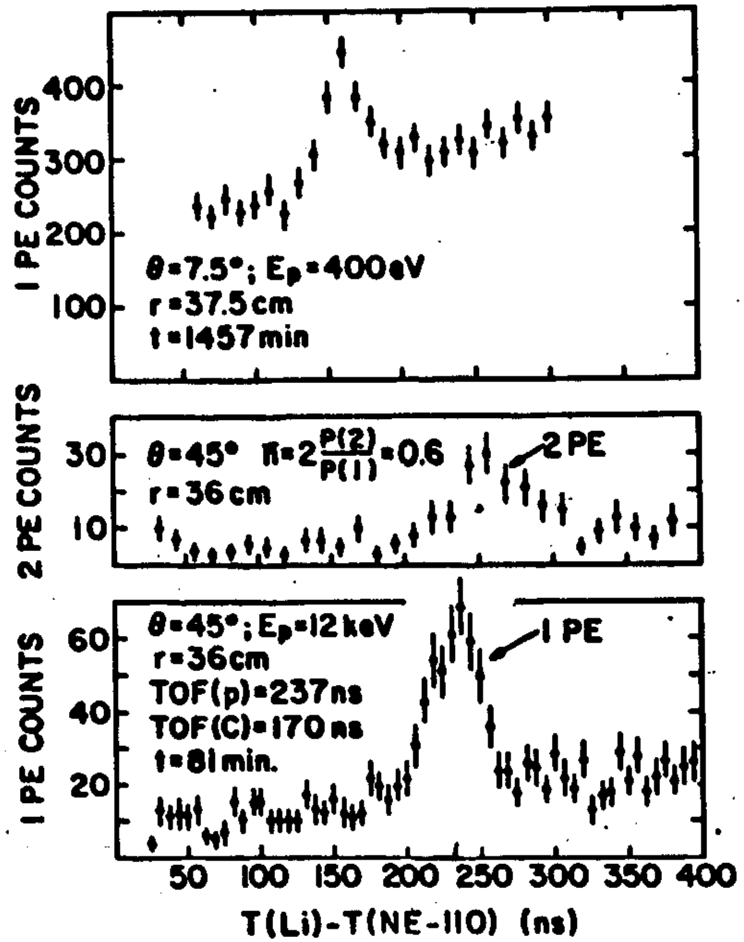
Do low velocity particles produce detectable scintillation light in scintillators?



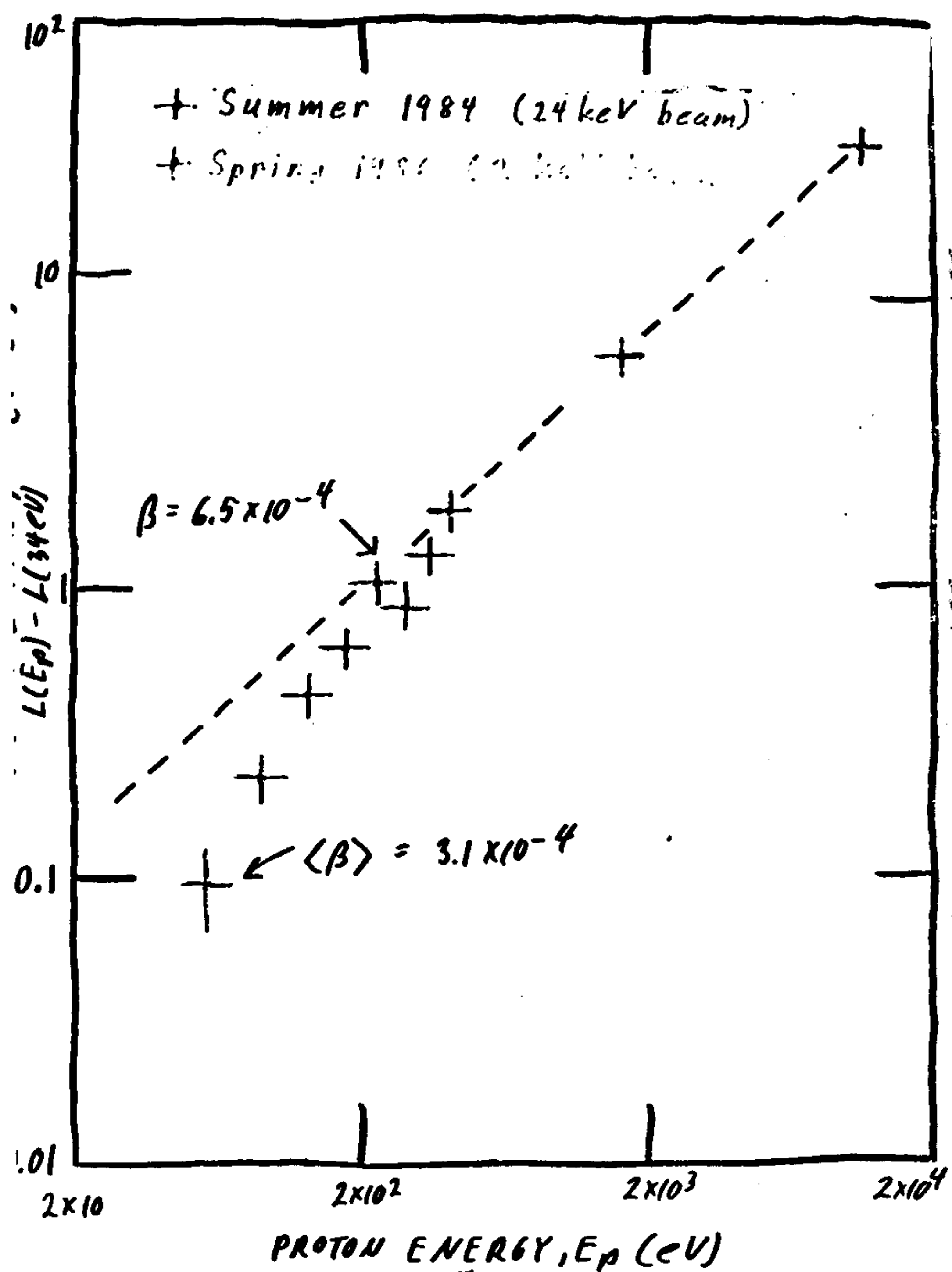


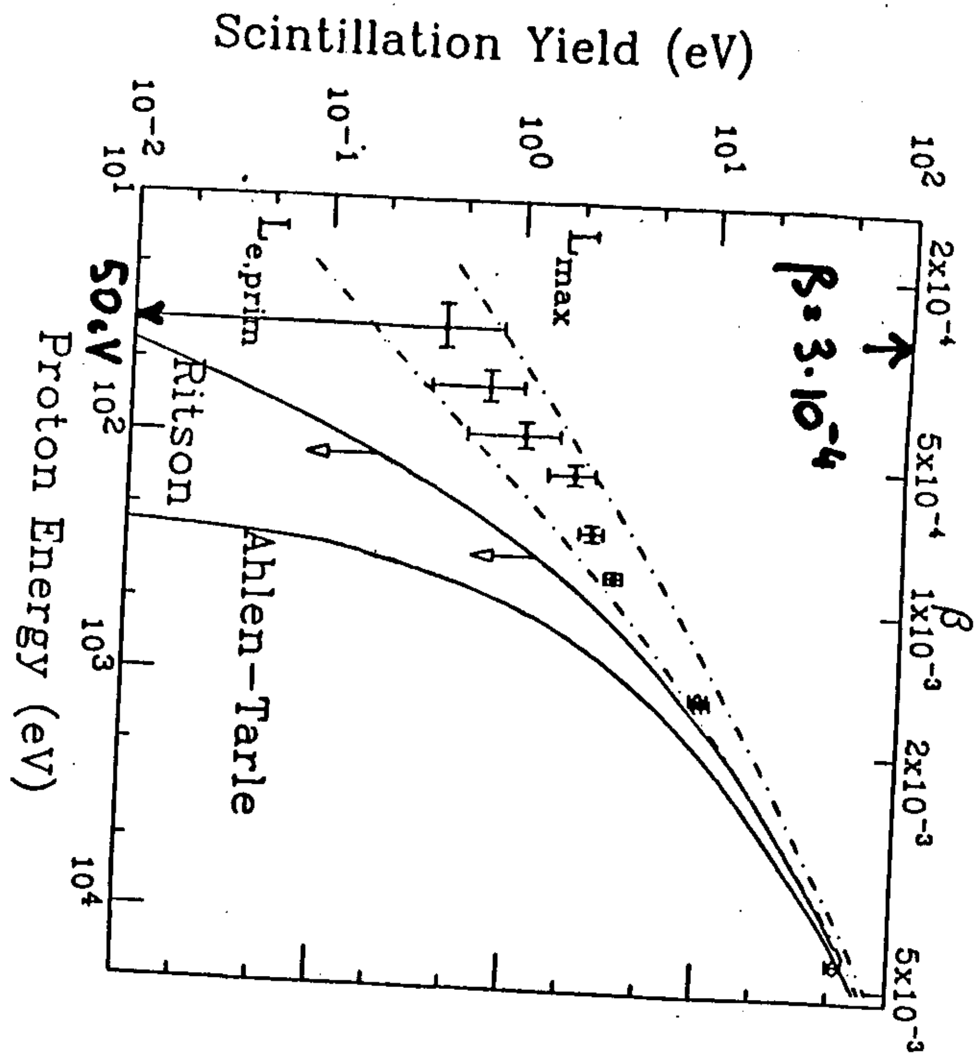
TOKYO

$\text{te} + CH_4$
(Drell)

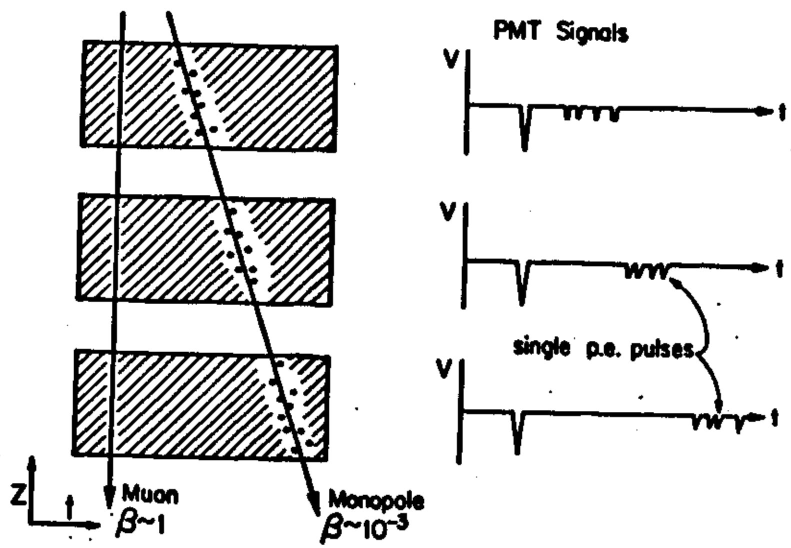


Clear Kinematic peaks from TOF of neutron give recoil proton energy





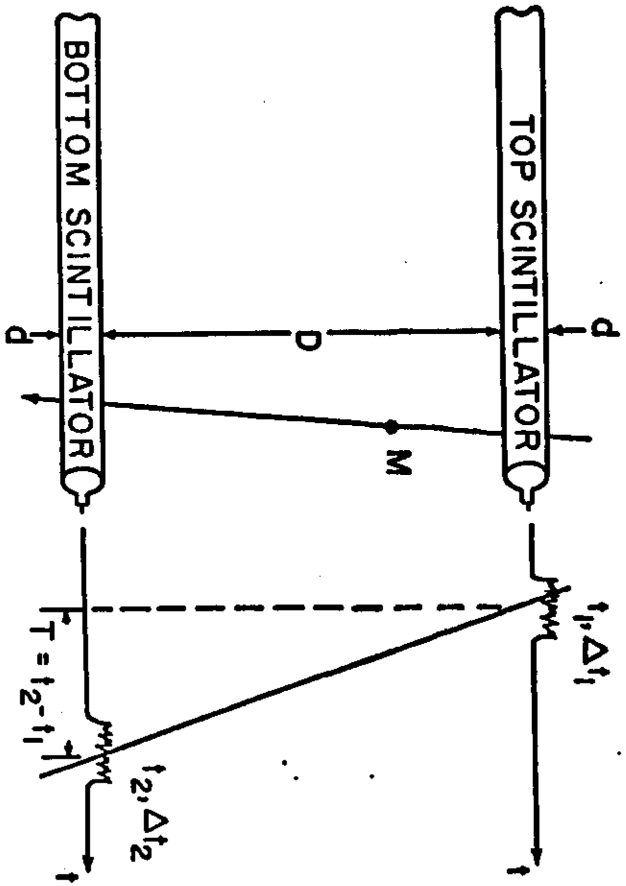
Comparison of Monopole and Muon Signals
in layers of Liquid Scintillator Tanks



⇒ Independent triggers and electronics for fast and slow particles

Fig. 6

Redundancy of Slow Particle Detection by the Scintillators

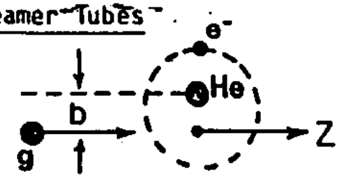


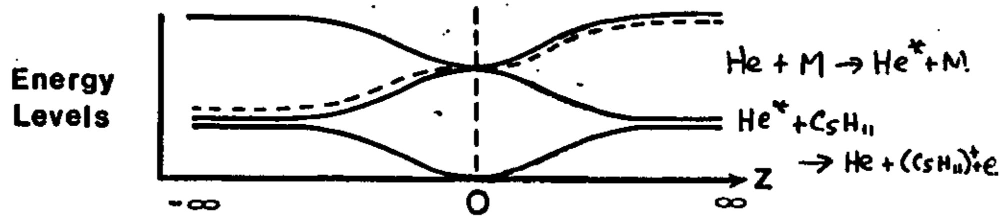
$\Delta t_1 : T : \Delta t_2 = d : D : d$

Monopole Detection With the Streamer Tubes

Gas: He + n-pentane [redacted] + CO_2
57% 15% 28%

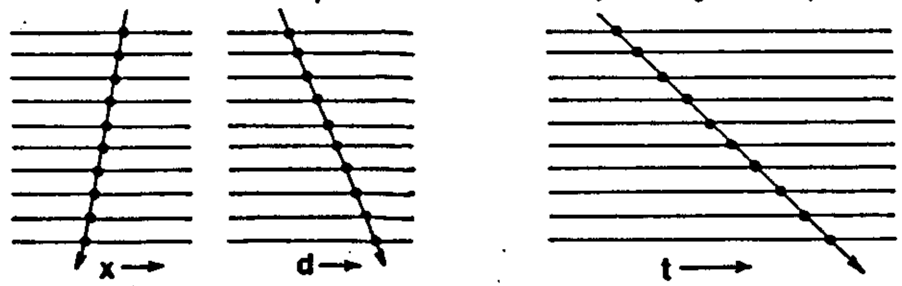
Drell et al. (1983) mechanism





Monopole induced level mixing modifies kinematic constraints on energy loss

Implementation: ***bare*** monopoles ⟹ He excitation
n-pentane ionization (Penning effect)



Track in Both Stereo Views | Lineraly Delayed Hits

- Background: radioactive accidentals
- Trigger concept ~ Mont Blanc Experiment

Spatial Accuracy ~ 1cm
Angular Accuracy ~ 0.2°

β - Threshold

Drell - Penning: $\beta_{min} \simeq 10^{-4}$
Direct Ionization C_5H_{11}
$\beta_{min} \lesssim 10^{-3}$

MACRO at GRAN SASSO

a Large Area Detector at

the Gran Sasso Laboratory

- dedicated to the study of the Natural *Penetrating* Radiation

Monopoles ⇒ most sensitive search to date, 12000 $m^2 sr$ redundancy
↳ any massive, low velocity, penetrating particle

Astrophysics: V.H.E. γ and ν astronomy ⇒ supernovae, point sources, ν - oscillations, WIMPS

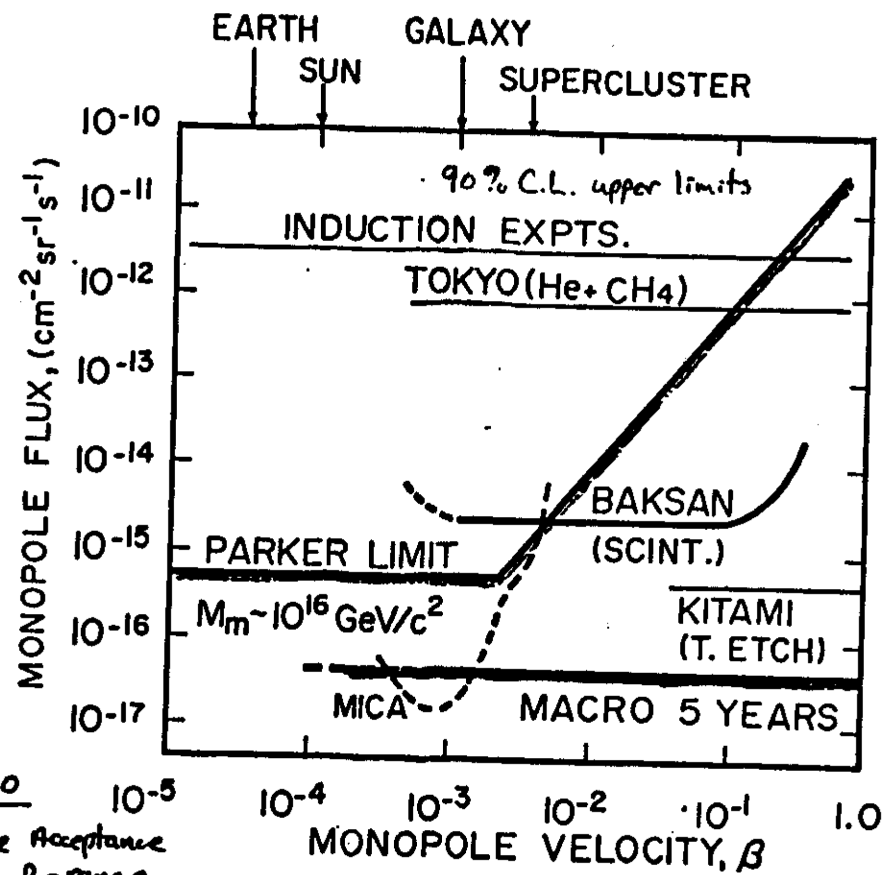
Cosmic

Radiation

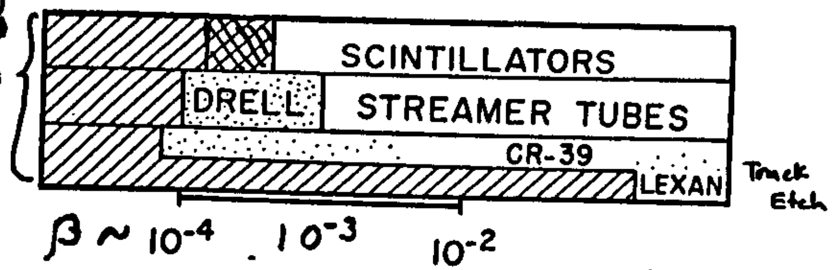
Observatory

- μ's, multi μ's ⇒ chemical composition of cosmic rays
- time variations, anisotropies
- exotica

⇒ 150 m^2, 1st sm, largest underground w/ tracking

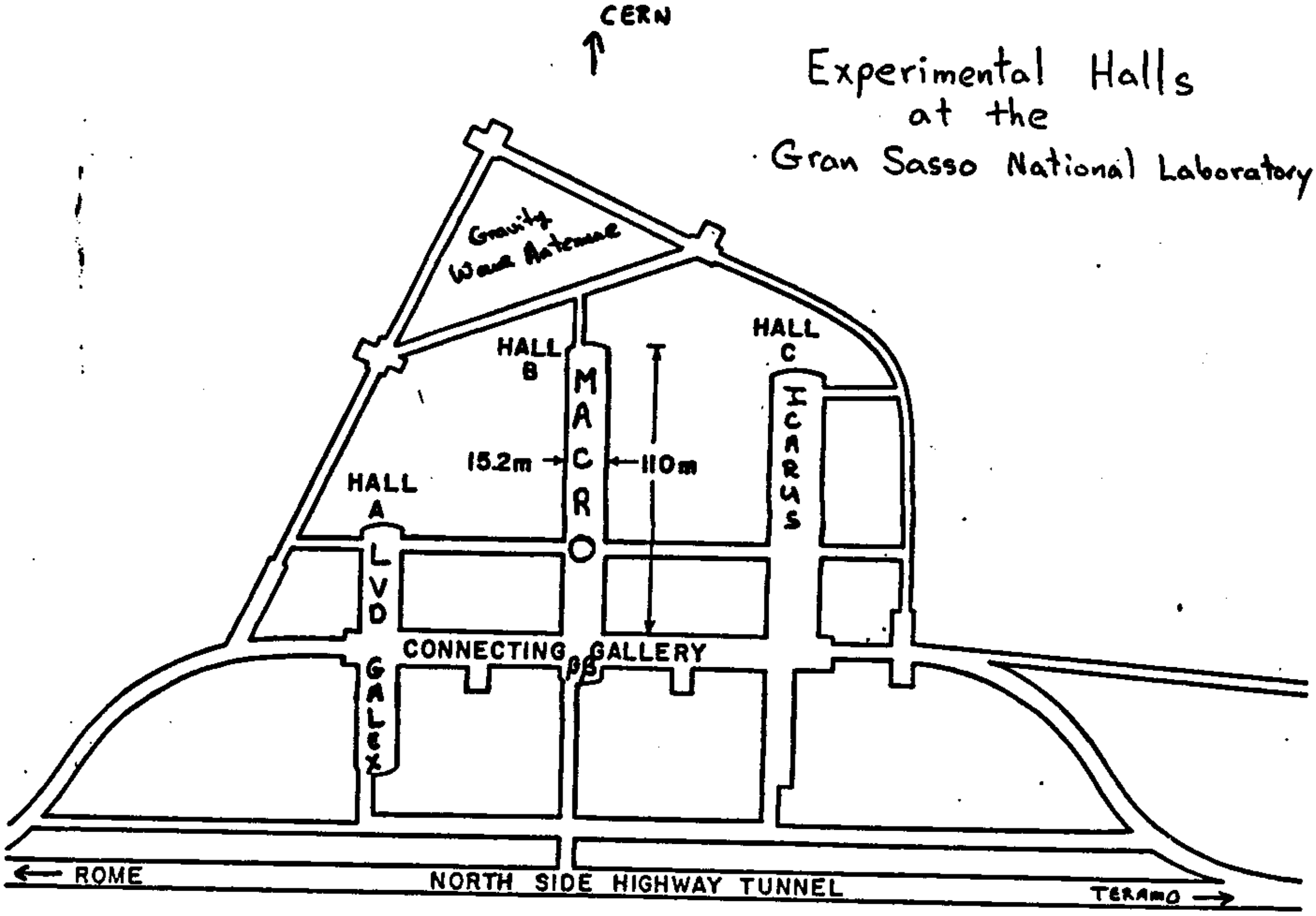


MACRO
Large Acceptance
Large β-range
3 Independent Techniques



For Grand Unified Monopoles $M_m \sim 10^{16}$ GeV/c^2

Experimental Halls at the Gran Sasso National Laboratory



Gran Sasso Rock Profile

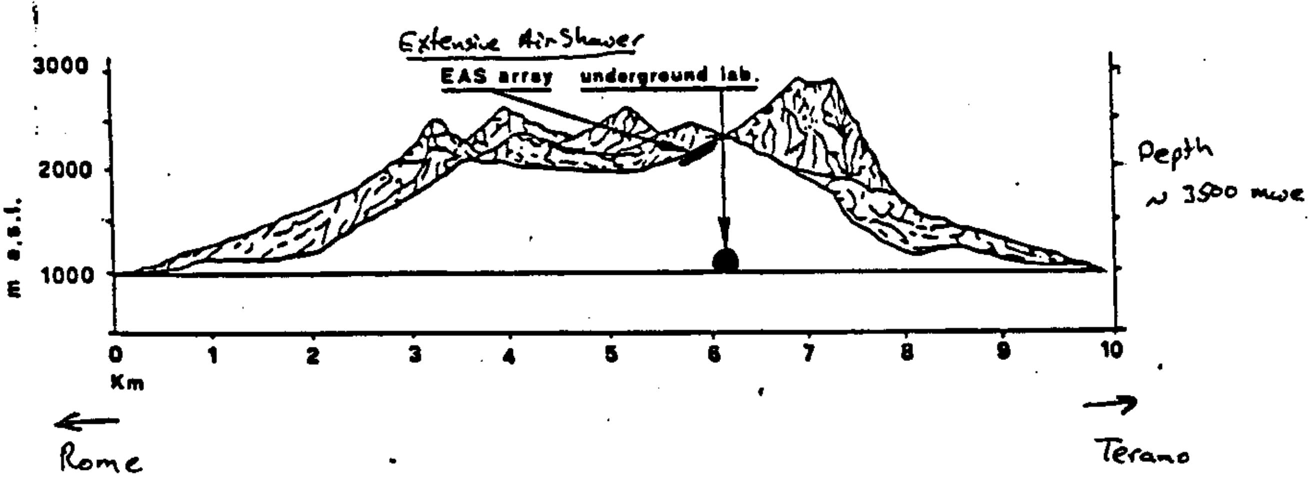
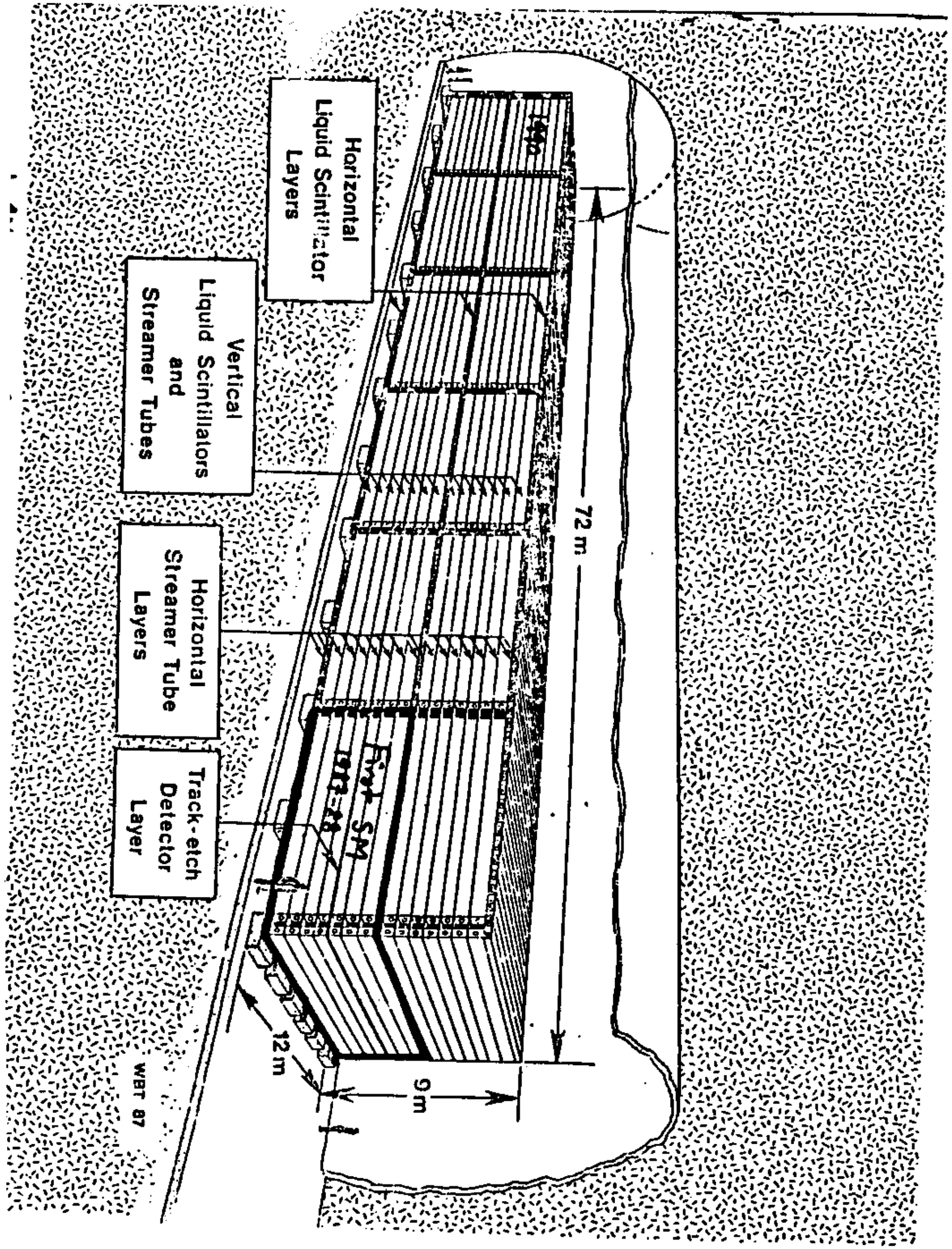
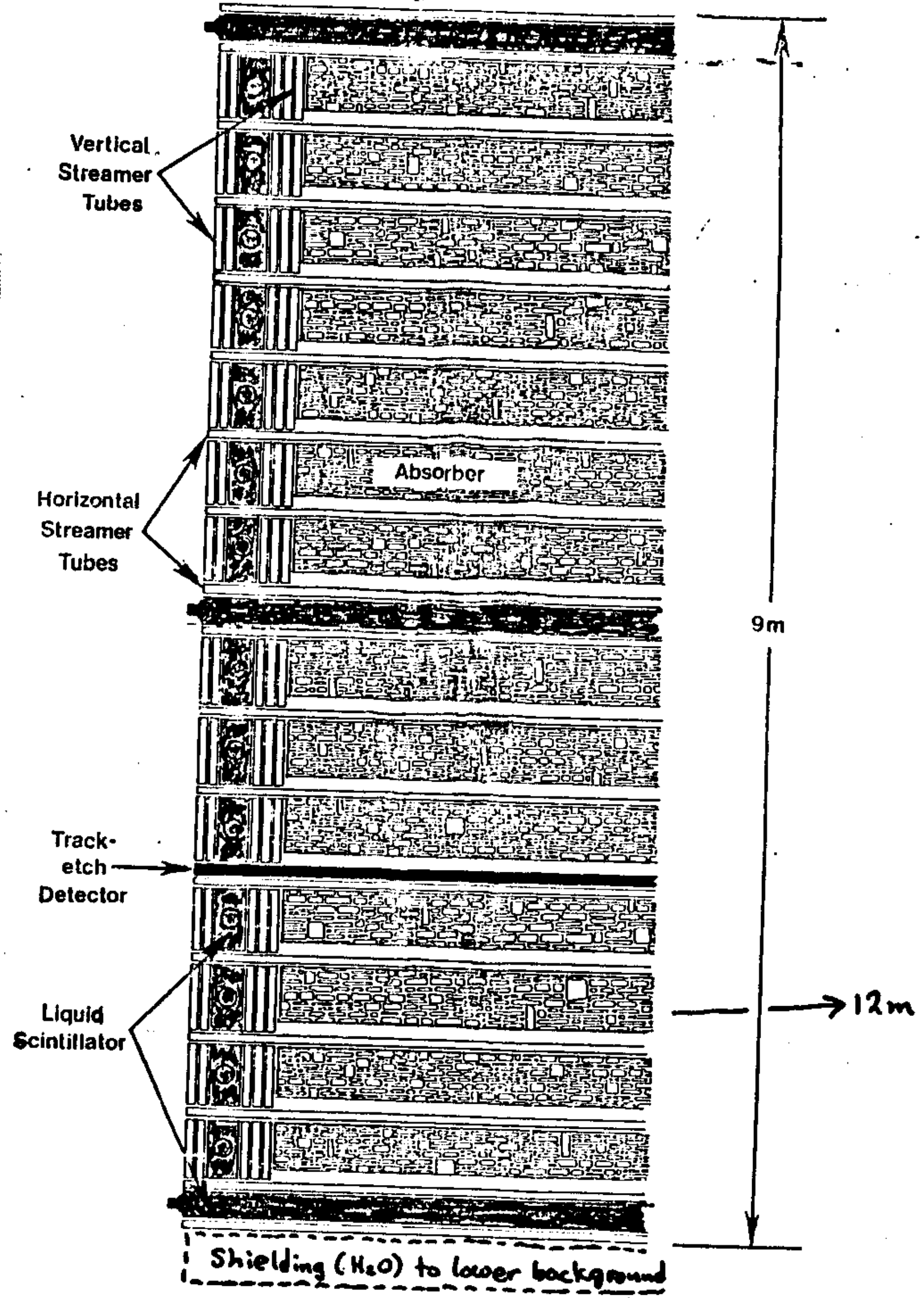


Fig 3



MACRO... Penetrating Particle Identifier



Scintillation Counter Optics

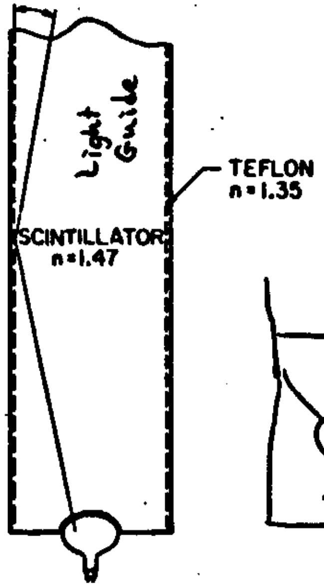
Dimensions:

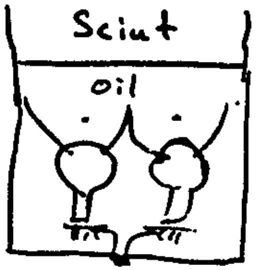
75cm X 12m X 25cm

Viewed by 2 X PMTs (8"φ) at each end

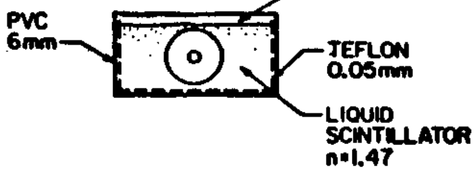
TOP VIEW Uses total internal reflecti-

23.3° = critical angle.

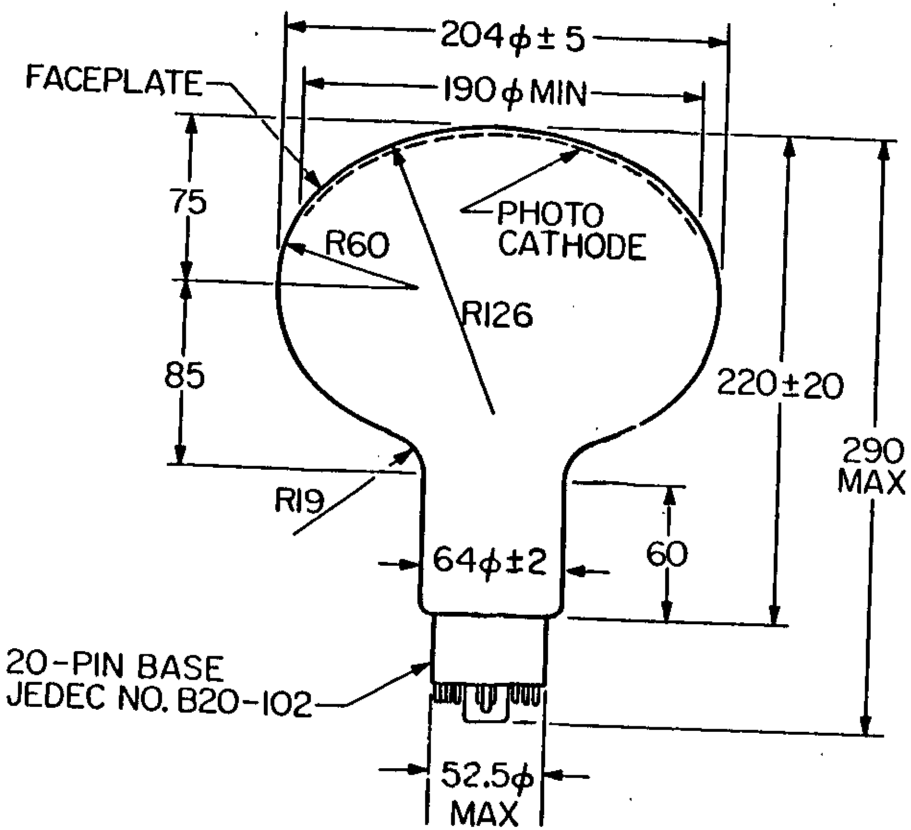


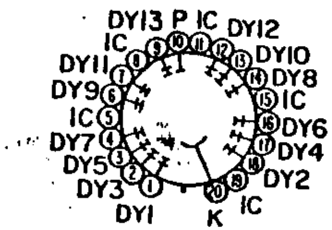


END VIEW



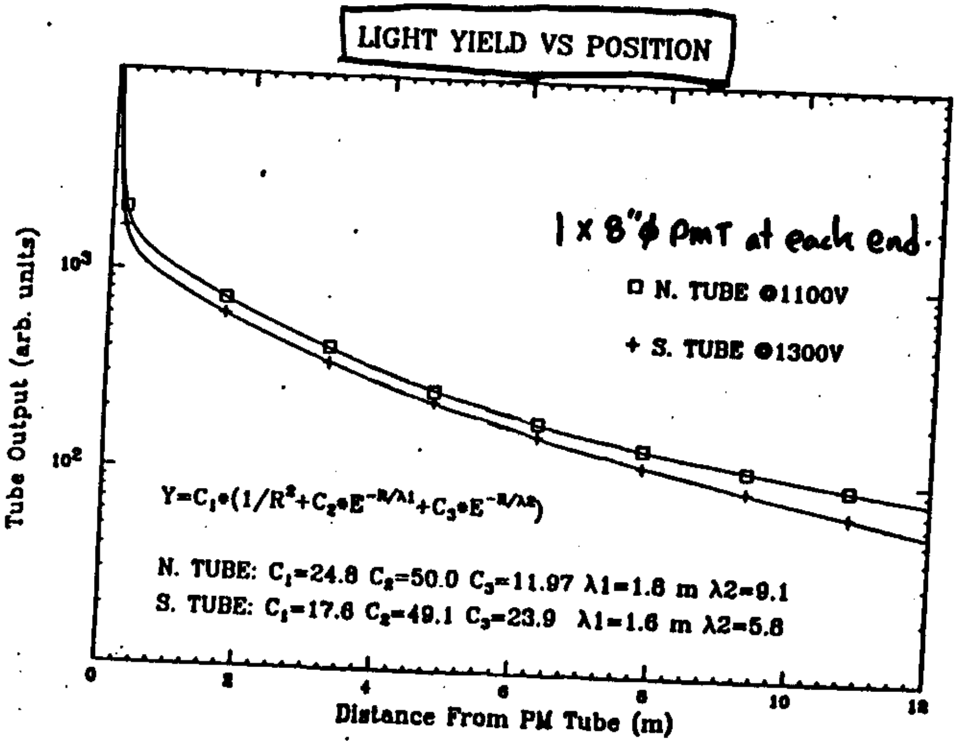
Hamamatsu R1408 8" diameter PMT





(B)5

12 m long Scintillator Boxes



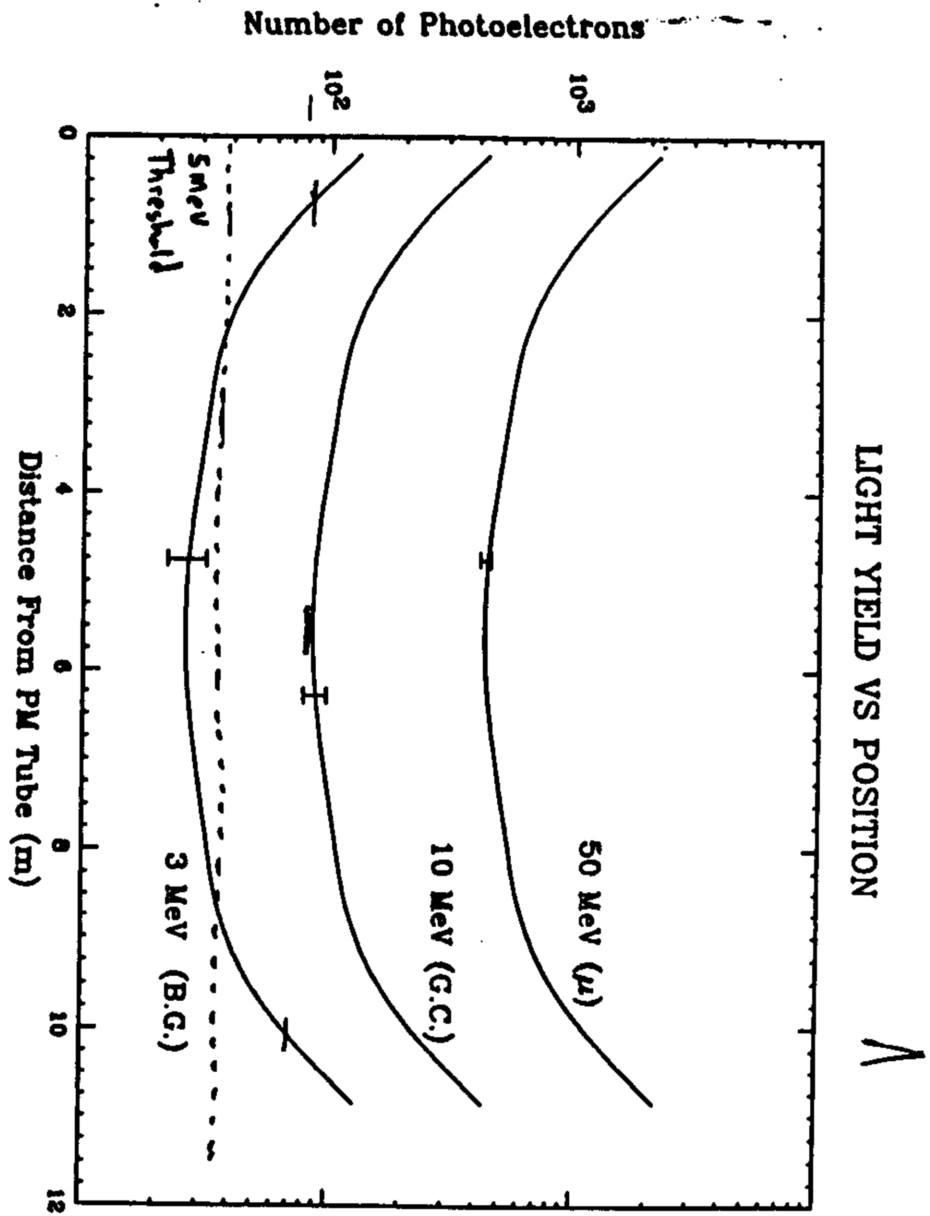
Solid angle near PMT

Attenuation of Liq. Scintillator (λ~8m)

Total Internal Reflection ≤ 23.3°

Collection efficiency of PMT

∴ Problem of triggering on low energy events.



... How

MACRO DETECTOR

GENERAL (COMPLETE DETECTOR)

ACCEPTANCE: 11000 m^2sr
DIMENSIONS: 72 m X 12 m X 9 m HIGH
DEPTH: 3600 mwe
PRINCIPLE ELEMENTS: STREAMER TUBES
LIQUID SCINTILLATOR TANKS
TRACK-ETCH DETECTORS

STREAMER TUBES

- 18 HORIZONTAL LAYERS INTERSPERSED WITH 0.35 m ABSORBER OF LOW ACTIVITY ROCK, 5 LAYERS ON SIDES
- CELL SIZE: 3 cm X 3 cm X 12 m
- GAS MIXTURE: He+CO_2+n-pentane
- SPATIAL RESOLUTION: 1 cm
- ANGULAR RESOLUTION: 0.2°
- TIME RESOLUTION: 150 ns

LIQUID SCINTILLATOR COUNTERS

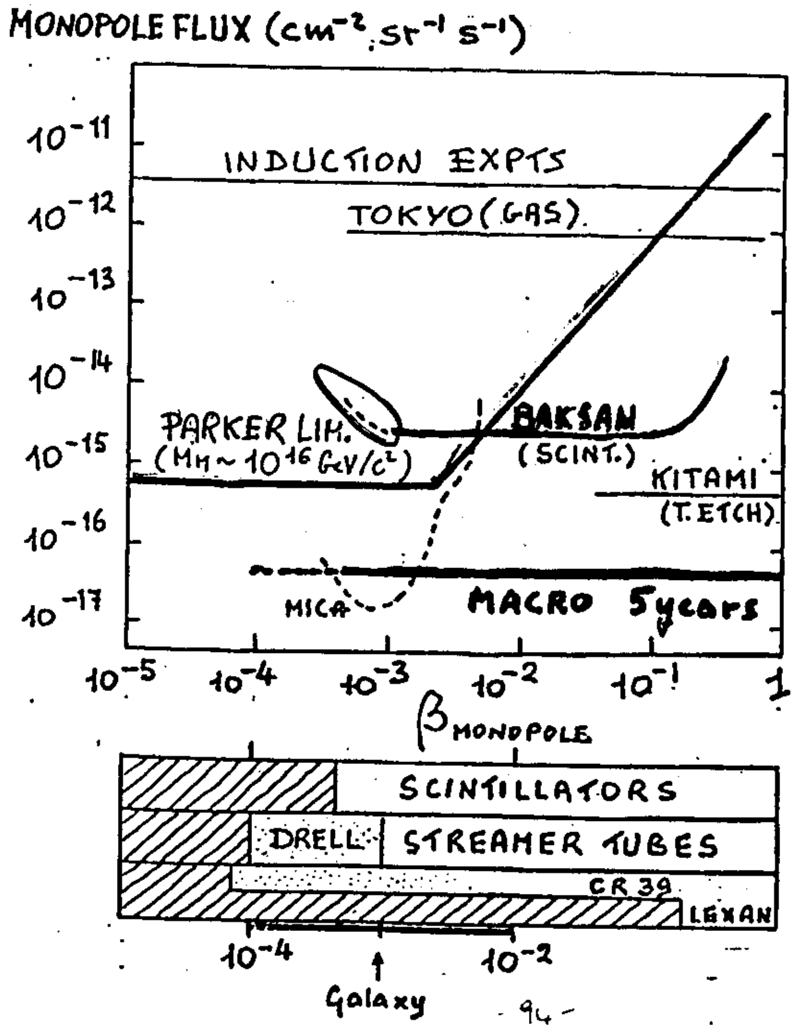
- 3 HORIZONTAL LAYERS WITH 4.5 m SEPARATION
- SIDES CLOSED WITH ONE LAYER
- DIMENSIONS: 75 cm X 50 cm X 12 m (horizontal tanks)
  25 cm X 50 cm X 12 m (side tanks)
- TECHNIQUE: TANKS LINED WITH CLEAR TEFLON SO LIGHT IS COLLECTED BY TOTAL INTERNAL REFLECTION
- ACTIVE MASS: 1000 TONNES OF LIQUID SCINTILLATOR
- INSTRUMENTATION: ADC's, TDC's, WAVEFORM DIGITIZERS
- TIME RESOLUTION: 1 ns

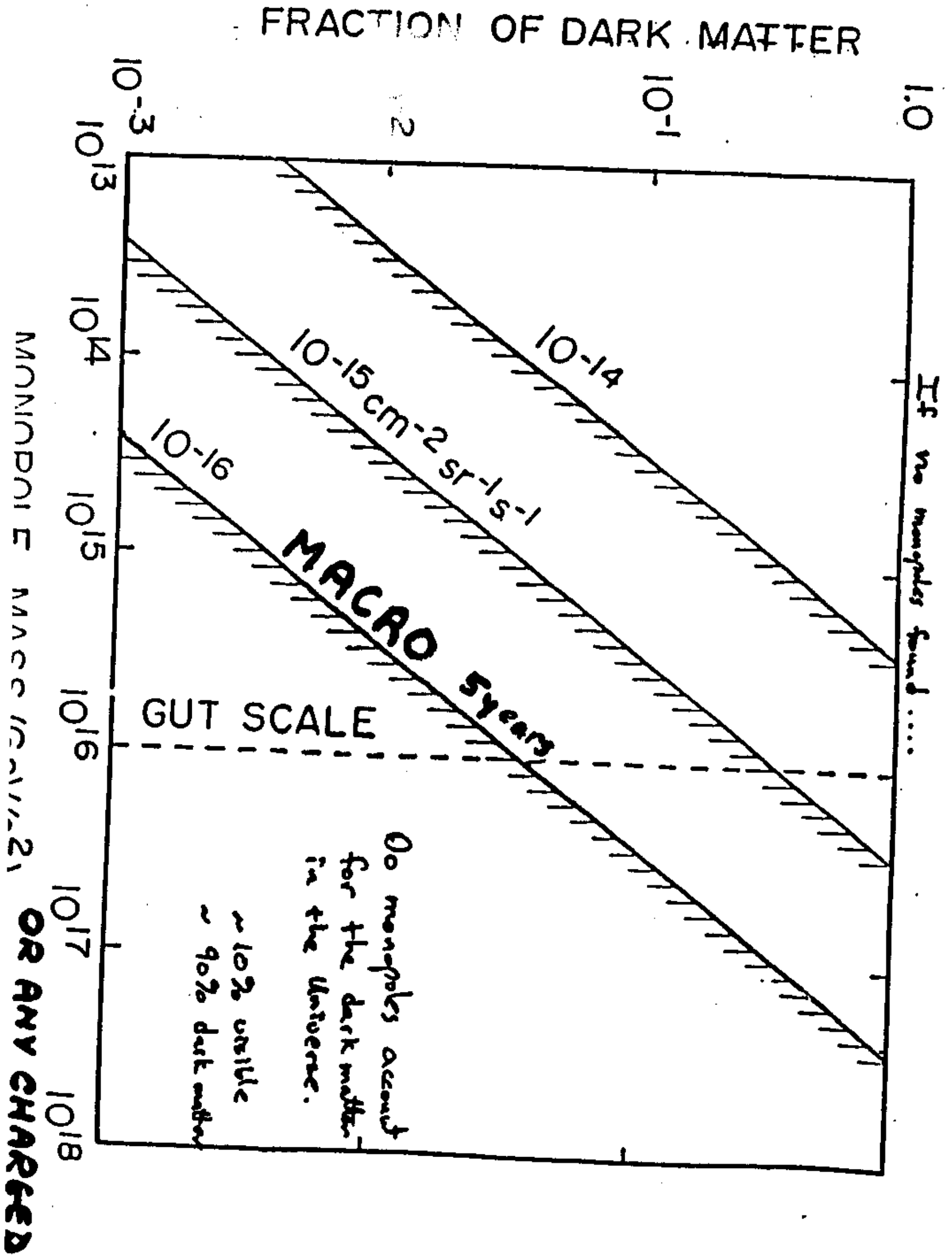
TRACK-ETCH DETECTORS

- 3 LAYERS OF CR-39 AND 4 LAYERS OF LEXAN

- by excitation-ionization methods
- beyond the astrophysical bounds (12 000 m^2sr)
- by redundant and complementary technique

How does MACRO compare with other experiments?
...a question of area & β sensitivity





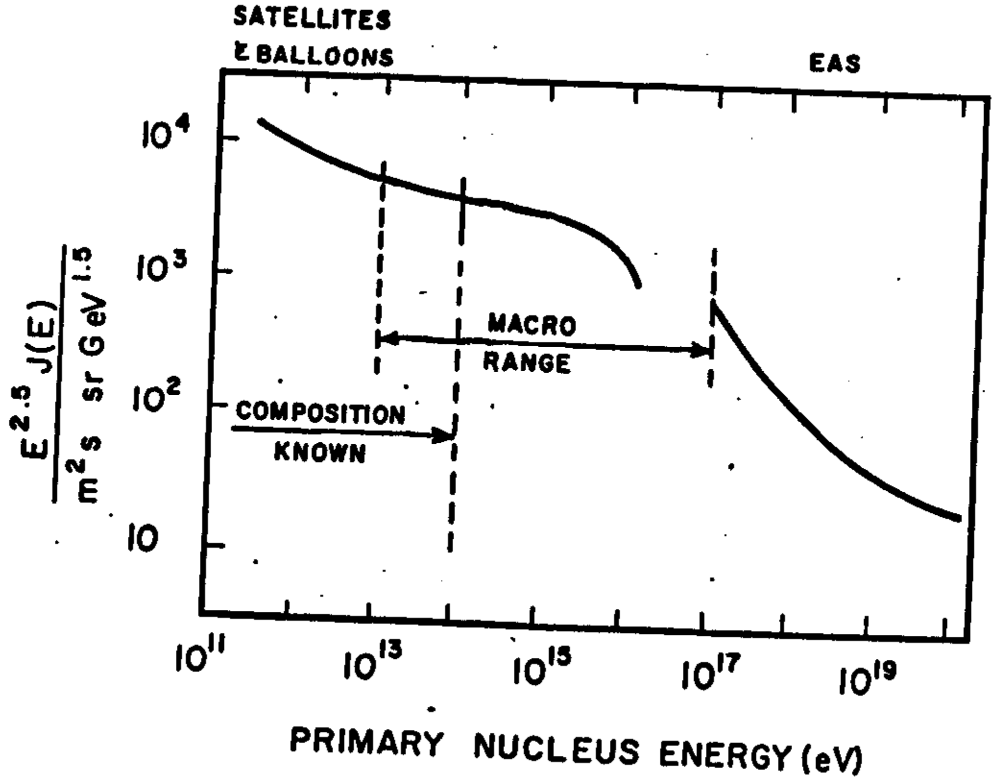
<u>Cosmic Ray Muons at Gran Sasso</u> (Min. Depth ~ 3600 MWE)

MACRO single-μ's ≈ 10^7/year

multi-μ's ≈ 3×10^5/year

$f(N_\mu)$ <u>vs.</u> depth (θ,ϕ) ⟹ Primary E spectrum

⟹ Chemistry of primaries
(Test models)
(ORIGIN of Cosmic Rays)



Detection of (γ's) muons from Cyg X3

- Surface detector measurements (KIEL,...) Extensive Air Shower Array

  $\phi_\gamma(>10\ \mathrm{TeV}) \approx 3 \times 10^{-11} cm^{-2} s^{-1}$

  $\phi_\gamma(E) \propto E^{-2}$ D.F. ~ 1%

- MACRO Background (within ± 0.5°) ~ 10 ev/year

  γ - air interactions (Monte Carlo)

  1 { Vector dominance model
  $\sigma_{\gamma N} \propto \sigma_{pN}$ above 200 GeV
  Signal ~ 20 ev/year

  2 { High μ content (KIEL)
  Signal ~ 300 ev/year for MACRO

- Mont Blanc and Soudan μ signals

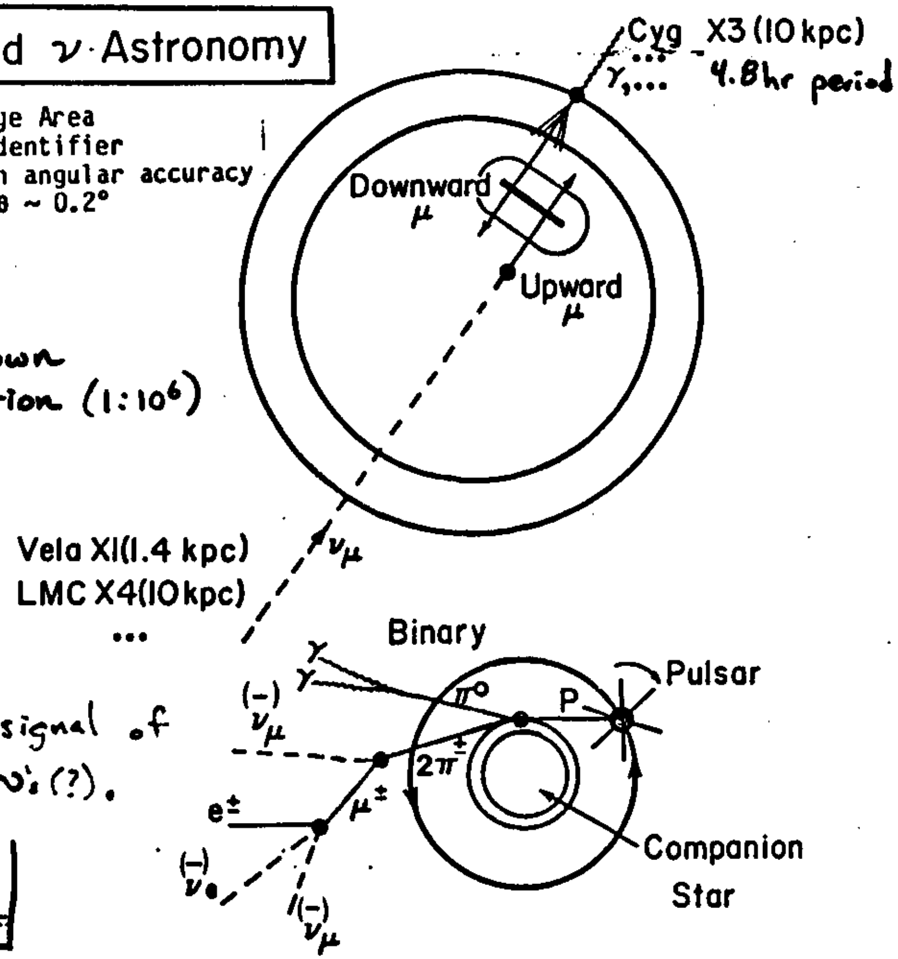
  ⟹ ~ 10,000 ev/year in MACRO

Mont Blanc ~ 15 m^2 5000 MWE ⟹ ~ 10 ev/year

MACRO x100 x10 ⟹ ~ 10,000 ev/year
(4260 MWE)

γ-and ν·Astronomy

- Large Area
- μ-identifier
- high angular accuracy
  Δθ ~ 0.2°

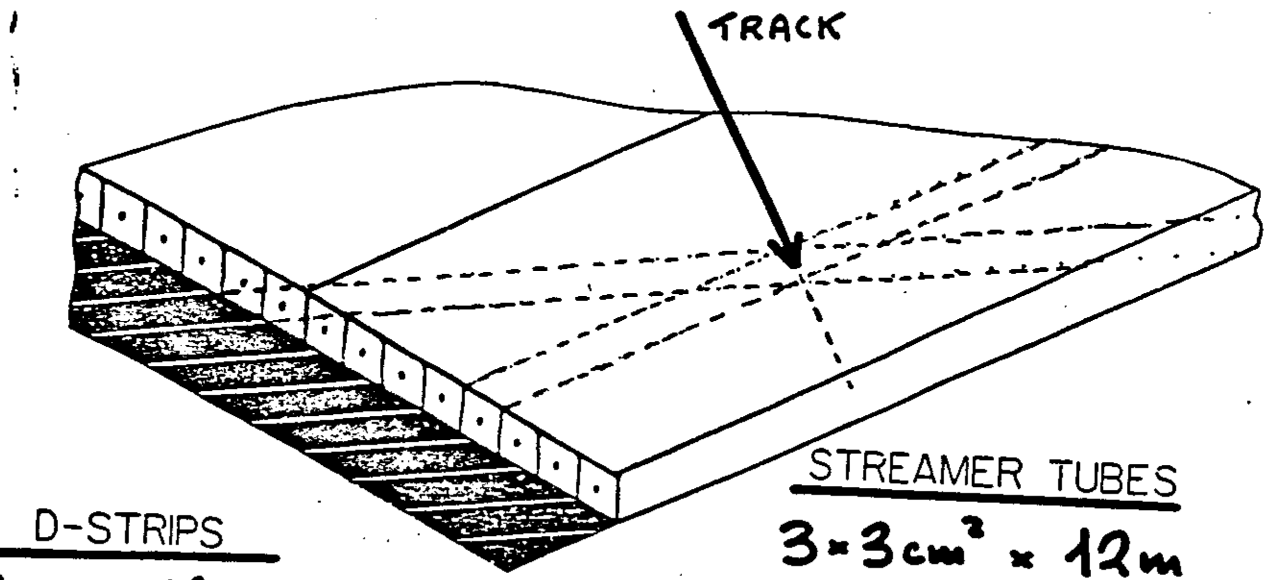


› vs. Down
μ detection (1:10⁶)

Periodic signal of
γ's and ν's (?).

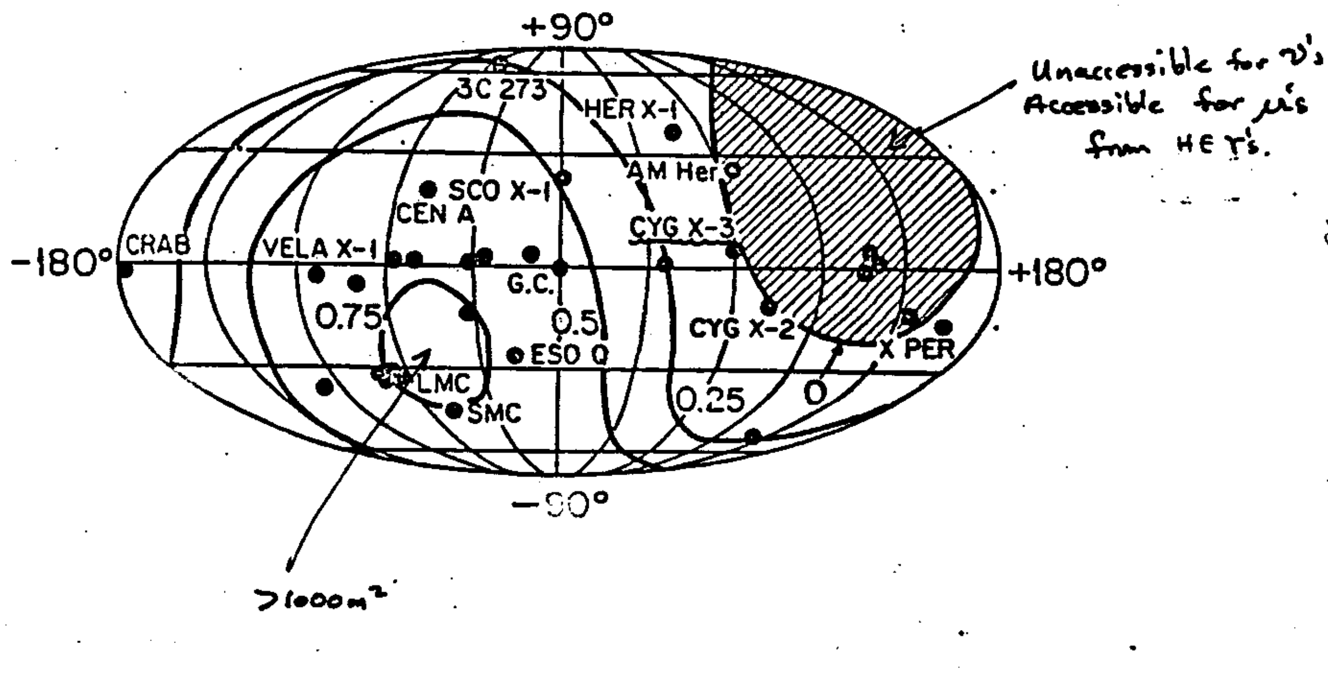
$\phi_{\nu_\mu}(E)$ =	$2\phi_\gamma(2E)$ x	$\frac{(DF)_\nu}{(DF)_\gamma}$ x	$\frac{1}{T_\gamma}$	Upward μ Events/year
VELA X1 ⟶	E_ν^{-2} ·	20	1	~ 6
LMC X4 ⟶	"	"	3	~ 20

* Background Δθ ± 1° ~ 0.1 events/year

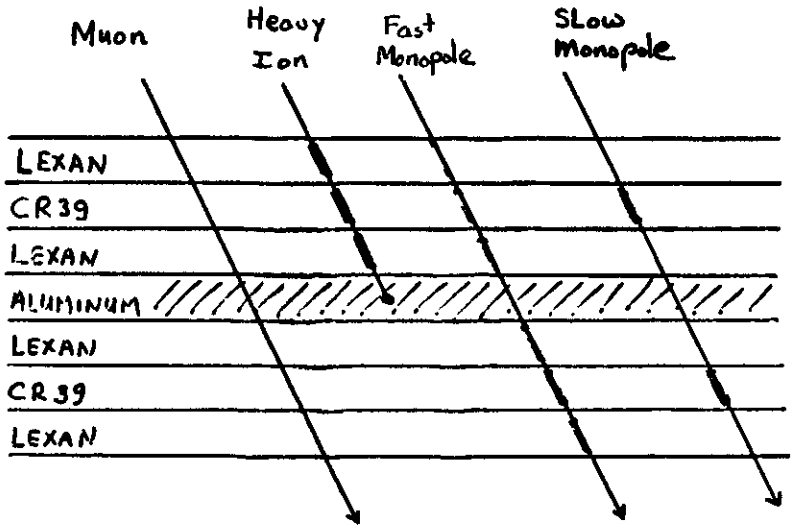


$\Delta x \sim \Delta y \sim \Delta z \sim 1\,cm$

Average Exposed Area Factor for upward going Muons
(Galactic Coordinates)



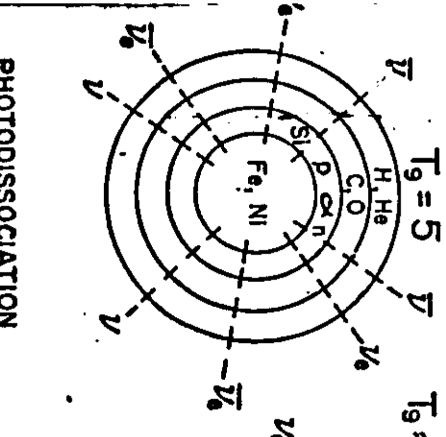
Monopole Detection w/ Track Etch Plastics

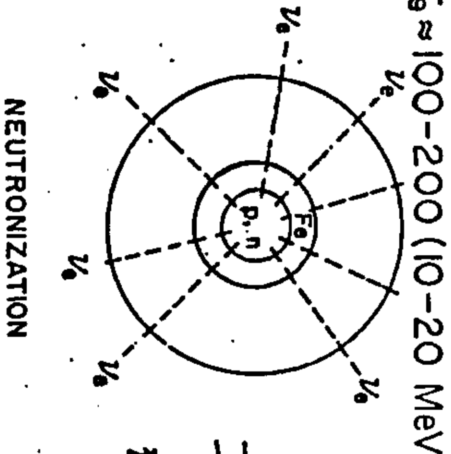


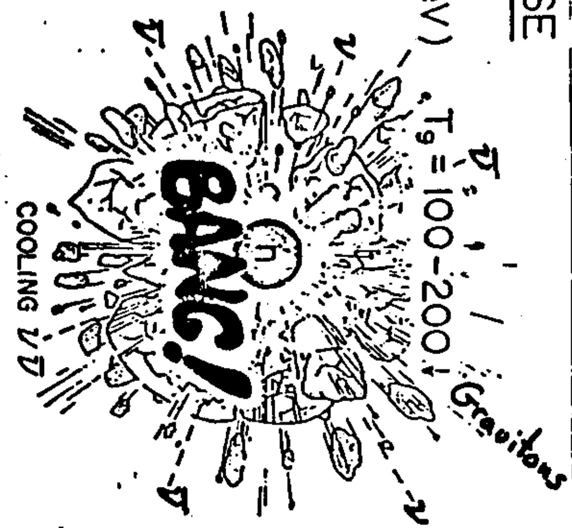
- If a monopole candidate is found in the active detectors (scintillators and/or streamer tubes), Then the corresponding local track-etch module will be removed and processed.

- The track-etch system adds redundant and complementary information,
  - velocity
  - ionizing power

NEUTRINOS FROM STELLAR COLLAPSE







PHOTODISSOCIATION

$Fe \rightarrow 13\alpha + 4n - 100\,MeV$
$\hookrightarrow 26p + 26n$

$\frac{du}{dt}\nu\bar{\nu} \sim T^9 \quad \tau \sim 10s$

NEUTRONIZATION

$e^- + p \rightarrow n + \nu_e$

10^{53} ergs $\tau \sim 10^{-3}s$

COOLING $\nu\bar{\nu}$

10^{53} ergs

$\tau_{peak} \sim 30ms$, $\tau_{decay} \sim 1s$

- ν Opacity: 1) σ increases with E. 2) νN elastic coherent scattering by Z^0 exchange. $\sigma \sim A^2 \sim 3136$ for Fe.

- DETECTION: $\bar{\nu}_e + p \rightarrow n + e^+$ (10 MeV) @ Galactic Center $D = 3 \times 10^{22}$ cm $\quad \frac{10^{53}\ erg/10\ MeV}{4\pi D^2} = 10^{12}\ \bar{\nu}_e/cm^2$

MACRO $\quad \sigma = 7.5 \times 10^{-44} E_\nu^2\ cm^2 \Longrightarrow 1\ e^+/6 \times 10^{29}$ p's

... $\longrightarrow$ ... $\Longrightarrow$ 500 events/1s $\quad$ 10 MeV