Donaldson LRTML LECTURE 4 TEX

LECTURE 4 K. McDONALD Begin with FIG 86 ref 91

DETECTORS FOR THE REST OF THE UNIVERSE

THE SITUATION IN ASTROPHYSICS IS NOW RATHER DESPARATE:

- 2/3 OF THE SUN IS MISSING - THE SOLAR-NEUTRINO PROBLEM
- 9/10 OF THE UNIVERSE IS MISSING - THE DARK-MATTER PROBLEM

WE HAVE ALREADY MENTIONED 2 PIECES OF EVIDENCE FOR DARK MATTER:

- RED-SHIFT DISTRIBUTIONS OF GALAXIES SUGGEST THE UNIVERSE IS CLOSED, BUT VISIBLE MATTER HAS ONLY ~1/10 CLOSURE DENSITY
- X-RAY PROFILES OF GAS IN ELLIPTICAL GALAXIES EXPLAIN ONLY 1/10 THE MASS NEEDED FOR DYNAMICAL UNDERSTANDING

OTHER EVIDENCE:

- ZWICKY (1933) NOTED THAT THE VISIBLE MASS CAN'T EXPLAIN FACT THAT MOST SPIRAL GALAXIES ROTATE ALMOST AS A SOLID OBJECT.
- DYNAMICS OF CLUSTERS OF GALAXIES ALSO INCONSISTENT WITH GRAVITATIONAL EFFECTS OF THE VISIBLE MASS.

THE MASS OF THE BASIC MISSING ENTITY IS THE POOREST KNOWN NUMBER IN SCIENCE TODAY!

MASSIVE BLACK HOLES	$\sim 10^{6} M_{\odot}$	$\sim 10^{40}$ gm
VERY LIGHT AXIONS	$\sim 10^{-10}$ eV	$\sim 10^{-40}$ gm

$\Rightarrow$ 80 ORDERS OF MAGNITUDE UNCERTAINTY!

TYPICAL EXPERIMENT: SURVEY ONE ORDER OF MAGNITUDE

$\Rightarrow$ NEED 80 TYPES OF EXPERIMENTS

MOST LIKELY GUESS (?) – PROTONS

COUNTER ARGUMENT: ^7Li ABUNDANCE (OBSERVED AT 10^{-9} OF p) SHOULD BE LARGER IF MORE PROTONS IN EARLY UNIVERSE.

HERE WE CONSIDER DETECTION OF 3 CLASSES OF PARTICLES WHICH MIGHT BE RELEVANT TO THE DARK-MATTER PROBLEM.

- MAGNETIC MONOPOLES
- AXIONS (LIGHT, WEAKLY COUPLED)
- WIMP's (WEAKLY INTERACTING MASSIVE PARTICLES)

I. MAGNETIC MONOPOLES

[REVIEW: D.E. GROOM, PHYS. REP. 140, 323 (1986)]

DIRAC (1931) NOTED THAT THE MAGNETIC CHARGE OF A MONOPOLE SHOULD BE QUANTIZED IN TERMS OF THE ELECTRON'S CHARGE:

$$g = n \frac{\hbar c}{2e} \qquad n = \pm 1, \pm 2 \ldots$$

RECENT THEORETICAL INTEREST IN MONOPOLES ARISES FROM THEIR READY ACCOMODATION IN GRAND-UNIFIED THEORIES, WHICH SUGGEST $M_{MONOPOLE} \sim 10^{16}$ GeV.

MONOPOLES MIGHT BE THE ONLY STABLE ELEMENTARY PARTICLE OF SUCH A LARGE MASS, AND SO COULD PLAY AN IMPORTANT ROLE IN COSMOLOGY.

GALACTIC MONOPOLES WOULD LIKELY HAVE A TYPICAL GALACTIC VELOCITY: ~ 300 KM/s $\Longleftrightarrow \beta \sim 10^{-3}$

FOUR WAYS OF DETECTING MONOPOLES HAVE BEEN PURSUED:

A. INDUCTION OF CURRENTS IN A LOOP

B. dE/dx LOSS IN SCINTILLATOR

C. CATALYSIS OF PROTON DECAY

D. LATENT TRACKS IN GEOLOGICAL MICA

THE EXPERIMENTAL SITUATION IS SUMMARIZED IN THE FIGURE. →

THE PARKER LIMIT IS BASED ON THE REQUIREMENT THAT THE DENSITY OF GALACTIC MONOPOLES BE LOW ENOUGH NOT TO AFFECT THE OBSERVED MAGNETIC FIELD ($\sim 10^{-6}$ GAUSS).

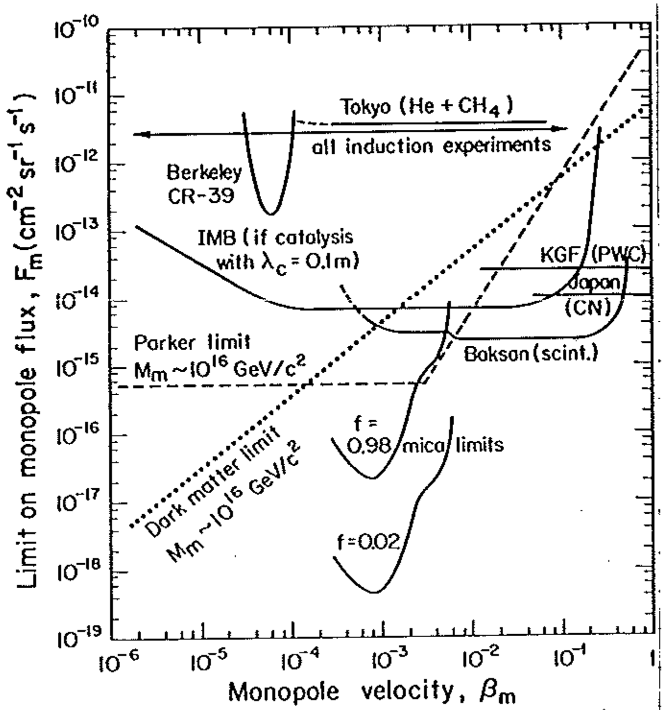


FIG. 3. Monopole flux upper limits (90% C.L.) for several direct searches (solid curves) and indirect astrophysical arguments (dashed curves). Mica limits are calculated for the extreme cases of 2% of monopoles initially bound to protons and for 98% bound to protons.

A. <u>INDUCTION EXPERIMENTS</u>

THE EXCITEMENT WAS CAUSED BY THE EXPERIMENT OF B. CABRERA, PHYS. REV. LETT. 48, 1378 (1982).

IF A MONOPOLE PASSES THRU A SUPER CONDUCTING LOOP OF SELF-INDUCTANCE L, THERE IS AN INDUCED CHANGE IN THE CURRENT:

$$\Delta I = \frac{4\pi g}{L} = \frac{2n\phi_0}{L}$$

WHERE $\phi_0 = hc/2e$ = FLUX QUANTUM OF A SUPERCONDUCTOR.

The small step in current is readily recognized with a superconducting quantum interference device (SQUID).

A particular merit of this approach is that the signal is independent of monopole velocity.

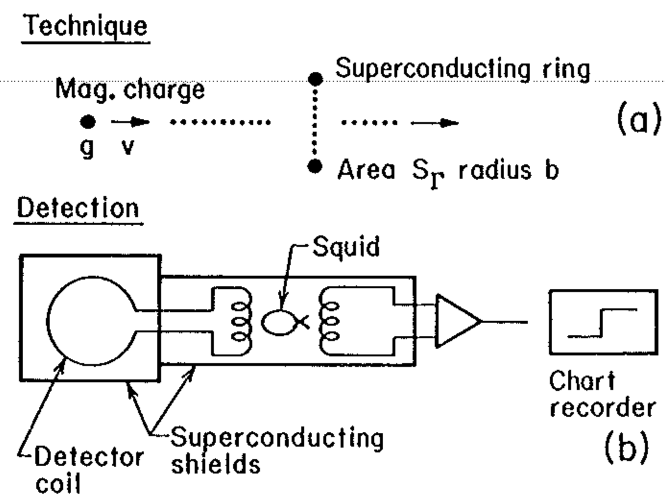


Figure 1: A schematic diagram showing the experimental arrangement for the superconducting coil-SQUID induction technique for monopole detection. The s.c. detection coil, SQUID, and shields are enclosed in a cryostat to maintain the operating temperature of ~4.2°K.

A limitation is the small detector size.

Cabrera's event was obtained in a single-coil detector, when no one was present on Feb. 14, 1982.

If real, the corresponding monopole flux would be $\sim 10^{-9}/cm^2/sr/s$, and 99.9% of the mass of the universe would be monopoles.

Subsequent induction experiments have found no further events, with 1000 times better sensitivity.

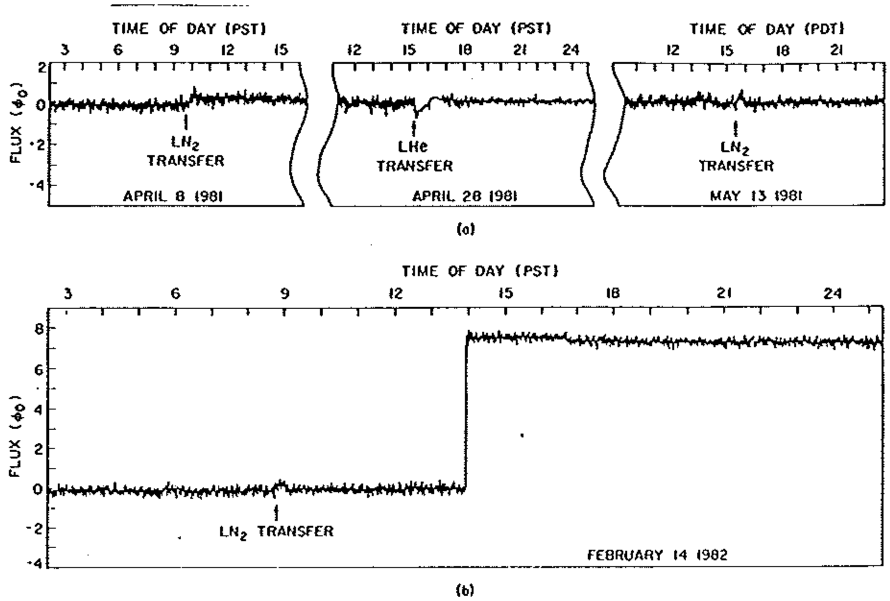


FIG. 2. Data records showing (a) typical stability and (b) the candidate monopole event.

B. Scintillation Detectors

If a monopole passes by an atom it will transfer energy to the electrons, leading to scintillation light. But if the monopole is moving slower than the atomic electrons ($\beta \sim 10^{-3}$ at 1 eV) the energy transfer is difficult to calculate, and is considered small for $\beta_M < 5\times10^{-4}$.

The best limit is from the large underground scintil at Baksan (which also reported a few SN1987A neutrinos. Their limit is about a factor of 10 above the Parker bound at $\beta \sim 10^{-3}$, and excludes galactic monopoles as a major component of the dark matter.

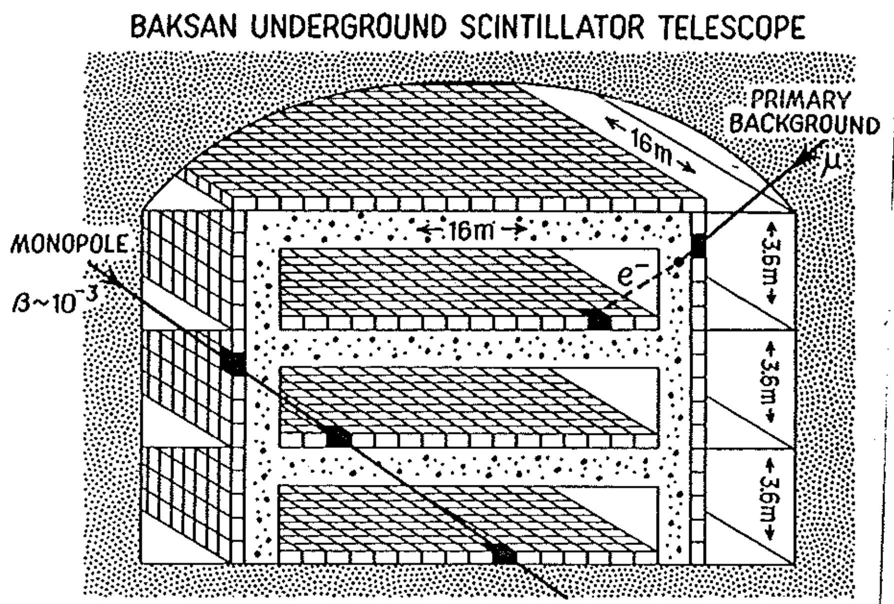


Figure 5: Cross sectional view of the Baksan underground scintillator telescope.

C. Catalysis of Proton Decay

A surprising prediction of the grand-unified theories [Rubakov, 1981; Callan, 1982] is that the monopole may have a cross section of order 10^{-27} cm^2 to interact with a proton, causing the latter to decay;

$$g + p \to g + e^+ \pi^0$$

⋮

IF SO, THE SEVERAL UNDERGROUND PROTON-DECAY DETECTORS (LECTURE 3) IMMEDIATELY CAN SET LIMITS ON THE MONOPOLE FLUX. WITH SUCH A LARGE CATALYSIS CROSS SECTION THERE MIGHT BE ONE PROTON DECAY PER METER OF MONOPOLE PATH IN THE DETECTOR.

THE PRESENT BEST LIMITS USING THIS TECHNIQUE COME FROM THE IMB DETECTOR, THE LARGEST OF THE OPERATING WATER ČERENKOV EXPERIMENTS.

THIS TECHNIQUE IS SUITABLE FOR ESCALATION TO VERY LARGE UNDERWATER DETECTORS.

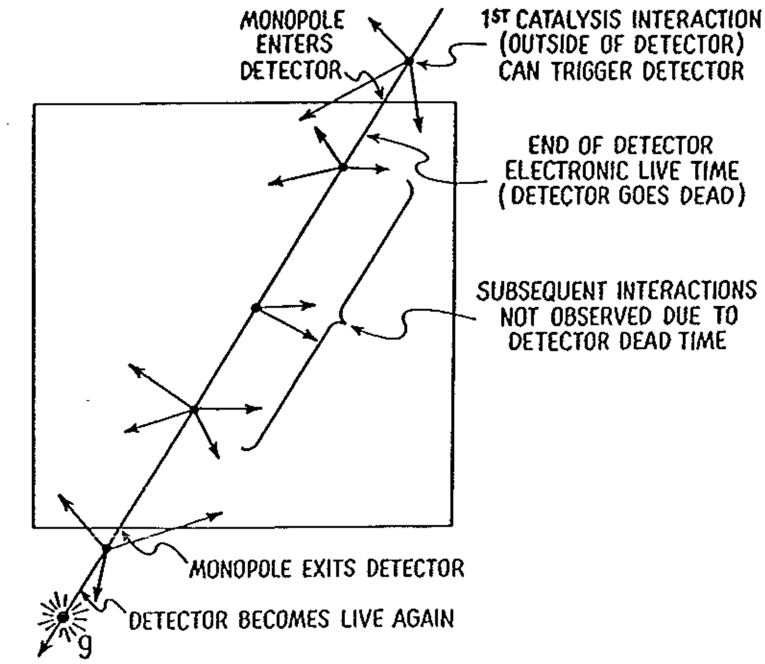


Figure 8: Technique for searching for ≥ 2 monopole catalysis of nucleon decay events. The deficiencies of the technique due to detector electronic livetime and deadtime are indicated.

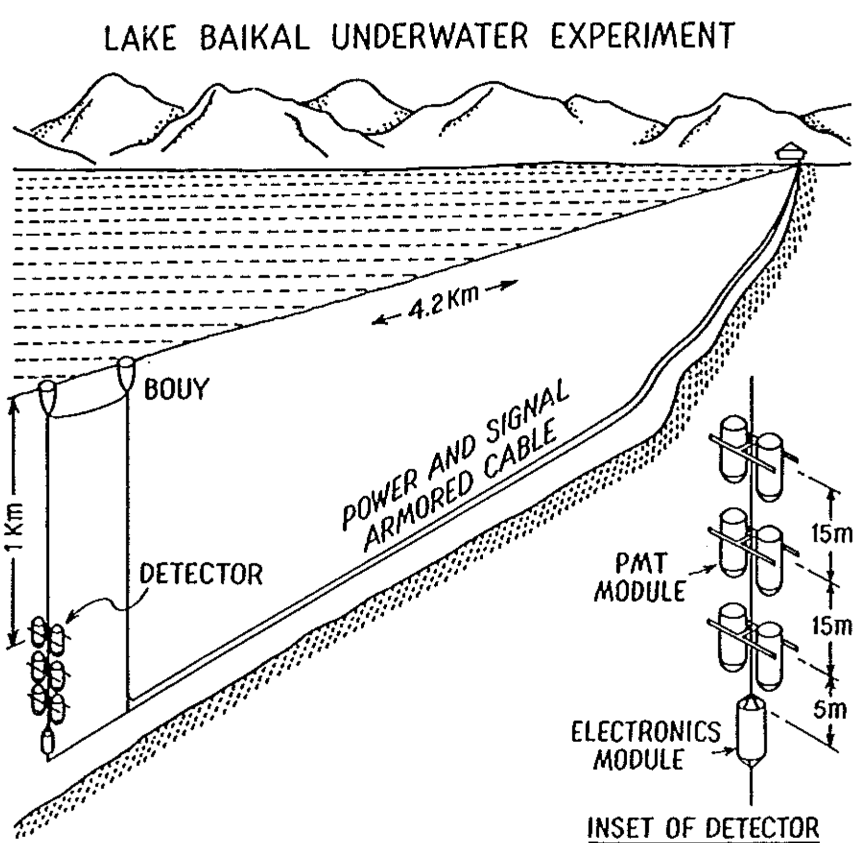


Figure 11: Deployment of the deep underwater PMT string at Lake Baikal.

D. Geological Mica Detector

An interesting technique is based on the possibility that a monopole passing thru crystals of mica deep in the earth has left latent tracks — due to ionization-induced defects in the crystal. These can be made visible by the track-etching method [Price & Salamon, Phys. Rev. Lett. 56, 1226 (1986)].

For this to work the monopole needs to attach some nucleus from crustal material, such as ^{27}Al, via the magnetic dipole of the nucleus. It is the electric charge of the nucleus, moving with $\beta \sim 10^{-3}$, which causes the defects in the mica.

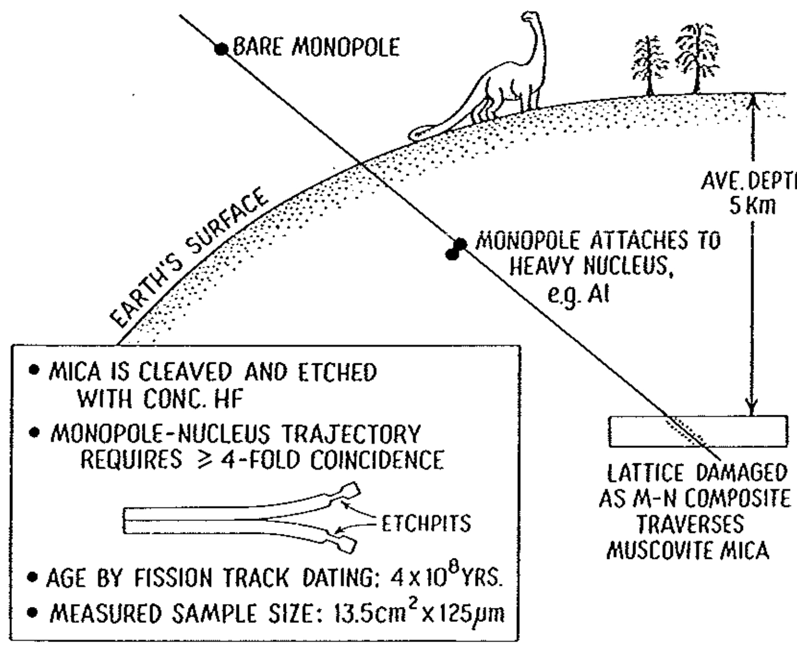


Figure 7: Scenario of the Berkeley Mica Experiment.

From sheets of mica $\sim 5 \times 10^8$ years old a very stringent limit on monopole flux has been set. Of course, there is no evidence that monopoles actually attach nuclei in the required manner.

A SEARCH FOR MONOPOLES VIA THE TRACK-ETCHING TECHNIQUE WILL BE INCORPORATED IN THE MACRO DETECTOR IN GRAN SASSO. THIS DETECTOR (AND ALSO SUPER-KAMIOKANDE) SHOULD LOWER THE LIMIT ON MONOPOLE FLUX IN DIRECT SEARCHES BY A FACTOR OF ~100.

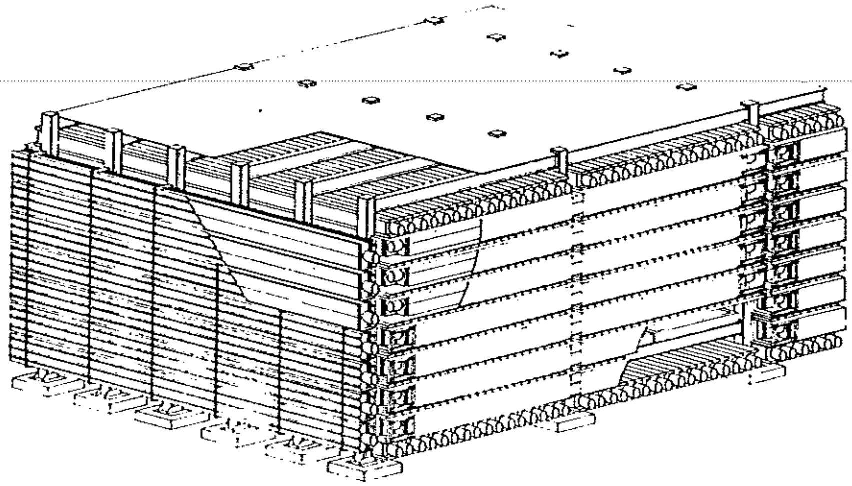


Fig. 2. General view of one of the 12 MACRO supermodules (12×12×5 m³).

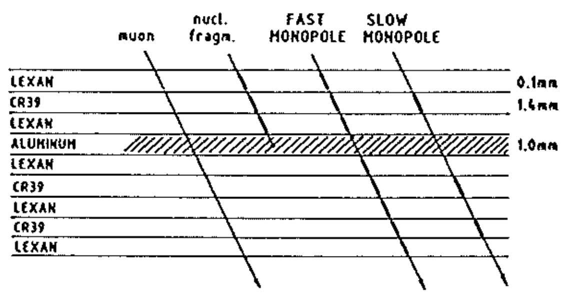


Fig. 9. The track-etch detector sandwich, with a schematic description of its response to different particles.

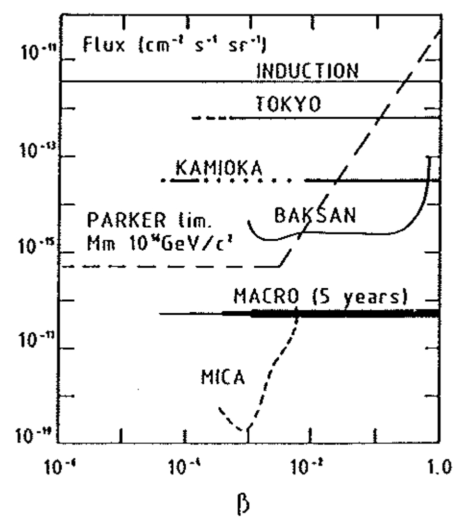


Fig. 10. MACRO 90% c.l. limit on monopole flux after 5 years of operation. The different thickness of the line is to indicate the redundancy of information from the different detectors. The most significant existing results are also shown. The mica track-etch experiment is very sensitive, but relies on a number of restrictive assumptions.

II AXIONS

THE AXION, BROADLY CONSIDERED, REPRESENTS THE POSSIBILITY THAT DARK MATTER CONSISTS OF VERY LIGHT NEUTRAL PARTICLES ($M_A < M_e$).

THE ORIGINAL AXION WAS CONCEIVED AS A SOLUTION TO A PARTICLE-THEORISTS' PROBLEM - WHY DOES THE STRONG INTERACTION CONSERVE CP? (ALL PROBLEMS IN PARTICLE PHYSICS ARE SOLVED BY NEW PARTICLES!) THE ORIGINAL PREDICTION SEEMS TO BE RULED OUT BY ACCELERATOR EXPERIMENTS, BUT THE CONCEPT HAS BEEN ENLARGED TO INCLUDE ALMOST ANY CONCEIVABLE LIGHT OBJECT.

THE PUZZLING POSITRON PEAKS OF DARMSTADT LED TO A FLURRY OF SEARCHES FOR A AXION WITH $M_A \sim 1.7\,\text{MeV}$. THIS NOW SEEMS EXCLUDED, AGAIN DUE TO MANY ACCELERATOR EXPERIMENTS [SEE RIORDAN ET AL, PHYS. REV. LETT. 59, 755 (1987) FOR A RECENT RESULT.]

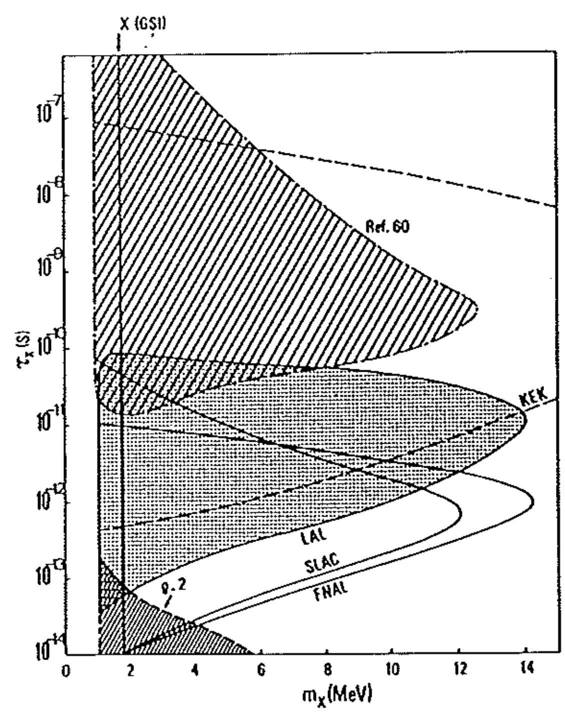
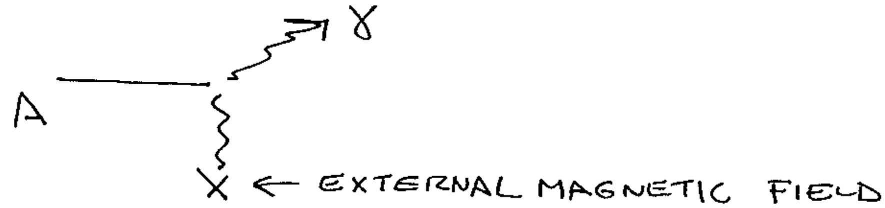


Fig. 30 - Excluded domain in the mass-lifetime plane for weakly interacting particles coupled to the electron and decaying into e^+e^- pairs

INTEREST NOW CENTERS ON THE RANGE $10^{-5}\,eV < M_A < 10\,eV$ (THE 'INVISIBLE' AXION). IN THIS CASE THE ONLY USEFUL INTERACTION OF AN AXION WITH ORDINARY MATTER IS THE DECAY $A \to \gamma\gamma$, OR THE RELATED 'MAGNETIC PRIMAKOFF EFFECT'



ACCORDING TO SIKIVIE [PHYS. REV. LETT. 52 695 (1984)] THE STRENGTH OF THE AXION'S ELECTROMAGNETIC COUPLING VARIES AS $\bar{E}\cdot\bar{B}$. FOR CONVERSION OF AXIONS TO PHOTONS IN A STATIC MAGNETIC FIELD $\bar{E}$ IS THAT OF THE PHOTON PRODUCED, AND $\bar{B}$ IS THAT OF THE STATIC MAGNETIC FIELD.

THIS IDEA HAS BEEN IMPLEMENTED IN THE EXPERIMENT OF DEPANFILIS ET AL, PHYS. REV. LETT. 59, 839 (1987). SEE ALSO MOSKOWITZ, N.I.M. A264, 98 (1988).

THE GALACTIC AXIONS MIGHT CONVERT TO PHOTONS IN THE 60-KG MAGNETIC FIELD. IF $\beta_A \sim 10^{-3}$ AS FOR OTHER GALACTIC PARTICLES, THE WIDTH OF THE PHOTON FREQUENCY SPECTRUM SHOULD BE VERY NARROW:

$$\Gamma \sim 10^{-6} M_A .$$

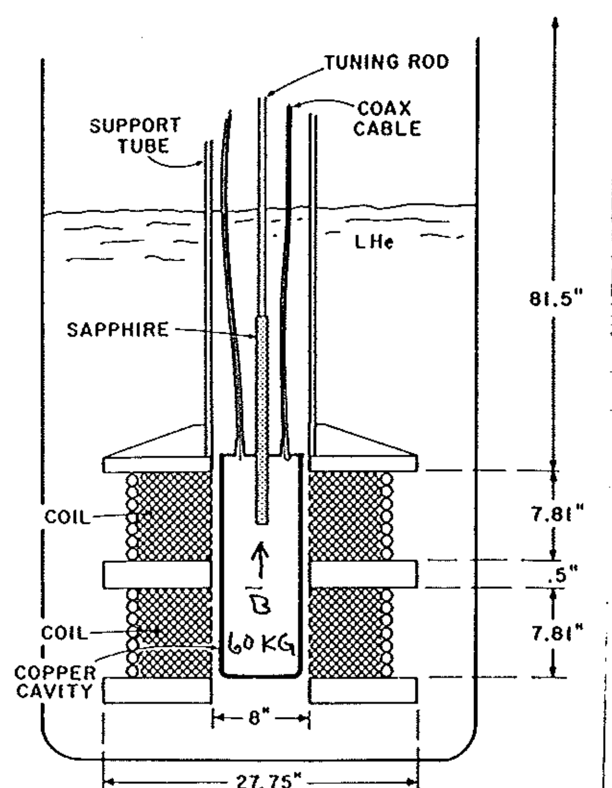


FIG. 2. Schematic diagram of the apparatus.

THEY SEARCH FOR PHOTONS WHOSE FREQUENCIES LIE WITHIN THE TUNING RANGE OF A SMALL RF CAVITY $\to$ 1 GHz $\leftrightarrow$ $M_A \sim 5 \times 10^{-6}$ eV. THE SIGNAL WOULD BE A NARROW SPIKE OF EXCESS POWER IN THE CAVITY DURING A FREQUENCY SWEEP.

SO FAR, NO SIGNAL HAS BEEN SEEN, WITH A LIMIT ~ 300 TIMES LARGER THAN THE AXION FLUX NEEDED TO CLOSE THE UNIVERSE. CLEARLY ONE WOULD LIKE TO EXTEND THIS TECHNIQUE TO A WIDER RANGE OF AXION MASSES $\Rightarrow$ MUCH LARGER CAVITIES & MAGNETIC FIELD VOLUMES.

KEPHART & WEILER [PHYS. REV. LETT. 58, 171 (1987)] POINT OUT THAT IF AXIONS DOMINATE THE DARK GALACTIC HALO THE LATTER MIGHT NOT ACTUALLY BE DARK, DUE TO THE DECAY $A \to \gamma\gamma$. THE DECAY PHOTONS WOULD BE NEARLY MONOCHROMATIC: $E_\gamma \sim \frac{M_A}{2}$ AND $\Gamma \sim \beta E_\gamma \sim 10^{-3} E_\gamma$ FOR USUAL GALACTIC VELOCITIES.

IF $M_A > 1$ eV THE LIGHT SHOULD BE DETECTABLE IN OPTICAL OR UV SPECTROMETERS (ON SATELLITES).

A VARIATION ON THE INVERSE PRIMAKOFF EFFECT LENDS ITSELF TO A LABORATORY SEARCH FOR AXIONS, AS NOTED BY VAN BIBBER ET AL. PHYS. REV. LETT. 59, 759 (1987). A LASER BEAM ($E_\gamma \sim 2$ eV) INTERACTS WITH A STATIC MAGNETIC FIELD TO PRODUCE AN AXION, WITH $M_A < 2$ eV. THE AXION READILY PENETRATES AN OPAQUE WALL, BUT MIGHT INTERACT WITH A 2ND MAGNETIC FIELD TO PRODUCE AN OPTICAL PHOTON ON THE FAR SIDE OF THE WALL.

THE EXPERIMENT IS SENSITIVE TO ALL $M_A < 2$ eV AT ONCE, BUT PROVIDES LITTLE MEASURE OF THE MASS.

IF A SIGNAL WERE FOUND ONE CAN IMAGINE EXPERIMENTS WITH 3 MAGNETS OF VARIABLE SEPARATION TO DEDUCE THE MASS VIA INTERFERENCE EFFECTS.

AN INITIAL EXPERIMENT COULD REACH A SENSITIVITY STILL SOMEWHAT ABOVE THE AXION COUPLING STRENGTH NEEDED TO CLOSE THE UNIVERSE.

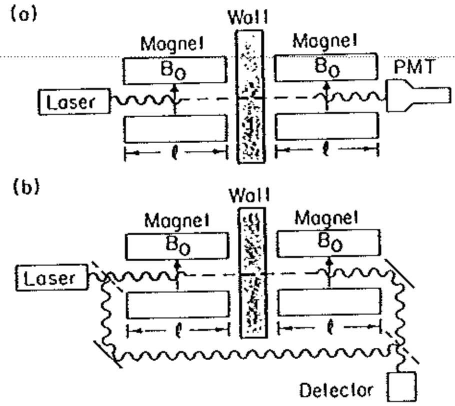


FIG. 1. Experimental setups. (a) Photons from a laser are shone into the bore of a dipole magnet. There the real laser photons interact with the virtual photons from the magnetic fields, producing pseudoscalars. The weakly interacting pseudoscalars penetrate the wall and then convert in the second magnet. The resulting photon is detected in the phototube (PMT). (b) A similar experiment, except that interference is used to increase the signal-to-noise ratio.

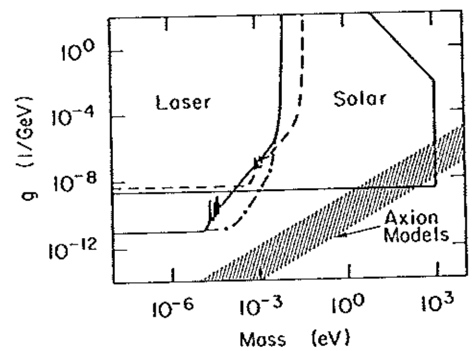


FIG. 2. Limits on light pseudoscalars. The proposed laser experiments could exclude regions in the upper-left-hand corner of this plot. Dashed line: Region that a null experiment of type (i), shown in Fig. 1(a), could exclude. The ripples come from the form factor, $F(q)$. Solid line: Region that a null experiment of type (ii), with use of SSC dipoles, a CO_2 laser, and interference, could exclude. Dot-dashed line: Region that could be excluded by an experiment of type (iii), where magnet polarity is alternated. Also shown are the solar limit (Ref. 6) and the expectations from a variety of axion models (Ref. 4).

III WIMP'S

INTERMEDIATE IN MASS BETWEEN THE HEAVY MONOPOLES AND THE LIGHT AXIONS ARE THE DARK-MATTER CANDIDATES CALLED WIMP'S (WEAKLY INTERACTING MASSIVE PARTICLES).

THE VERSION OF A WIMP CLOSEST TO THE PRESENT STANDARD MODEL OF ELEMENTARY PARTICLES IS THE 'MAGNINO' OF RABY & WEST [PHYS. LETT. 194B, 557 (1987)] THIS IS A HEAVY NEUTRINO, OF A 4TH TYPE, POSSESING A LARGE MAGNETIC MOMENT – SO ITS INTERACTIONS ARE NOT ALL THAT WEAK. THIS COULD HAVE ESCAPED DETECTION IN PRESENT ACCELERATORS EVEN IF ITS MASS IS AS LOW AS 5 GeV.

IF THE MAGNINO HAS AN INTERACTION CROSS SECTION OF $\sim 10^{-36}\,cm^2$, AND A MASS OF 5-15 GeV IT COULD SOLVE THE SOLAR-NEUTRINO PROBLEM AS WELL AS THE DARK-MATTER PROBLEM [FAULKNER, GILLILAND, PRESS & SPERGEL] SUCH WIMP'S INTERACT ENOUGH TO BE CAPTURED IN THE SUN, AND THEN CARRY ENERGY OUT FROM ITS CENTER, LOWERING T_c BY THE 6% NEEDED TO EXPLAIN THE ^{37}Cl RESULTS.

THE WIMP'S MIGHT BE DETECTED BY THE RECOIL OF A NUCLEUS THEY OCCASIONALLY STRIKE. THE ENERGY TRANSFER IS SMALL: $KE_{NUC} \sim \beta_W^2 \cdot \frac{M_W}{M_{NUC}} \cdot M_W$

WITH $\beta \sim 10^{-3}$ FOR A GALACTIC WIMP, AND A NUCLEUS WITH $A=100$,

$KE_{NUC} \sim 1\,KeV$ WHEN $M_{WIMP} = 10\,GeV$.

(FOR A COLLISION WITH AN ELECTRON, $KE_{ELECTRON} \sim M_e \beta_W^2 \sim 1\,eV$.)

A. Ge DETECTORS (USED IN ββ-DECAY EXPERIMENTS)

As noted in lecture 1, of existing detectors solid-state devices based on Si or Ge have the best energy resolution. By a happy coincidence, ^{76}Ge makes up 8% of natural Ge, and is 'stable', but a good candidate for double-β decay:

$$^{76}Ge \rightarrow {}^{76}Se + 2e^- + 2\bar{\nu}_e$$

$$\text{or} \quad ^{76}Ge \rightarrow {}^{76}Se + 2$$

Several Ge detectors have been set up to look for this (with no signal thus far). Two report limits on WIMP's:

PNL-USC : Ahlen et al. Phys. Lett 195B, 603 (1987)

UCSB-LBL: Caldwell, N.I.M. A264, 106 (1988)

PNL-USC

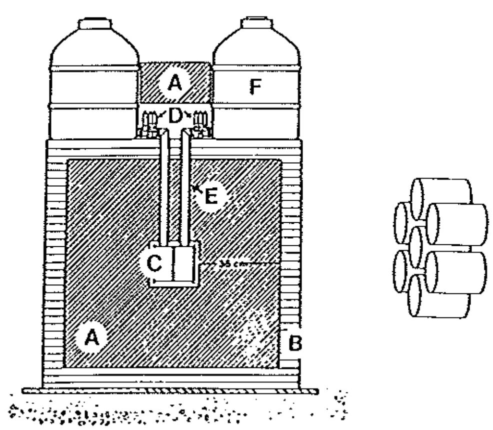
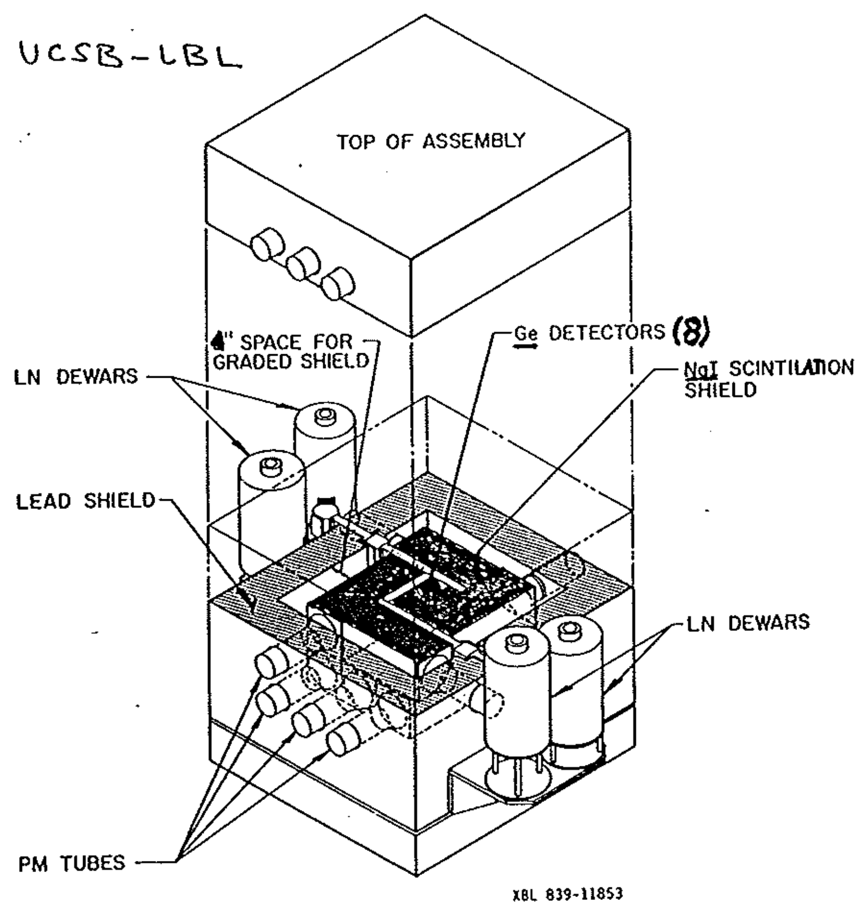


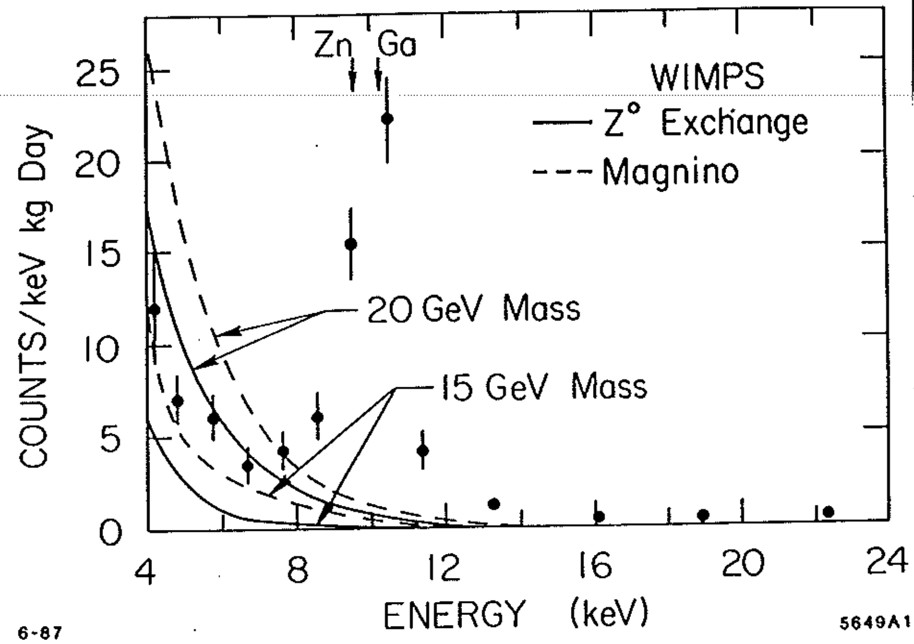
Fig 2. Schematic representation of large (1440 cm³) germanium diode spectrometer system. A = lead shielding, B = anticosmic scintillator, C = diode cryostat each containing seven germanium crystals arranged as shown at right, D = externally mounted preamps, E = cold finger, and F = liquid nitrogen dewar.

UCSB-LBL



600 m.w.e.

THE PRESENT LIMITS ARE $M_{WIMP} > 17$ GeV. IT IS HOPED THAT THIS CAN BE REDUCED TO ~ 8 GeV WITH BETTER SHIELDING AND LOWER ELECTRONIC NOISE.



A Si DETECTOR IS BETTER FOR WIMP'S (THO NOT USEFUL FOR $\beta\beta$ DECAY) AS THE RECOIL ENERGY FROM A WIMP COLLISION IS TWICE THAT FOR Ge. PERHAPS A 4-6 GeV UPPER LIMIT CAN BE SET WITH A 'CONVENTIONAL' Si DETECTOR.

B. Novel Detectors

A WIMP-NUCLEUS COLLISION WOULD LEAVE THE NUCLEUS WITH A FEW KeV KINETIC ENERGY.

EVEN MORE CHALLENGING IS THE DETECTION OF RECOIL NUCLEI FROM SOLAR NEUTRINOS, WHERE A NEUTRAL-CURRENT REACTION $\nu_\mu + A \to \nu_\mu + A$ LEAVES THE NUCLEUS WITH

$$KE_{NUC} \sim \frac{E_\nu^2}{M_{NUC}} \sim 10\,eV \quad \text{FOR } E_\nu \sim 1\,MeV.$$

THIS HAS SUGGESTED THE DETECTION OF THE BREAKUP OF COOPER PAIRS IN SEMICONDUCTOR, $\Delta E \sim 10^{-3}\,eV$, OR PHONONS, $\Delta E \sim 10^{-4}\,eV$, IN CYROGENIC DETECTORS.

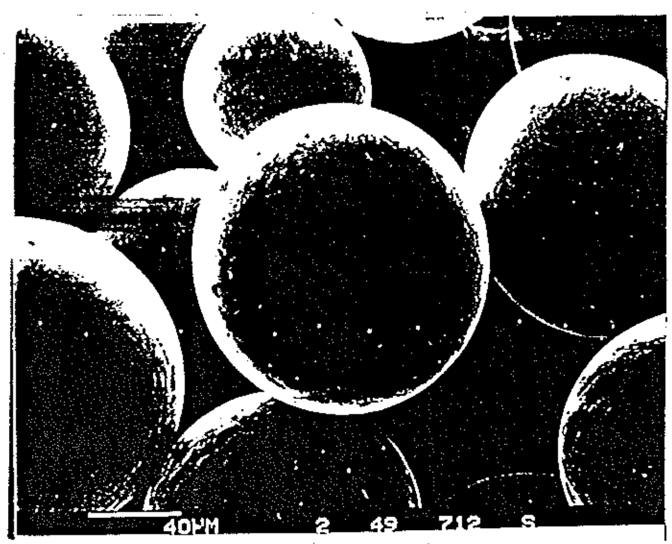
HERE WE SKETCH 5 VARIATIONS ON THESE IDEAS:

1. COOPER-PAIR BREAKUP DETECTED VIA LOSS OF MEISSNER EFFECT IN GRANULES.
2. COOPER-PAIR BREAKUP DETECTED VIA CURRENTS IN TUNNEL JUNCTIONS.
3. PHONONS DETECTED VIA THERMISTORS.
4. BALLISTIC PHONONS.
5. ROTONS IN LIQUID He DETECTED VIA EVAPORATION.

A RECENT REVIEW IS BY SADOULET, IEEE NUCLEAR SYMPOSIUM, OCT. 1987. SEE ALSO 'LOW-TEMPERATURE DETECTORS FOR NEUTRINOS AND DARK MATTER', ED BY PRETZL ET AL (SPRINGER-VERLAG, 1987)

C. SUPER-HEATED SUPERCONDUCTING GRANULES

THE IDEA GOES BACK TO BERNAS ET AL, PHYS. LETT 24A, 721 (1967). MICRON-SIZED SUPERCONDUCTING GRAINS, PERHAPS OF TIN, ARE PLACED IN A MAGNETIC FIELD AND HELD CLOSE TO THE CRITICAL TEMPERATURE. IF SUFFICIENT ENERGY IS DEPOSITED IN A GRAIN IT WIL GO NORMAL AND NO LONGER EXPEL THE EXTERNAL MAGNETIC FIELD. THE CHANGING FLUX PATTERN WILL BE DETECTED IN AN X-Y ARRAY OF LOOPS CONNECTED TO SQUID'S. LEGROS ET AL, N.I.M. A263, 229 (1988) REPORT THE DETECTION OF 90 KEV X-RAYS WITH THIS TECHNIQUE.



NO DETAILED MEASURE OF THE ENERGY DEPOSITED IS MADE, BUT GOOD TIME AND POSITION RESOLUTION CAN BE OBTAINED IN PRINCIPLE.

SINCE ENTIRE GRAINS MUST MAKE THE SUPERCONDUCTING → NORMAL TRANSITION THE ULTIMATE ENERGY THRESHOLD IS NOT THE LOWEST. ALSO, A LITER CONTAINS ~10^{13} 5-μm GRAINS, SO MATERIAL UNIFORMITY IS A PROBLEM.

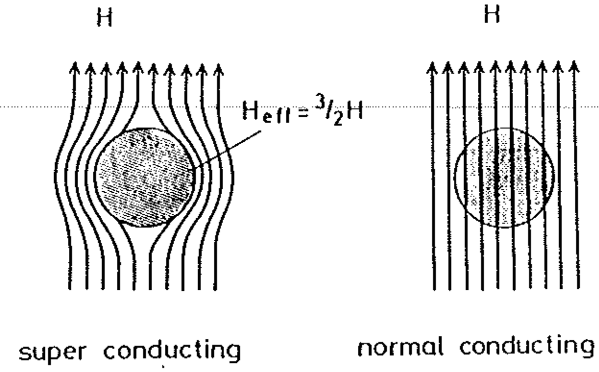


Fig. 3 : Meissner effect of a superconductor.

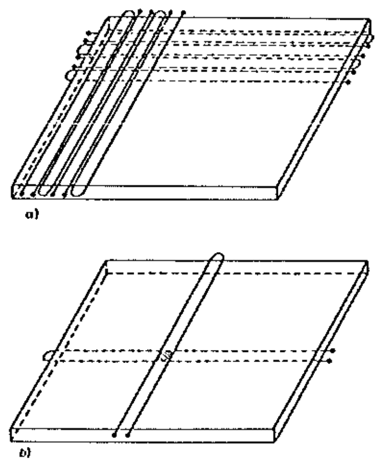


Fig. 4 : a.) A foil of grains surrounded by a (X,Y)-coordinate system of pick up loops.
b.) A localized event detected by a coincidence of two loops perpendicular to each other.

D. TUNNEL-JUNCTION DETECTORS

HERE THE BREAKUP OF COOPER PAIRS LEADS TO ELECTRONS (OFTEN CALLED 'QUASIPARTICLES') WHICH ARE COLLECTED AT THE SURFACE OF THE SUPERCONDUCTOR BY THEIR ABILITY TO TUNNEL THRU A THIN INSULATING LAYER.

A VARIATION INCLUDES A TRANSITION LAYER OF Al AT THE SURFACE WHICH LOWERS THE ELECTRON ENERGY SLIGHTLY (BY PHONON EMISSION) UNTIL THEY ARE BELOW THE CONDUCTION BAND OF THE BULK SUPERCONDUCTOR, AND CANNOT RETURN INTO IT.

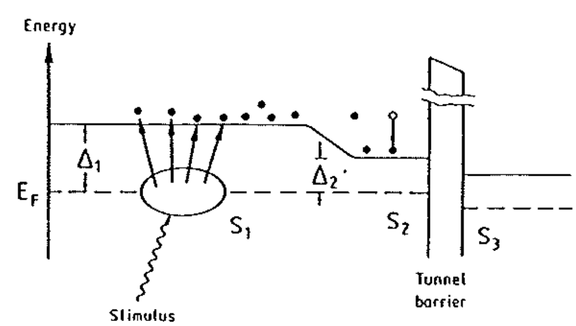
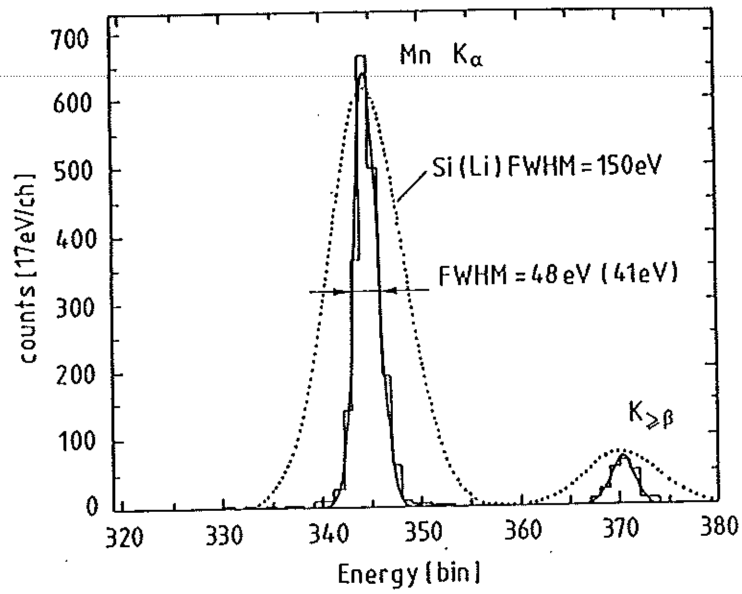


Fig. 4. Energy diagram showing trapping of excess quasiparticles produced in superconductor S_1 by an adjacent superconductor S_2 of lower gap.



A RATHER IMPRESSIVE ENERGY RESOLUTION HAS BEEN OBTAINED IN Si FOR 5.9 KeV X-RAYS BY ZEHNDER ET AL [SIN PR-87-08, OCT. 1987]. THIS IS 3 TIMES BETTER THAN A CONVENTIONAL Si(Li) DETECTOR, BUT PERHAPS 10 TIMES THE ULTIMATE RESOLUTION.

AN AMBITIOUS APPLICATION OF THIS TECHNIQUE FOR SOLAR-NEUTRINO DETECTION IS PROPOSED BY BOOTH ET AL [EVETTS ET AL, N.I.M. A264, 41 (1988)], USING SUPERCONDUCTING INDIUM. THE REACTION IS

$$\nu_e + {}^{115}\mathrm{In} \to {}^{115}\mathrm{Sn}^* + e^-$$
$$\hookrightarrow 115\ \mathrm{KeV} + 500\ \mathrm{KeV}\ \text{X-RAYS}$$

(SIMILAR IN NATURE TO THE ^{40}Ar ABSORPTION REACTION, LECTURE 3). THE THRESHOLD IS 0.13 MeV, SO In IS SENSITIVE TO THE PP NEUTRINOS. THE PRESENTLY OBSERVED RESOLUTION IN Si IS ALREADY GOOD ENOUGH, BUT THE In DETECTOR MUST BE BUILT ON A LARGE SCALE.

DEVELOPMENT IS UNDERWAY OF READOUT JUNCTIONS AS SKETCHED, BUT THE SCALE IS GRAMS, NOT TONS.

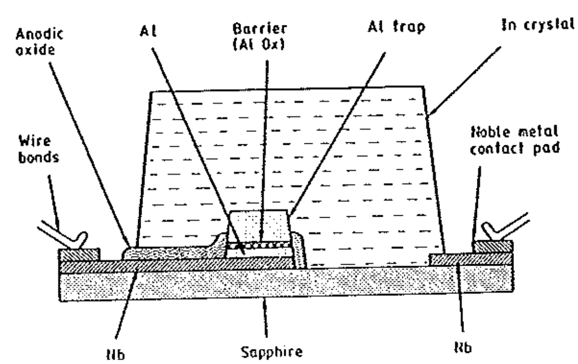


Fig. 8. Cross-sectional view of the type of In detector incorporating an Al trap which is presently under development.

D. CALORIMETRY VIA THERMISTORS (BOLOMETERS)

IN A DETECTOR OF HEAT CAPACITY C AN ENERGY DEPOSITION E LEADS TO A TEMPERATURE CHANGE ΔT : $E = C \Delta T$.

SMALL TEMPERATURE CHANGES IN A COLD DETECTOR CAN BE MONITORED VIA A THERMISTOR, SUCH AS Si DOPED WITH P OR As, SO THAT THE RESISTANCE IS A RAPID FUNCTION OF TEMPERATURE.

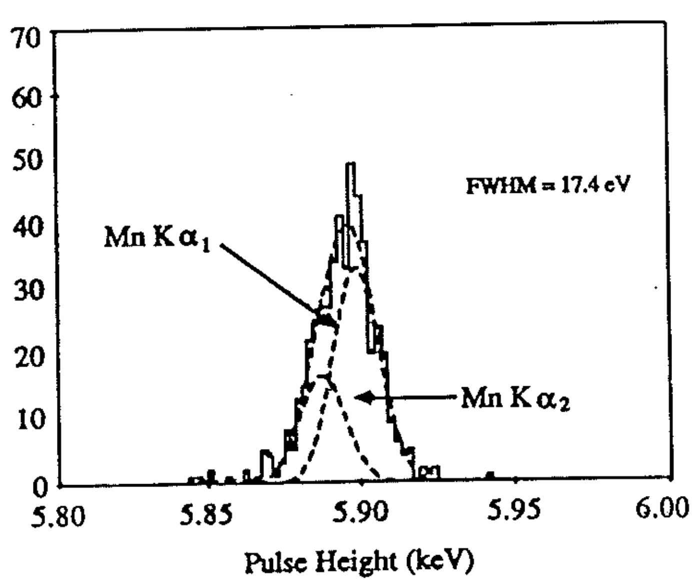
IN PRINCIPLE THE NOISE CONTRIBUTION VARIES AS

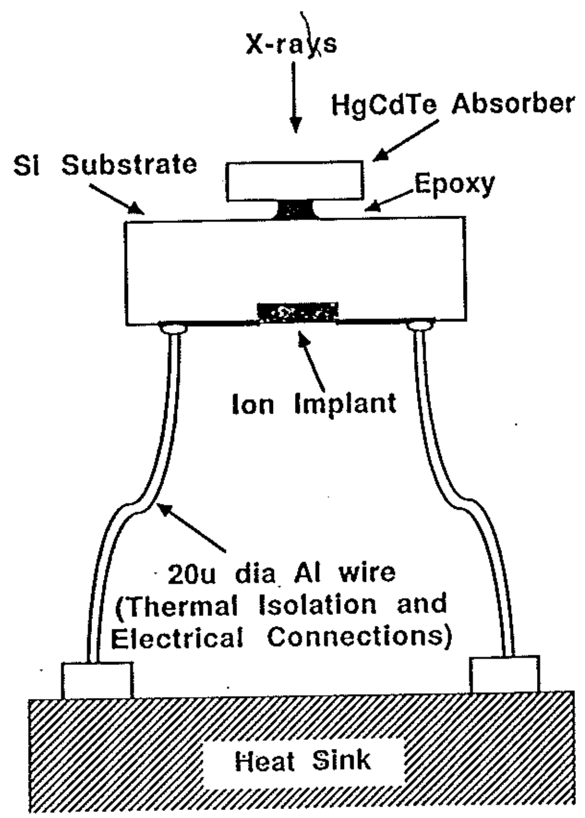
$$\delta E \sim T\sqrt{C}$$

WHICH FAVORS LOW TEMPERATURES AND SMALL DEVICES.

MOSELEY ET AL (1987) HAVE OBSERVED A RESOLUTION OF 17 eV FOR 5.9 KeV X-RAYS AT 0.08°K. THE TIME RESPONSE WAS ~1 MSEC IN THEIR TINY DEVICE.

SCALING TO LARGE DETECTORS MAY BE DIFFICULT AS THE HEAT CAPACITY C VARIES LINEARLY WITH M. GOING TO LOWER TEMPERATURES TO COMPENSATE LEADS TO DIMINISHING RETURNS DUE TO NOISE FROM MATERIALS DEFECTS.





Pages 20 - 23 not included!

E. ACOUSTIC DETECTION OF BALLISTIC PHONONS

THE THERMALIZATION OF PHONONS IN A CRYSTAL TAKES OF ORDER 1 MSEC. ON A SHORTER TIME SCALE THE HIGH-FREQUENCY PHONONS DECAY UNTIL AFTER ~100NS A STABLE SPECTRUM EXISTS, WHICH PROPAGATES BALLISTICALLY FOR SEVERAL MICROSECONDS.

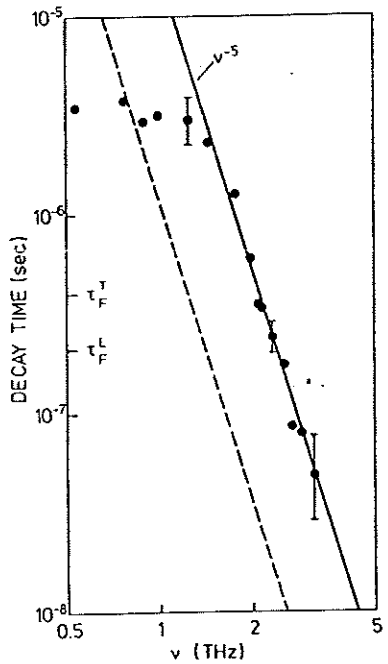


FIG. 3. Lifetimes of acoustic phonons in CaF_2 at low crystal temperature. $\tau_F{}^L$ is the (average) time of flight of longitudinal and $\tau_F{}^T$ that of transverse phonons out of the excited volume. The curves are discussed in the text.

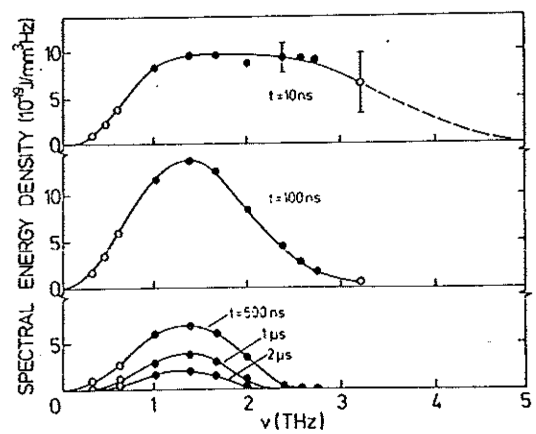


Fig. 3. Spectral energy density of nonthermal phonons in $CaF_2:Eu^{2+}$ for different times t after laser-pulse excitation. The frequency scale extends up to a frequency typical for transverse acoustic zone-boundary phonons in CaF_2. The dashed part of the upper curve is a guess (see text).

[BAUMGARTNER ET AL, PHYS. REV. LETT. 47, 1403 (1981); PHYS. LETT. 94A, 55 (1983)]

THE PHONON PROPAGATION IS NOT ISOTROPIC IN A CRYSTAL SUCH AS Ge OR Si, BUT LEADS TO A 'FOCUSING' EFFECT, WHICH CAN BE OBSERVED BY PLACING PHONON DETECTORS ON THE CRYSTAL SURFACE. [NORTHRUP & WOLFE, PHYS. REV B22, 6196 (1980); WOLFE, PHYSICS TODAY, DEC. 1980, p44]

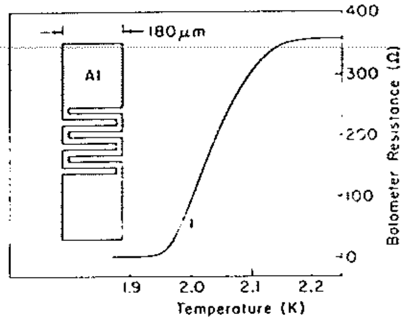
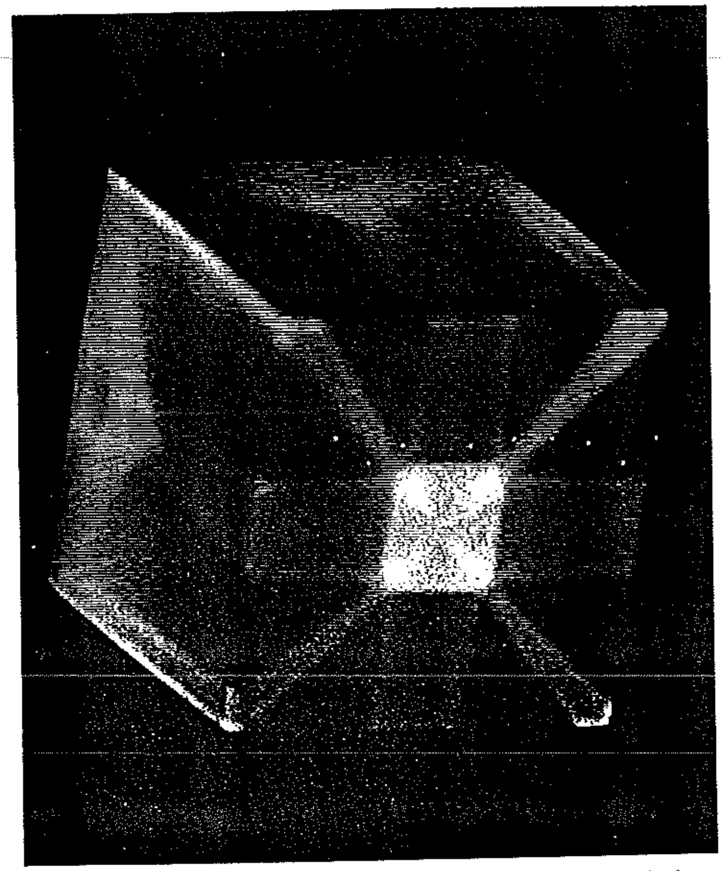
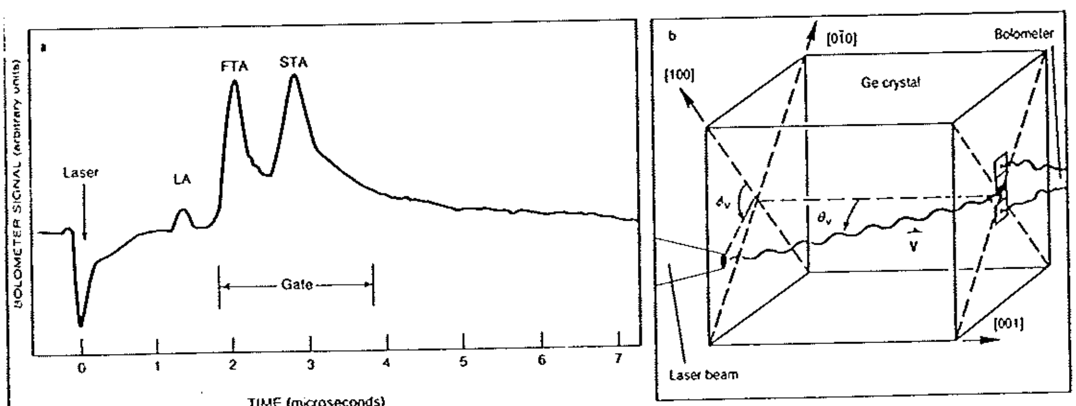


FIG. 3. Measured electrical resistance of an Al thin-film bolometer as the temperature is lowered through the superconducting transition. In a heat-pulse experiment, the temperature of the crystal and bolometer is biased at a point where dR/dT is a maximum, as indicated by the arrow, by regulating the pressure of the helium bath. Inset: Diagram of the Al film geometry which produces a bolometer with very small sensitive area and hence high solid-angle resolution.

↑
A 'SUPERCONDUCTING-EDGE' BOLOMETER.



Phonon focusing in germanium. The bright areas represent heat energy propagating from a point on the back surface of a germanium crystal, which was cooled to 1.9 K. The phenomenon is caused by intense channeling of heat flux along certain crystal directions. Gregory Northrup and James Wolfe devised the experiment, which was performed on a 1 cm^3 germanium crystal grown by E. E. Haller and W. L. Hansen of Lawrence Berkeley Laboratory. Figure 1



Heat-pulse experiment. The schematic view (right) shows heat generated at the left surface of the crystal producing phonons radiating in all directions. Those with propagation direction (θ_v, ϕ_v) impinge on the detector. Phonon pulses in germanium (left) are detected by sensing the resistance of the bolometer, biased near its superconducting transition. The longitudinal, fast transverse and slow transverse acoustic phonons, generated by a 200-nanosec laser pulse, are resolved by their differing times-of-flight across the crystal. The negative signal at $t = 0$ is due to photoexcited carriers. (From reference 10). Figure 2

THIS PHENOMENON IS BEING ADAPTED FOR ASTROPHYSICS BY CABRERA ET AL [PHYS. REV. LETT. 55, 25 (1985); STANFORD PREPRINT BC 67-87 (1987)]

A DETECTOR MIGHT CONSIST OF 1000 1-KG Si CRYSTALS WITH SUPERCONDUCTING TUNNEL JUNCTIONS ON THE SURFACE.

NOISE MEASUREMENTS ARE STILL TO BE MADE.

F. DETECTION OF ROTONS IN SUPERFLUID HELIUM

[LANOU ET AL, PHYS. REV. LETT. 58, 2498 (1987)]

A DETECTOR BASED ON LIQUID HELIUM WOULD BE OF THE HIGHEST PURITY. BUT BELOW 0.5°K THE SPECIFIC HEAT OF HELIUM IS $\sim 10^{5}$ THAT OF Si, SO TEMPERATURE CHANGES FROM KeV ENERGY DEPOSITION WOULD BE RELATIVELY SLIGHT.

IN SUPERFLUID HELIUM BELOW 0.1°K A LARGE FRACTION OF DEPOSITED ENERGY EXCITES ROTONS RATHER THAN PHONONS. A TYPICAL ROTON ENERGY IS $\sim 10^{-3}$ eV. THESE PROPAGATE BALLISTICALLY BUT HAVE REASONABLE PROBABILITY TO EVAPORATE A HELIUM ATOM WHEN THEY STRIKE THE LIQUID SURFACE.

THE HELIUM VAPOR COULD BE DETECTED WHEN IT STICKS TO Si BOLOMETERS SUSPENDED ABOVE THE LIQUID.

IT IS BELIEVED THAT AN ENERGY RESOLUTION OF 1-10 KeV COULD BE ACHIEVED, WITH TIME RESOLUTION OF $\sim 10\mu$SEC, AS DETERMINED BY THE ROTONS' VELOCITY. POSITION SENSITIVITY WOULD BE LIMITED BY THE GRANULARITY OF THE CELLS OF LIQUID HELIUM.

NO DEMONSTRATION OF THIS TECHNIQUE HAS YET BEEN MADE.

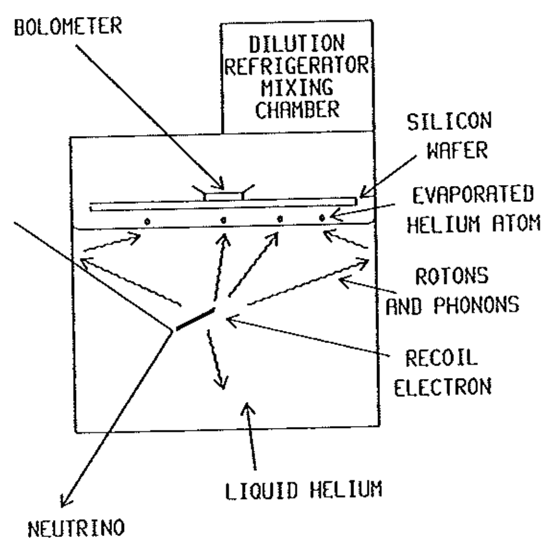


FIG. 1. Schematic design of the simplest version of the experiment. A neutrino is elastically scattered in liquid helium, and the recoil electron produces rotons and phonons. At the free surface of the liquid helium, the rotons induce evaporation of helium atoms, which are then captured by the silicon wafer. The rise in temperature of the silicon is measured by a bolometer.

Table I Cryogenic detector developments

	Institutions	Physics Interests
Phonon Detectors		
Mc Cammon, Moseley et al [3,4]	Wisconsin, Goddard	X Ray Astronomy
Silver et al [40]	Livermore, UC Berkeley LBL, UC Irvine	X Ray Astronomy
Coron et al [12]	"Bonus" Collab. Meudon, CERN, Aarhus, NYU	Ho (163), X Ray
Niinikoski [41]	CERN	Neutrino
Fiorini et al [14]	Milano	Double Beta
Smith et al [14]	Rutherford, Imperial Coll.	Dark Matter
Von Feilitzsch et al [31]	Munich: Technical University	Instrumentation, Neutrinos
Sadoulet et al [35]	LBL,UC Berkeley	Dark matter
Lanou, Seidel, Maris [42]	Brown University	Solar Neutrinos (rotons)
Cabrera et al [39]	Stanford, San Francisco State	Coherent neutrinos (Ballistic Phonons)

	Institutions	Physics Interests
Superconducting Granules		
Waysand et al [17]	Paris VII/College de France	Imaging/ Solar neutrinos
Gonzales et al [21]	Annecy	Solar neutrinos, Dark Matter
Von Feilitzsch et al [31]	Munich: Technical University	Instrumentation, Neutrinos
Pretzl, Stodolsky [22]	Munich: Max Planck Institute	Coherent neutrino scattering
Drukier et al [23]	U. British Columbia U. South Carolina	Dark matter, Double Beta
Superconducting films		
Cabrera et al [25]	Stanford, San Francisco State	Instrumentation
Tunnel Junctions		
Von Feilitzsch et al [31]	Munich: Technical University	Instrumentation, Neutrinos
Zehnder [30]	SIN	Neutrino, Instrumentation
Twerenbold	ESA	X ray Astronomy
Barone,Gray [29]	Napoli,Argonne	Instrumentation
Booth [16]	Oxford	Solar neutrinos
Bland	San Francisco State	Solar neutrinos

THE VARIOUS DETECTION SCHEMES CONSIDERED HERE MIGHT SEARCH FOR ELEMENTARY PARTICLES WITH MASSES IN THE LOWER 40 - OF THE 80-ORDER-OF-MAGNITUDE WINDOW FOR DARK MATTER. OBJECTS WITH MASSES IN THE UPPER 40 WOULD BE CLUMPS OF BARYONS, AND ARE OUT OF FASHION IN 1988. BUT IT'S STILL WORTH CONSIDERING THE QUESTION OF 200 YEARS AGO WHICH BEGAN ASTROPARTICLE PHYSICS:

COULD IT REALLY BE METEORS AFTER ALL?

WHAT IS THE CURE FOR INO-ITIS?

— J.A. WHEELER