40 MCi Tritium Source for Experiments with Low Energy Neutrinos

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Neutrinos in Cosmology, in Astro-, Particle- and Nuclear Physics,

16-24 September 2009, Erice, Sicily

"Neutrinos, they are very small.
They have no charge and have no mass.
And do not interact at all..."

John Updike,

American writer, non-physisist

"In some sense, tritium in nuclear and weak interaction physics is analogous to the drosofila fly in genetic studies"

V.M. Lobashev,
Russian physisist,
Leader of Troitsk neutrino mass experiment

Why?

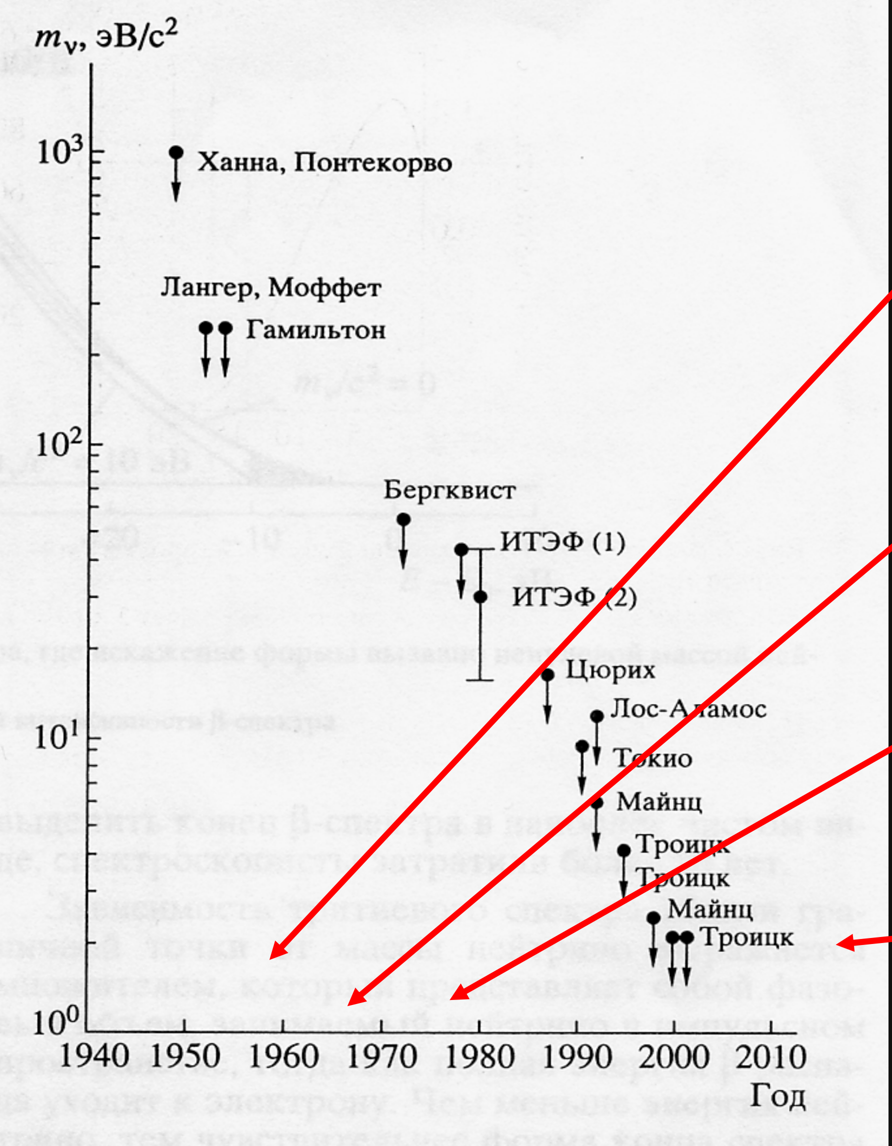
Triton is the lightest radioactive nucleus

β-decay: $T \rightarrow {}^{3}He + e^{-} + \tilde{\nu}_e + 18.6$ keV

The first estimation of the neutrino mass was done in 30-s, when a heavy hydrogen isotope – tritium – was discovered with a small decay energy. The fact of the existence of this allowed transition pointed at the extreme smallness of the neutrino mass:

$$m_\nu < 10 \text{ keV} < 0.02\, m_e$$

Search of the Neutrino Mass in the Tritium β-Decay



Chronology

Theory of two-component neutrino (1958) - $m_\nu = 0$

Hypothesis of neutrino oscillations (1960-s) - $m_\nu \neq 0$

Hypothesis of grand unification of all interactions (1972) $m_\nu \neq 0$

$m_\nu < 2.2$ eV/c^2

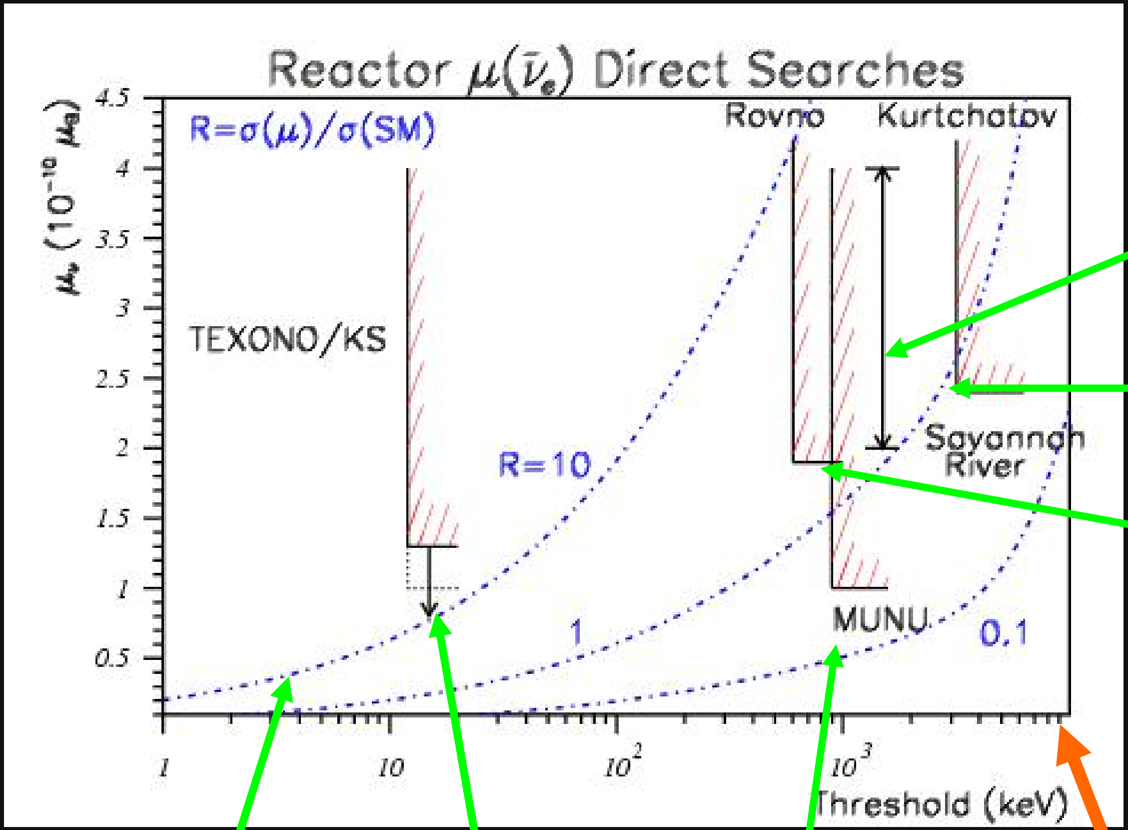
All experiments study the electron spectrum shape

Neutrino Magnetic Moment

theory

Standard Model	$\mu_\nu \cong 3(m_\nu/1\mathrm{eV})\,10^{-19}\,\mu_B$
Dirac neutrino	$\mu_\nu < 10^{-14}\,\mu_B$
Majorana neutrino MM (some MSM extentions)	$\mu_\nu \sim 10^{-(10\div12)}\,\mu_B$
Astrophysics & Cosmology (model dependent limit)	$\mu_\nu \le (1\div3)\times10^{-12}\,\mu_B$
Experimental laboratory limit (reactor experiment 2009)	$\mu_\nu \le 3.2\times10^{-11}\,\mu_B$ **90%CL**
A 40 MCi tritium source experiment	$\mu_\nu \le \underline{2.5\times10^{-12}}\,\mu_B$

Neutrino Magnetic Moment Measurement



1976
Reines, et al.

1992

1993

June 2009,
GEMMA

2007,
TEXONO

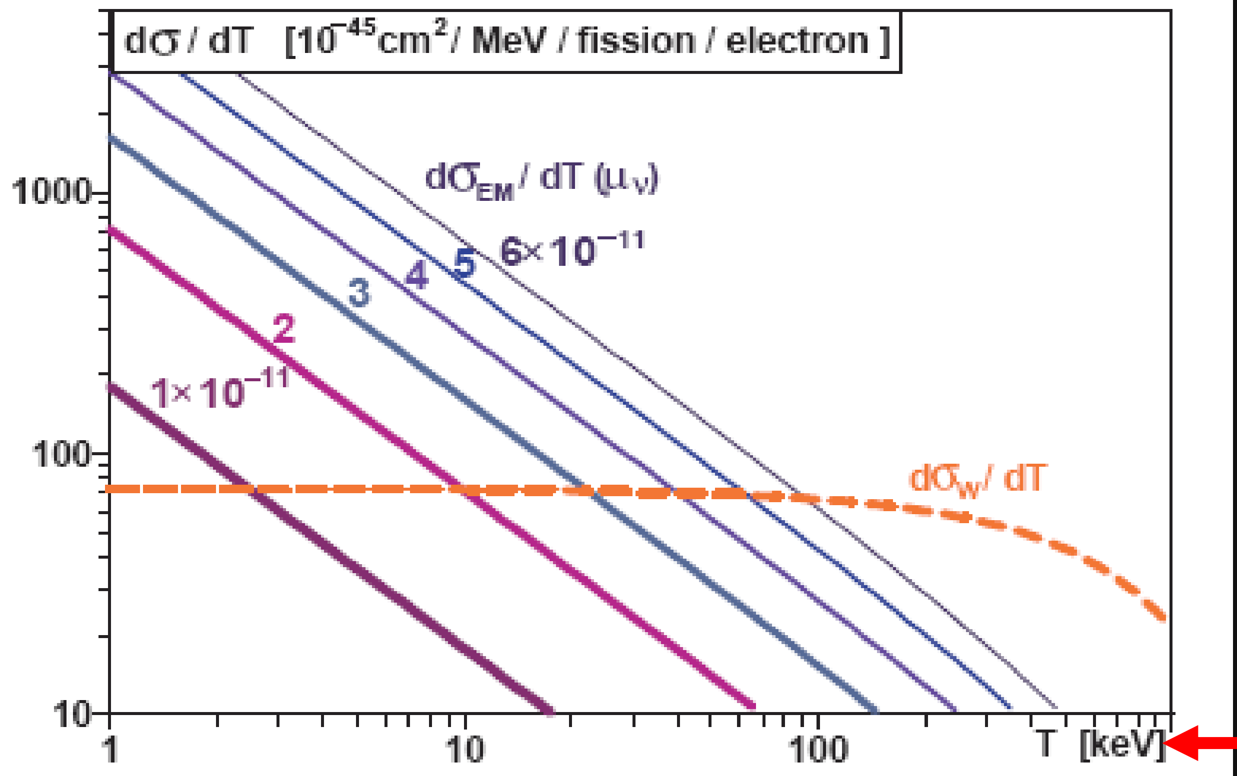
2002

Antineutrino flux
$F \approx (1 \div 5) \cdot 10^{13} cm^{-2} \cdot s^{-1}$

Detector threshold
(10÷3000) keV

Differential Cross Section of the ν-e Scattering for Reactor Antineutrino

$$\frac{d\sigma_{EM}}{dT} = \left(\frac{\mu_\nu}{\mu_B}\right)^2 \frac{\pi\alpha^2}{m_e^{\,2}} \left(\frac{1}{T_e} - \frac{1}{E_\nu}\right)$$



$\mu_\nu = 6\times10^{-11}\,\mu_B$
(2007)

$\mu_\nu = 3\times10^{-11}\,\mu_B$
(2009, GEMMA)

$\mu_\nu = 1\times10^{-11}\,\mu_B$
(planned)

T is the electron recoil energy

Beginning of the Story

In 1978 B. Neganov & V. Trofimov from JINR (Dubna) considered “Possibility of producing a bulky supersensitive thermal detector at a temperature close to absolute zero”

ОБЪЕДИНЕННЫЙ
ИНСТИТУТ
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ
ДУБНА

Р8 - 11681

Б.С.Неганов, В.Н.Трофимов

О ВОЗМОЖНОСТИ СОЗДАНИЯ
МАССИВНОГО СВЕРХЧУВСТВИТЕЛЬНОГО
ТЕПЛОВОГО ДЕТЕКТОРА
ПРИ ТЕМПЕРАТУРЕ,
БЛИЗКОЙ К АБСОЛЮТНОМУ НУЛЮ

1978

JETP Letters 28, 328 (1978)

Photo of the first ^{3}He-^{4}He dilution refrigerator T~70mK (B. Neganov, 1966)

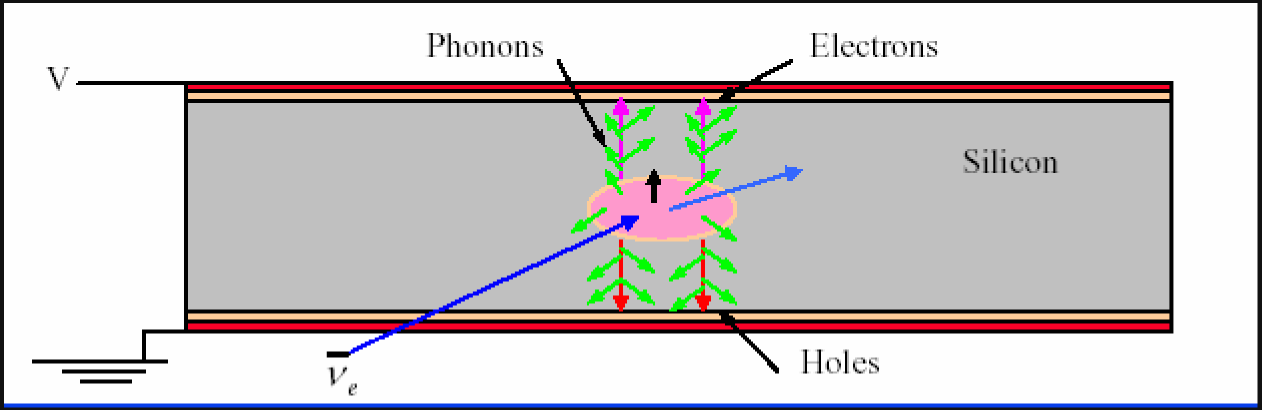
B.Neganov (center) with R.Gaitskell and D.Akerib from CDMS collaboration (JINR, 2001)

Ionization-into-Heat Conversion
(Neganov-Trofimov-Luke effect).

◆ **Drift primary ionization in high electric field**

◆ **Measure resulting heat**

Ideal gain for Silicon is $G_{th} = 1 + V_{applied}/3.8$ Volts



Allows obtaining few keV heat release per one charge carrier in cooled semiconductor under irradiation - demonstrated by N&T at Dubna (1981) and P.Luke at LBL (1988)

Single particle detection in a bulky detector

"We, experimentalists, are not like theorists: the originality of an idea is not for being printed in a paper, but for being shown in the implementation of an original experiment"

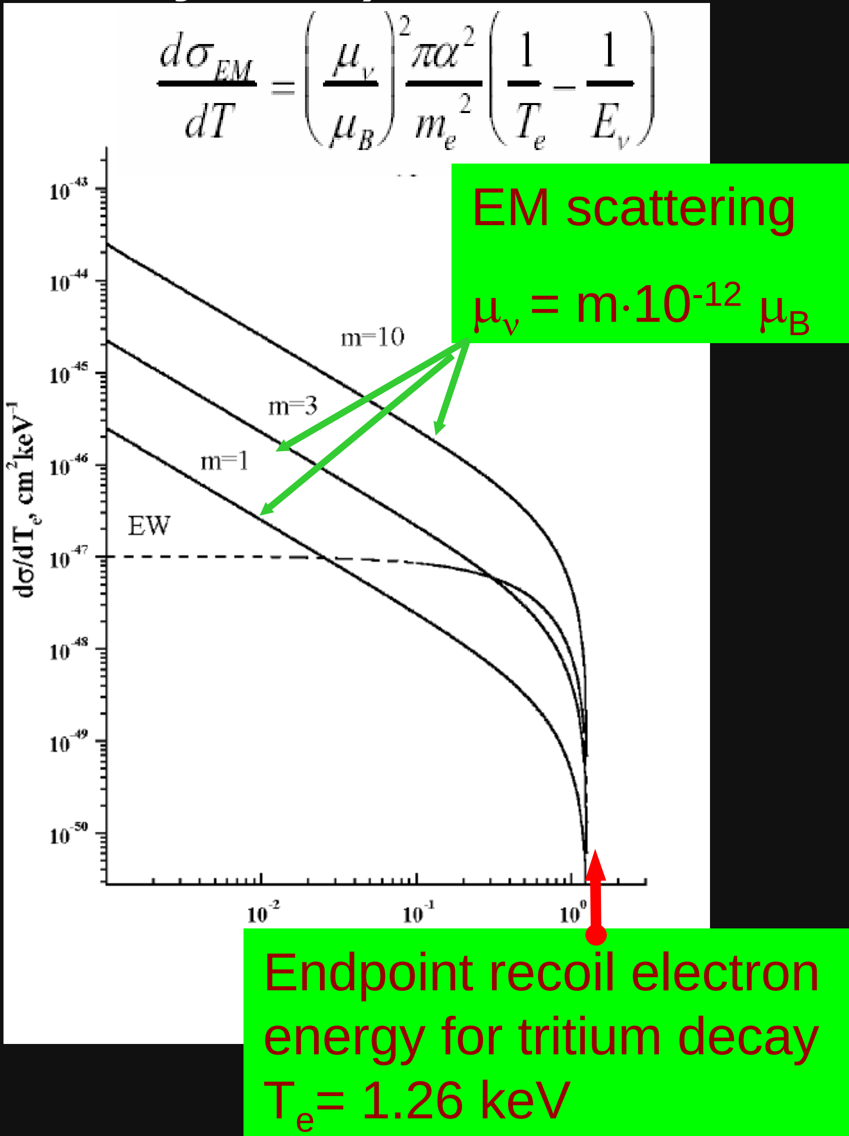
Patrick M.S.Blackett
(see at the entrance)

Proposal on Cryogenic Detection of the Neutrino Magnetic Moment with a Strong Tritium Source 1993 (J. of Low Temperature Physics)

Why Tritium?

- Low decay energy
- High radioactive purity
- Long enough life-time (12.5 years)

- Low radiation background
- No passive shielding – closer to detector - bigger ν flux
- Enough time for data taking (~1 year)



$$\frac{d\sigma_{EM}}{dT} = \left(\frac{\mu_\nu}{\mu_B}\right)^2 \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T_e} - \frac{1}{E_\nu}\right)$$

EM scattering

$\mu_\nu = m \cdot 10^{-12}\ \mu_B$

Endpoint recoil electron energy for tritium decay $T_e = 1.26$ keV

How "strong"?

ν Flux should exceed that from a power reactor by an order

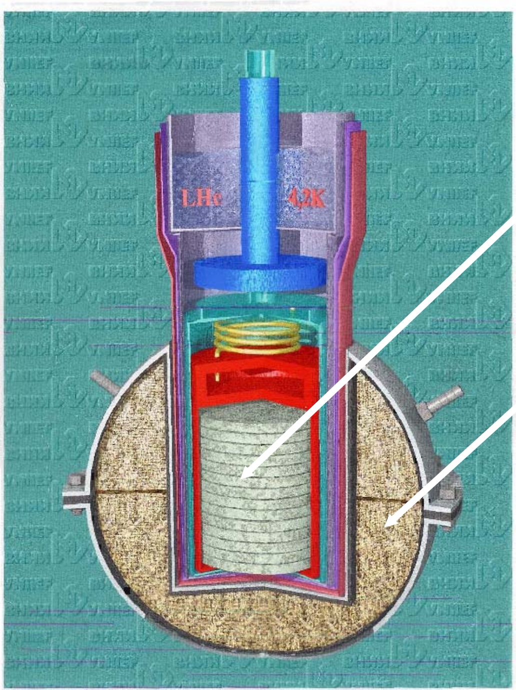
40 MCi (4 kg of ^{3}H)

Is it possible?

Problems to solve:

- Safety
- Long term stability
- Compactness

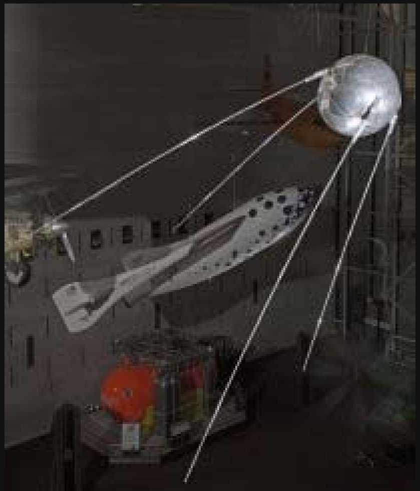
Original Design 1998



Cryodetectors

Tritium source

Rds-1

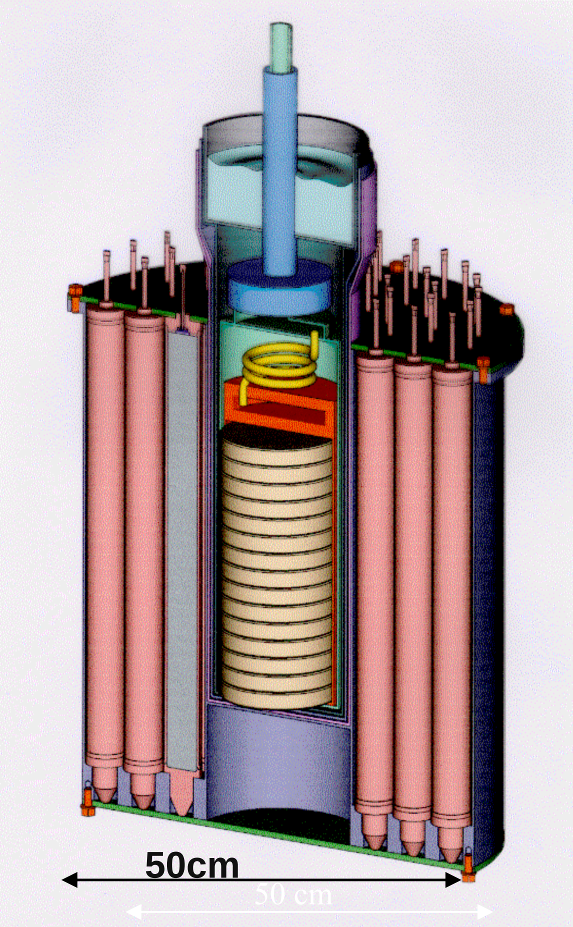


Sputnik 1
1957

Metals and Alloys for Hydrogen Isotope Storage

Materials	$P_{dec.}$, mm Hg at 25°C.	Decomposition temperature, °C	Sorption capacity H_2, cm^3/g	Density in H_2, cm^3/cm^3 (hydride)	Density, g/cm^3	
					metal	Hydride
U	10^{-6}-10^{-4}	420-430	~141	~1570	18.7	11.9
Ti	~10^{-9}	550-620	~468	~1760	4.5	3.7-3.9
Mg_2Ni	~10^{-2}	~240	~418	~1074		
ZrCo	~10^{-5}	340-350	~186	~1415		
$LaNi_3Mn_2$	~10^{-2}	270	~127			
$LaNi_{5-x}Al_x$ (x=1-1.3)	~10^{-1}-10	180-250	80-100	550-690		
$Zr_{1-x}Ti_xCo_{0.5}Ni_{0.5}$ (x=0.1-0.2)	10^{-2}-10^{-1}	200-300	160-180	1050-1180		
Pd	30-50	~150	~105	~800	11.9	
H liquid		-253		780		
T liquid		-251		1000		

Search for the Neutrino Magnetic Moment



Conceptual layout of the ν-e scattering experiment with 40 MCi tritium source

$\tilde{\nu}_e$ - e scattering

$\tilde{\nu}_e$ TRITIUM SOURCE of 40 MCi activity (4 kg of ^{3}H) with a flux density of 6×10^{14} cm^{-2}s^{-1}

ULTRA-LOW-THRESHOLD DETECTORS E_{th}~10 eV:

SILICON CRYODETECTOR @T=10mK,

15×100cm^3, M=3kg,

ionization-into-heat conversion effect

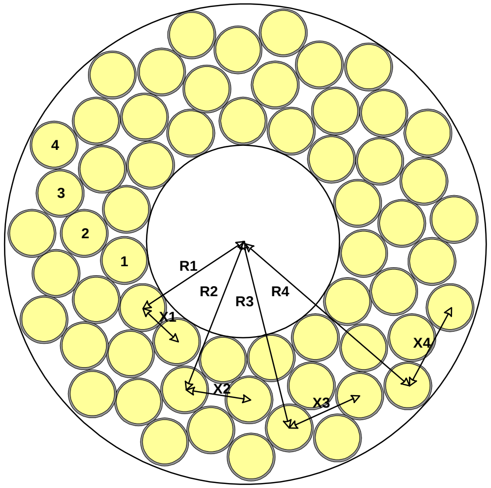
HIGH-PURITY-GERMANIUM DETECTOR

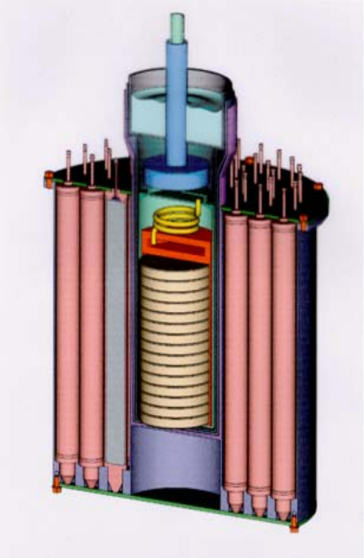
6×150cm3, M=4.8kg,

internal proportional signal amplification by avalanche multiplication in the electric field

SENSITIVITY (95% C.L.): $\mu_\nu \leq 2.5 \times 10^{-12} \mu_B$

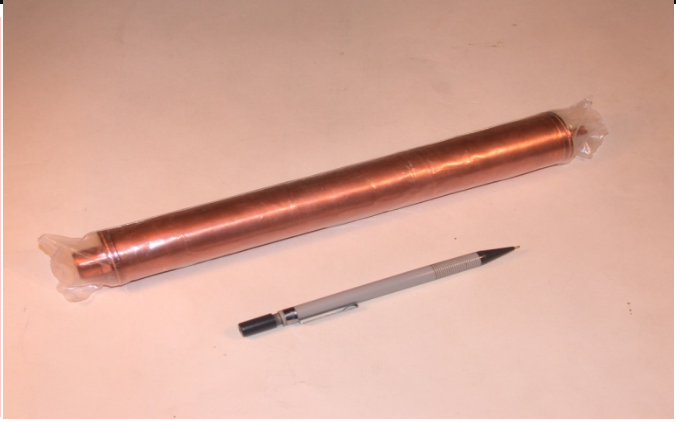
Neutrino Flux Inside the Source

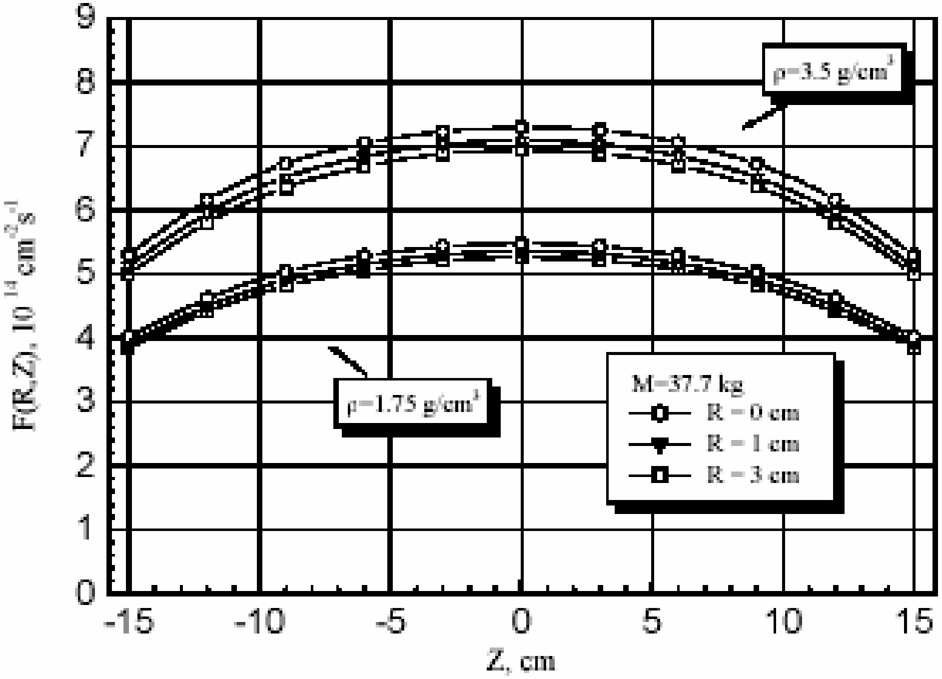




A cylinder-shaped source made of annular cells packed together and filled with titanium tritide

½ model

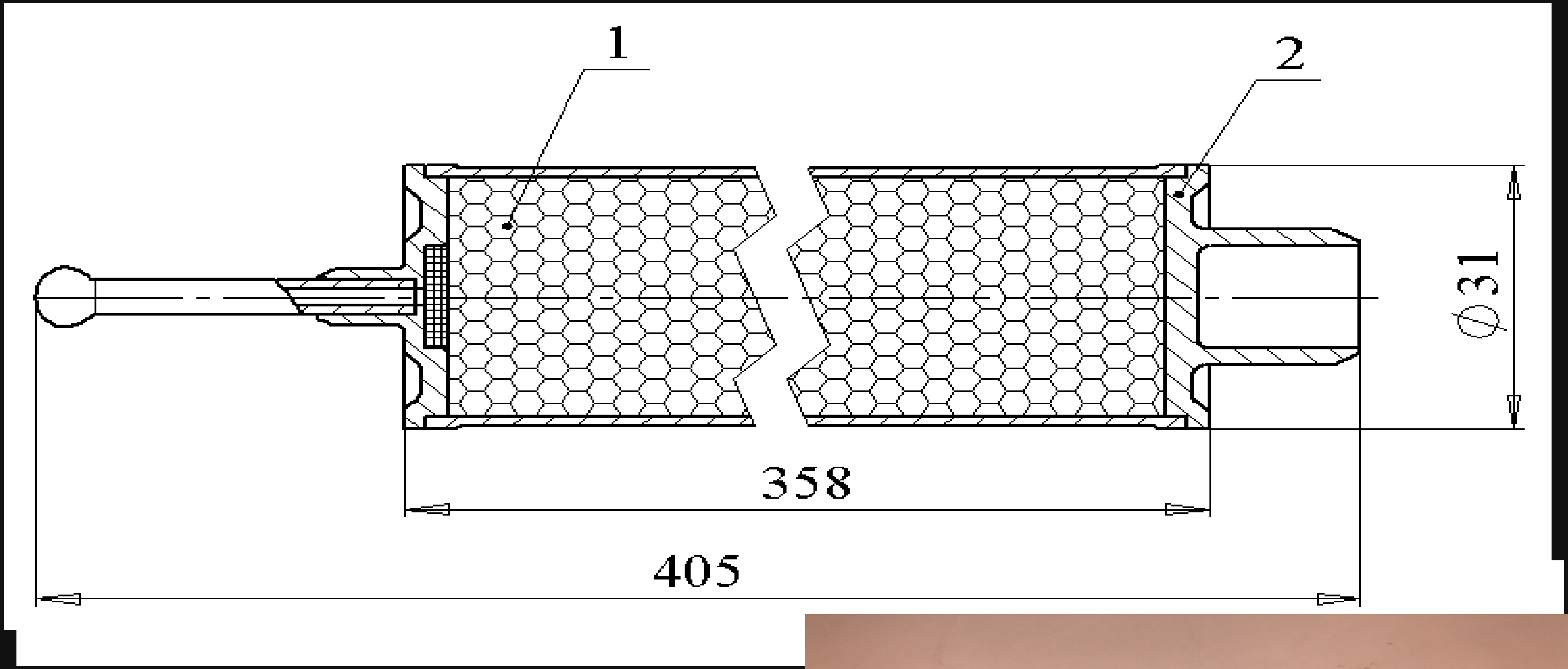


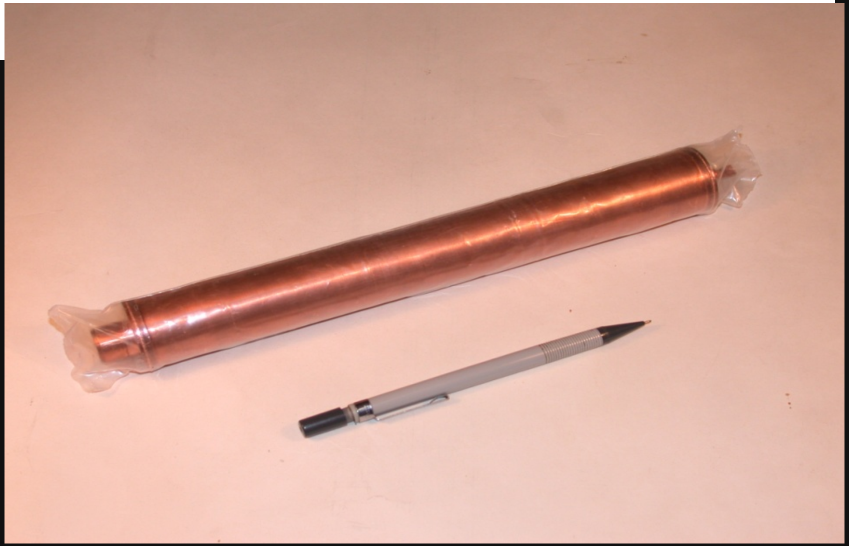


Neutrino flux density

$F \approx 6{\cdot}10^{14}\mathrm{cm}^{-2}\cdot \mathrm{s}^{-1}$ along the detector Z-axis for the multi-cylinder source design

Construction of the Tritium Cell





1 – titanium tritide

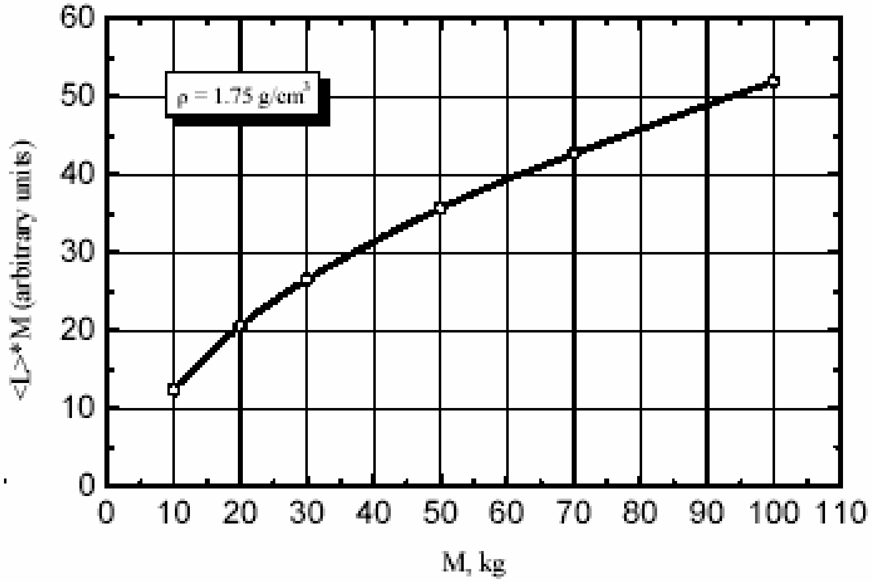
2 – copper body of the cell

How Much Tritium Can We Efficiently Add to?

Number of neutrino interactions can be increased by adding tritium mass. Source will get bigger, efficiency will be reduced.

efficiency

$$< L >= \frac{\sum_{i=1}^{N_{Det}} L_i}{N_{Source}}$$



Number of neutrino interactions with detector electrons versus TiT_2 mass.

- At tritium mass of 4 kg activity is $A=1.43\cdot10^{18}$ neutrino/s
- TiT_2 mass is 37.7 kg
- Maximum possible density of TiT_2 is $\rho_0=3.5 kg/cm^3$
- Applicable value of the working density depends on the duration of an experiment and is limited by the allowed deformation of the cell.

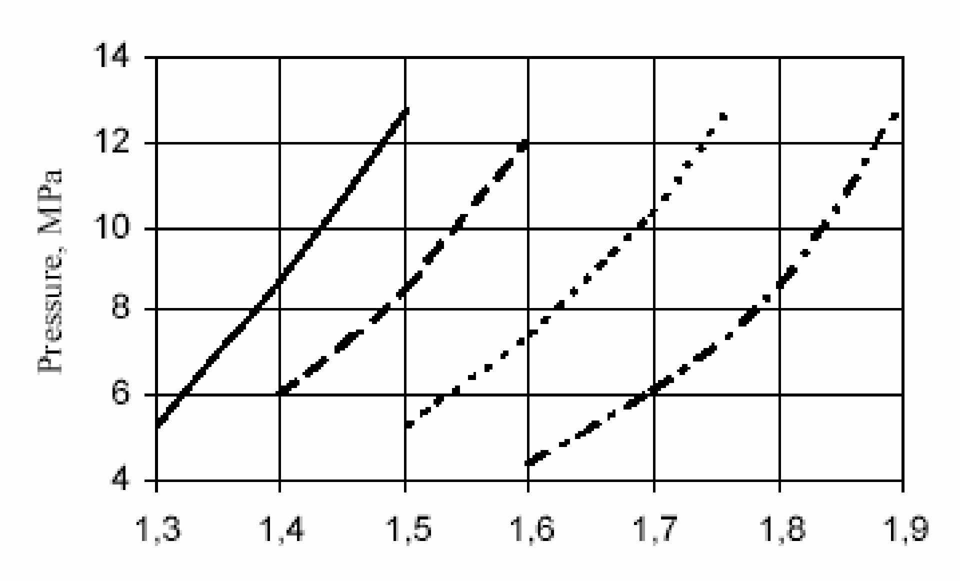
How Dense Titanium Tritide Can Be Packed?

The working substance TiT_2 swells inside the cell due to a deformation of pore structure and due to a storage of radiogenic helium.

At equal “swelling” of TiT_2 due to storage of radiogenic helium, the pressure from the titanium tritide will become smaller with increase of hydrogen content.

Maximum allowed pressure at the end of the exposure is

12 MPa – this enables safe dismounting of the cells (follows from the cell strength test and calculations).



Time dependency of the pressure in the cell versus the initial density (g/ccm) of titanium tritide:
solid – 4 years, dashed - 3 years,
dotted - 2 years, dash-dotted - 1 year.

From the final design report

A cylinder-shaped multipart source construction seems to be most attractive technologically.

As the source design, a configuration of annular cells filled with TiT_2 that are stacked into a hollow cylinder is chosen.

Detector array will be mounted in the hole inside.

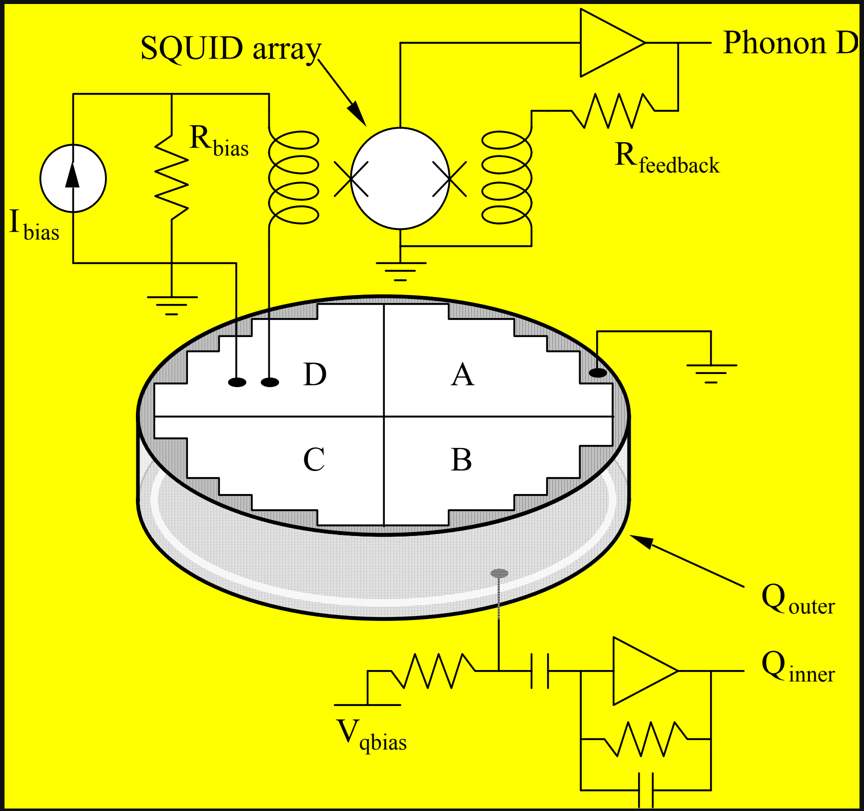
A multipart construction facilitates heat removal from and access to individual cells.

This design makes possible dealing with and transporting cells separately.

Special conditions are needed only when assembling the source of 40MCi activity to provide its safe operation.

Level of radiation purity of selected construction materials: Ti for T storage, electrolytic copper for cell body, satisfies the requirements of the physical experiment.

CDMS ‘ZIP’ Ionization & Phonon Detectors



Fast athermal phonon technology

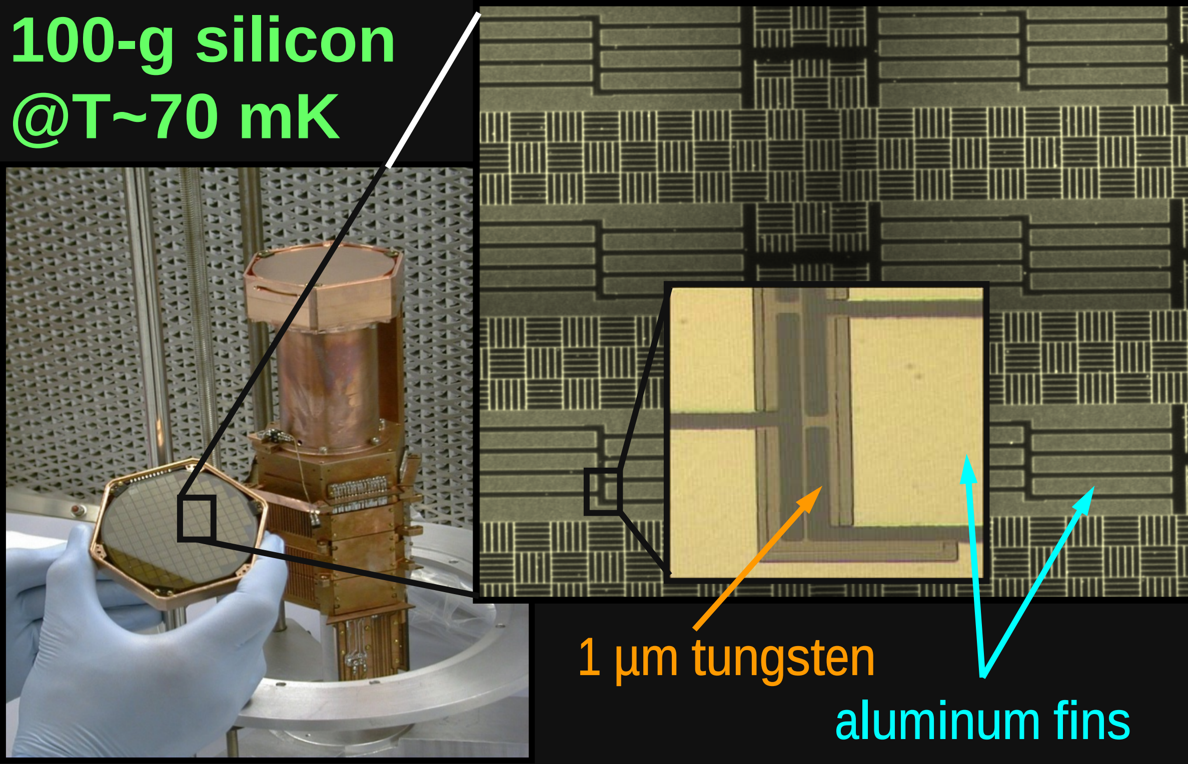
- Superconducting thin films of W, Al
- Stable Electrothermal Feedback
- Aluminum Quasiparticle Traps give area coverage

- Tests conducted in CWRU detector test facility
- S4 detector unsuited for CDMS
  - Only one working phonon channel
  - Poor energy resolution
- Sufficient resolution to see features in ^{241}Am energy spectrum
  - Spot illumination on single working quadrant
- Measure collected phonon energy versus V_{qbias}
- Observe heat amplification

Low-Threshold Cryogenic Detectors

- First detector results are promising
  - ◆Heat amplification observed to 200 Volts
  - ◆Estimated intrinsic threshold is ~30 eV
- CDMS-style detectors already useful prototype as the basis for a neutrino magnetic moment search
  - ◆Minimal manipulation of a maturing technology

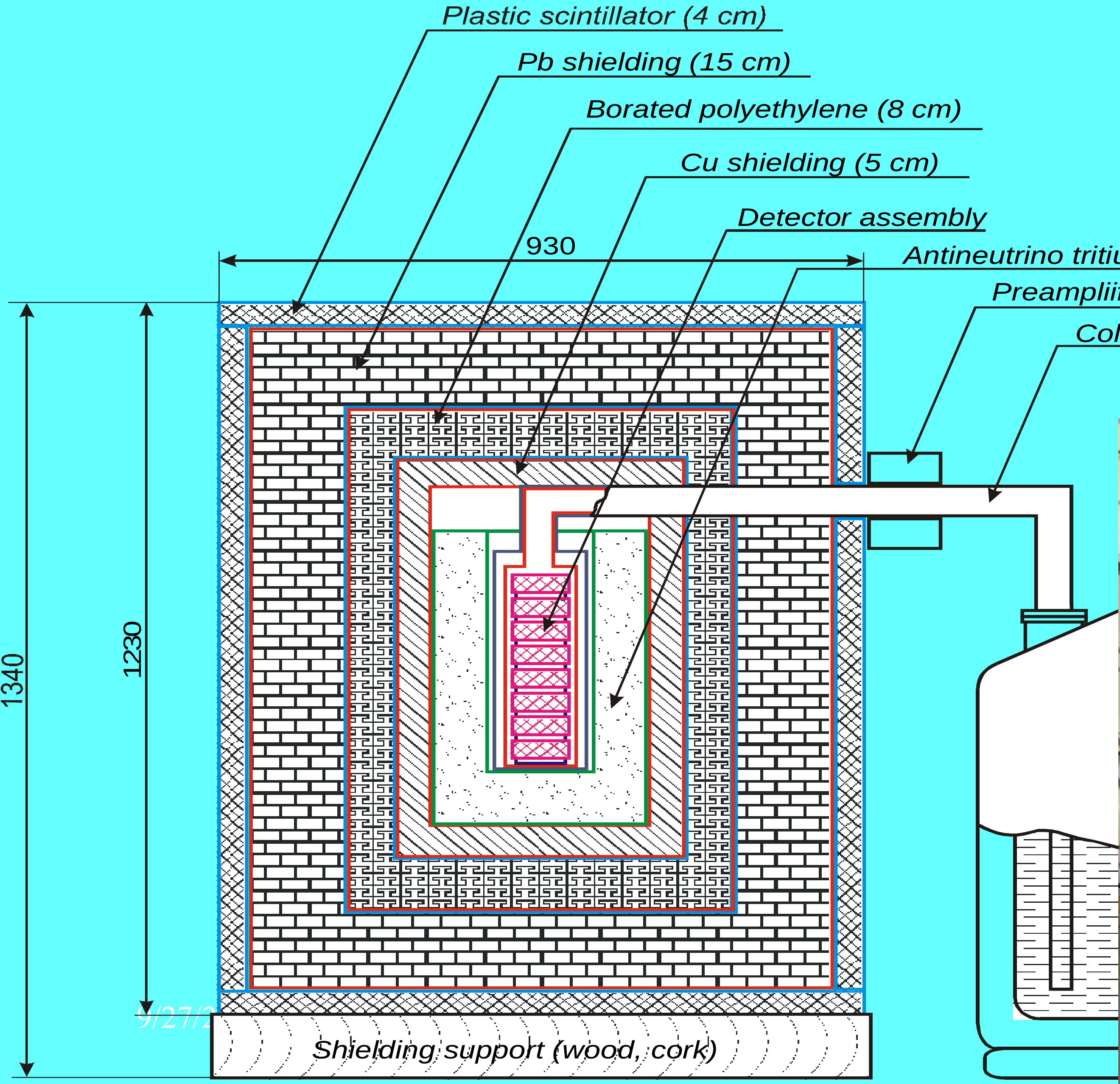
100-g silicon @T~70 mK



Superconducting thin films of W, Al, Al

200-day tritium exposure x 3 kg at 30 eV threshold improve sensitivity to 3×10^{-12} μ_B or 10x current reactor-based limits

Principal Scheme of the Installation



Plastic scintillator (4 cm)

Pb shielding (15 cm)

Borated polyethylene (8 cm)

Cu shielding (5 cm)

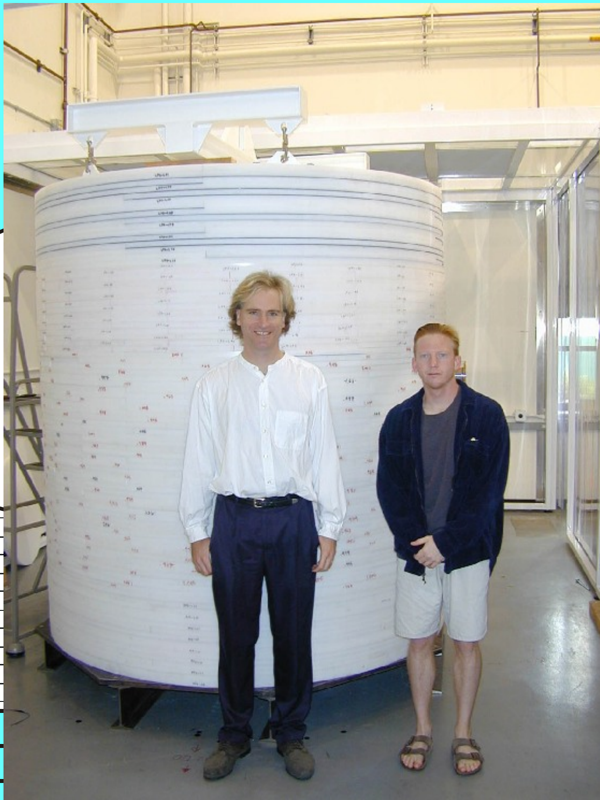
Detector assembly

Antineutrino tritium source (∅30 x h50 cm)

Preampliifiers, sensors

Cold finger

Shielding support (wood, cork)



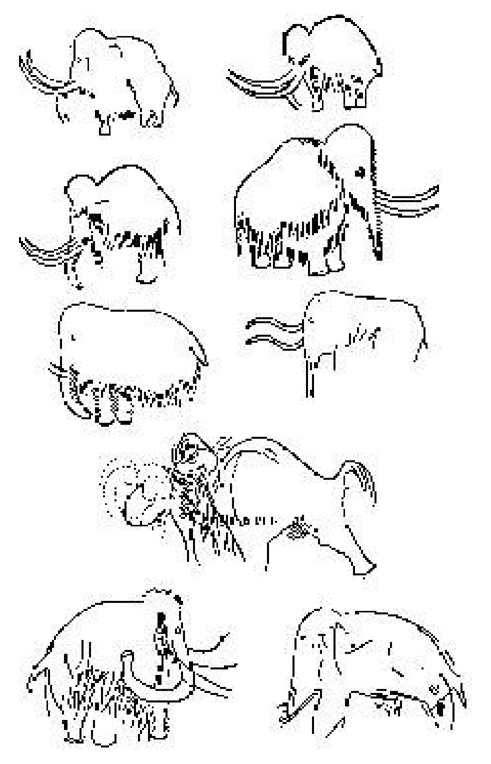
Sensitivity to the Neutrino Magnetic Moment

Energy interval, eV		**10 – 1260**	**10 – 200**
Magnetic scattering, $N_{M,}$ events/day	μ_ν~**1·10^{-11}**μ_B	**2.4**	**1.4**
	μ_ν~**3·10^{-12}**μ_B	**0.22**	**0.13**
Weak scattering, N_W, events/day		**0.15**	**0.04**
Background, N_B, (at the level 0.1 events/keV kg day)		**~0.5**	**~0.1**
Sensitivity to the magnetic moment at 95% C.L. "ON"/"OFF"-200/200 days		$\mu_\nu \leq 2.5 \cdot 10^{-12} \mu_B$	$\mu_\nu \leq 2.2 \cdot 10^{-12} \mu_B$

MAMONT*) collaboration

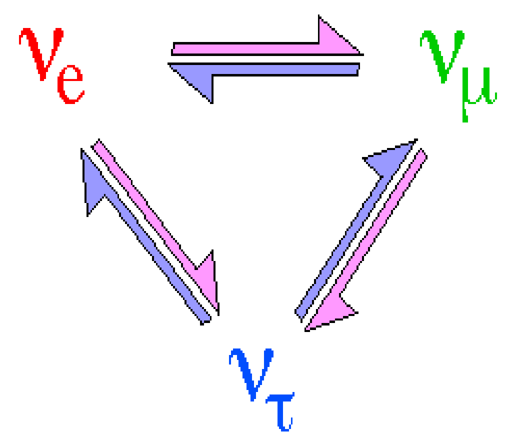
MAgnetic MOment Neutrino Tritium

- Brown University (Providence)
- Case Western Reserve University (Cleveland)
- Institute for Theoretical & Experimental Physics (Moscow)
- Institut fur Kernphysik (Julich)
- Joint Institute of Nuclear Research (Dubna)
- NIIMV (Zelenograd)
- Russian Federal Nuclear Center VNIIEF (Sarov)
- Stanford University (Stanford)



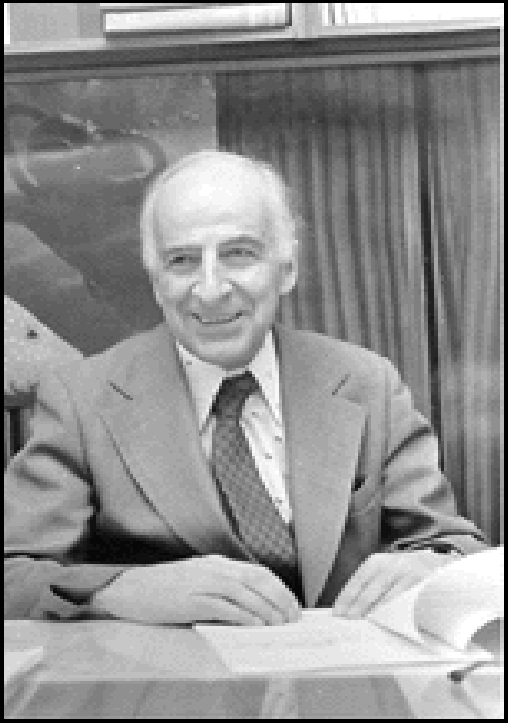
*)MAMONT (RUS) = MAMMOTH (ENG)

Neutrino Oscillations



Neutrino oscillations were predicted by Bruno Pontecorvo in 1957.

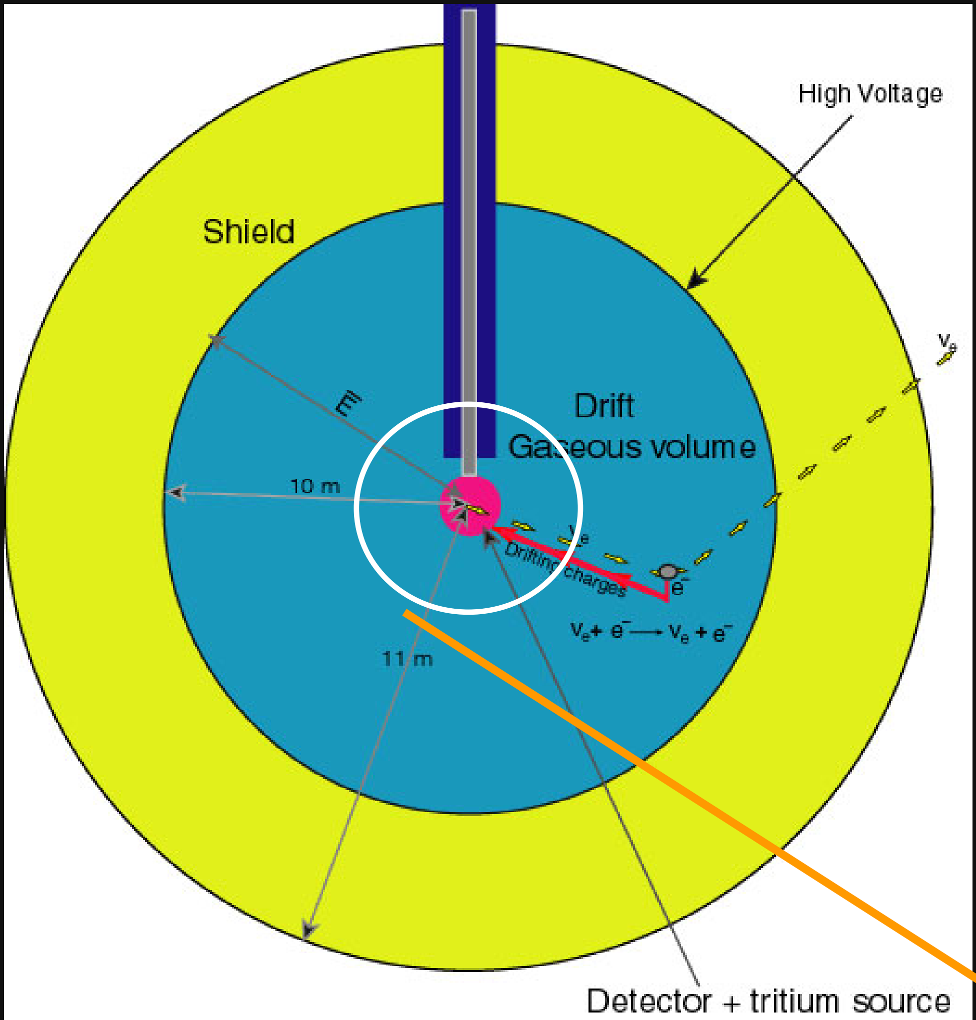
He discussed a possible solar neutrino deficit as a consequence of these oscillations.



Probability of oscillations between two neutrino flavors

$$P(\nu_1 \leftrightarrow \nu_2) = \sin^3 2\theta . \sin^2\left(\frac{\Delta m^2 . L}{4E}\right)$$

Neutrino Properties Studied With a Triton Source Using Large TPC Detectors



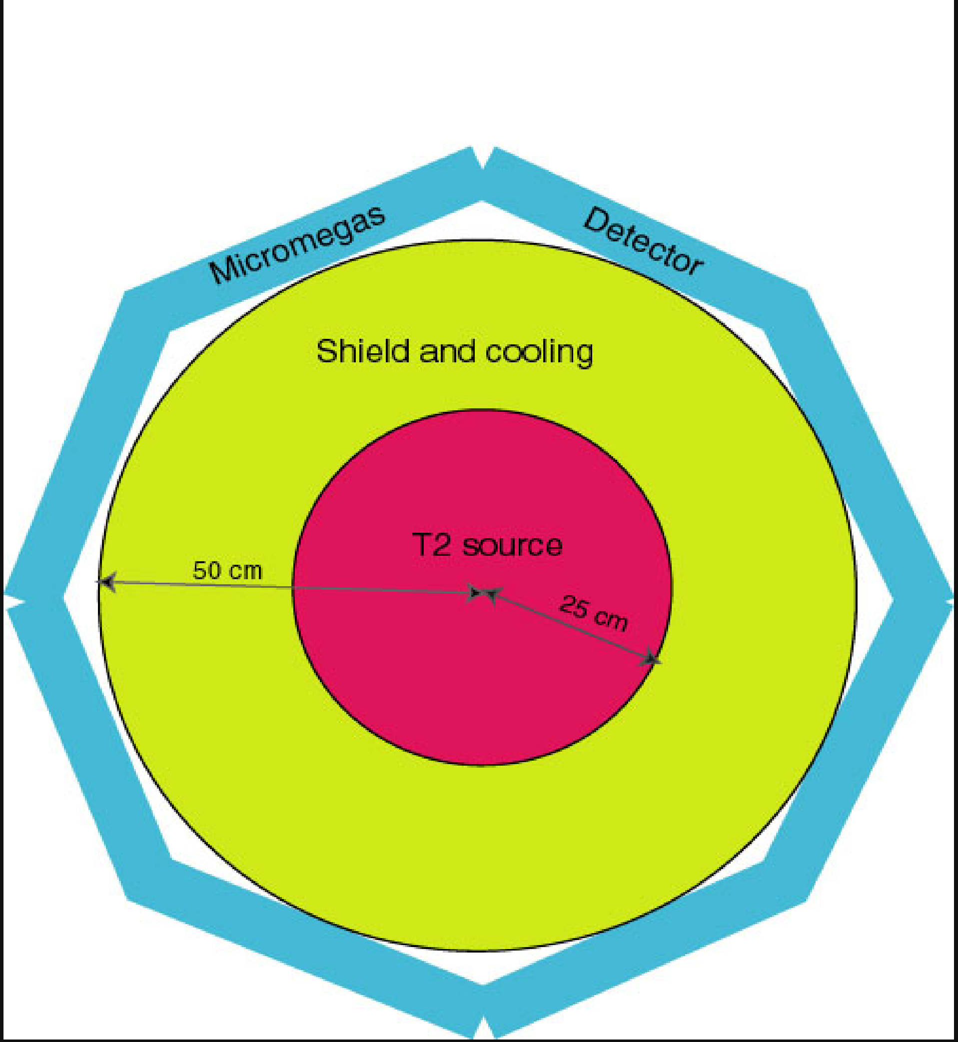
Proposal from CEA, Saclay, DAPNA, Gif-sur-Yvette, Cedex, France

Time Projection Chamber -large volume gaseous spherical vessel of 10-m radius that contains about 20 tons of gas (Xe).

Principal features of the proposed TPC - drift voltage of about ~100 kV

Next view (triton source)

A Schematic View of the Inner Part of the Vessel with the Detector and the Tritium Source



The 200 MCurie tritium source container is a sphere of ~25-cm radius.
The container of the source should fulfill the safety requirements and provide a flexible moving system for source on-off measurements.

“A unique sensitivity for the neutrino magnetic moment which is about two orders of magnitude beyond the current experimental limit”

Instead of Conclusion

1) 4 kg of tritium – not too big amount

How much tritium is needed for a thermonuclear reactor?

$$\mathbf{d + t \rightarrow {}^{4}He + n + 17.6\ MeV}$$

Constants: $\hbar = 1.054 \cdot 10^{-34}$ J·s = $6.582 \cdot 10^{-22}$ MeV·s,

1 J = $6.245 \cdot 10^{12}$ MeV, 1 year = $3.15 \cdot 10^{7}$s

1 GW of thermal energy during a year requires

10^{9} J/s $\cdot 3.15 \cdot 10^{7}$ s = $3.15 \cdot 10^{16}$J =

=$19.7 \cdot 10^{28}$ MeV / (17.6 MeV/fusion) = $1.12 \cdot 10^{28}$ fusions

1 g of ${}^{3}H$ produces →$6.023 \cdot 10^{23}$ fusions/3 ~ $2 \cdot 10^{23}$ fusions

1 GW(thermal) requires $0.56 \cdot 10^{5}$ g = 56 kg of T per year

~1 kg/week!

2) Strong Physical Motivation

Boris Kayser
Neutrino 2008
May 28, 2008

New Physics can produce larger dipole moments than the $\sim 10^{-20}\mu_B$ SM ones.

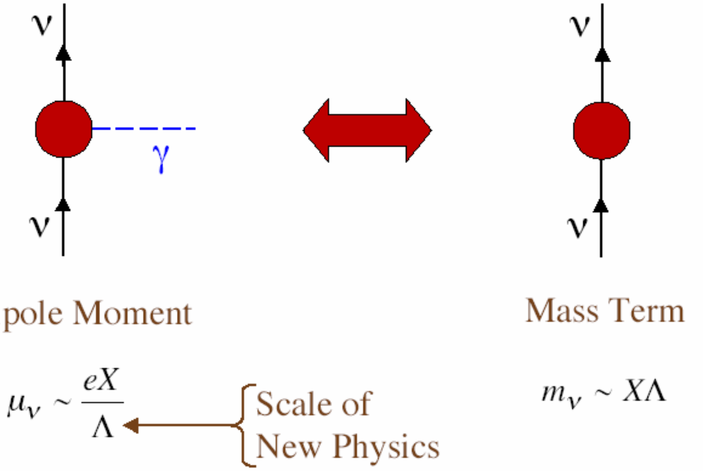
In the *Majorana* case, a *symmetry* suppresses the contribution of the dipole moment to the neutrino mass. So a bigger dipole moment is permissible. One finds —

For *Dirac* neutrinos, $\mu < 10^{-15}\,\mu_B$ for $\Lambda > 1$ TeV

For *Majorana* neutrinos, $\mu <$ *Present Bound*

An observed μ below the present bound but well above $10^{-15}\,\mu_B$ would imply that neutrinos are Majorana particles.

A dipole moment that large requires L-violating new physics $\lesssim$ 1000 TeV.



Dipole Moment

Mass Term

$\mu_\nu \sim \dfrac{eX}{\Lambda}$

Scale of New Physics

$m_\nu \sim X\Lambda$

R&D on 40 MCi Tritium Source

A.A. Yukhimchuk, Yu.I. Vinogradov,
A.N. Golubkov, S.K. Grishechkin,
R.I. Il’kaev, A.V. Kuryakin, B.L. Lebedev,
V.N. Lobanov, V.N. Mikhailov, D.P. Tumkin
Russian Federal Nuclear Center - VNIIEF,
Sarov