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Der doppelte Betazerfall: Experimente und Matrix-Elemente

DESY Zeuthen, 25.Feb.2010

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How to explain everything about double beta decay in 20 mins

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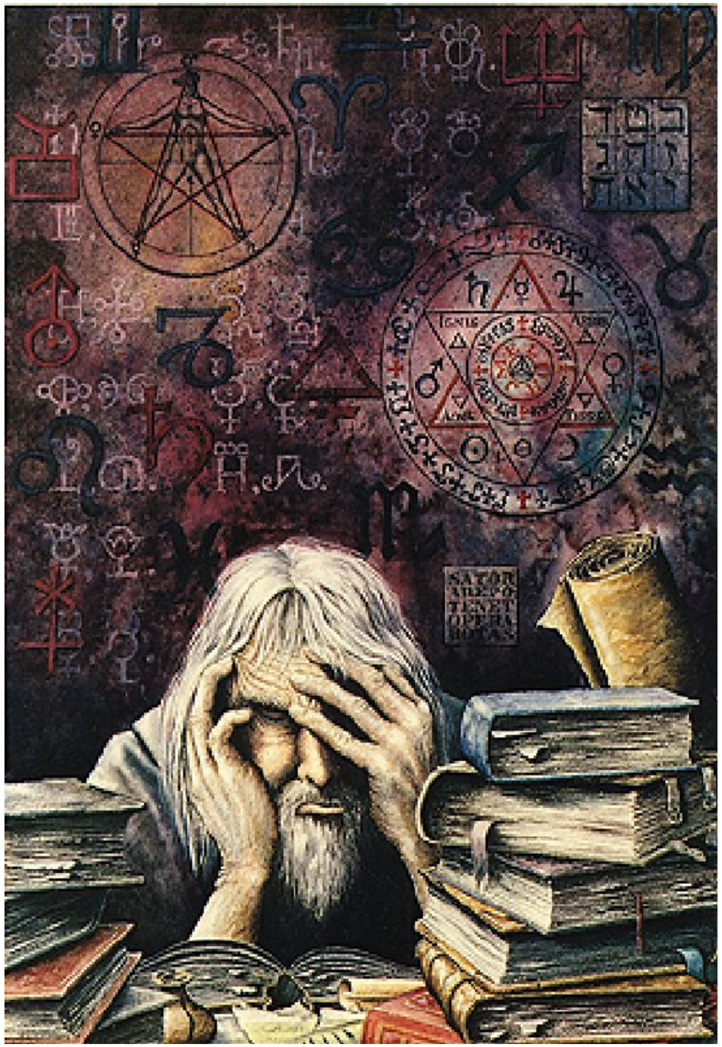

- Introduction
- General discussion on experimental issues
- COBRA
- SNO+
- Nuclear matrix element calculations – how experiments can help
- Conclusions and Outlook

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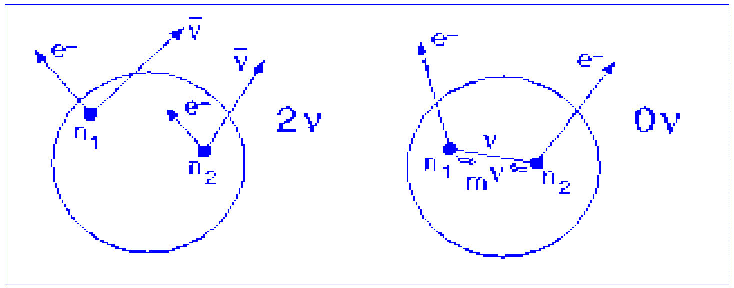
Double beta decay – Basics I

- $(A,Z) \rightarrow (A,Z+2) + 2\,e^- + 2\bar{\nu}_e$ — $2\nu\beta\beta$
- $(A,Z) \rightarrow (A,Z+2) + 2\,e^-$ — $0\nu\beta\beta$



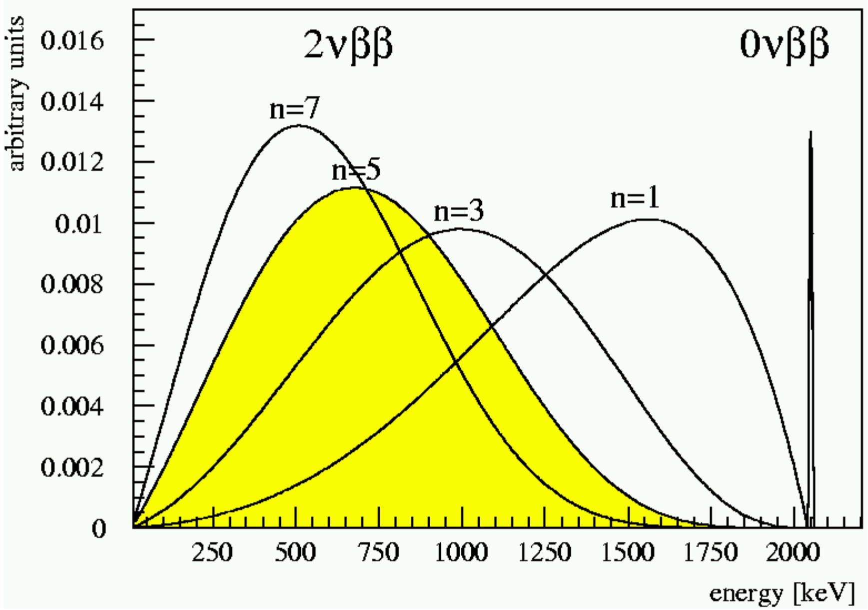
Unique process to measure character of neutrino

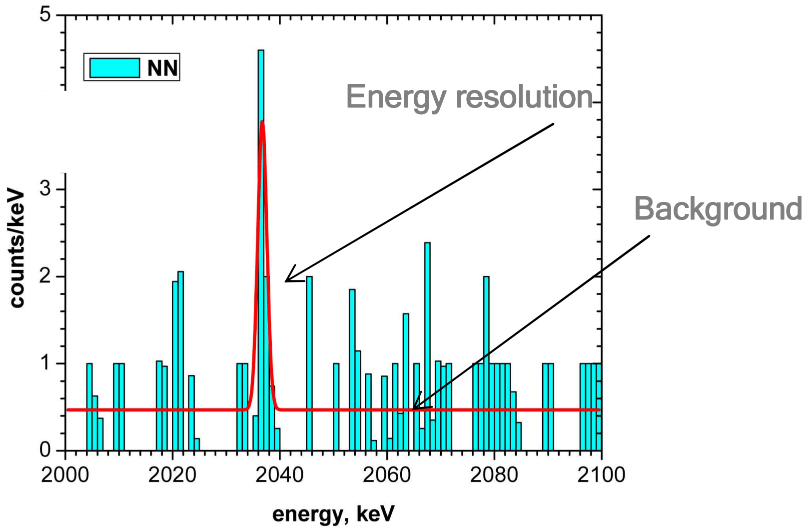
The smaller the neutrino mass the longer the half-life

Neutrino mass measurement via half-life measurement

Requires half-life measurements well beyond 10^{20} yrs!!!!

There are only 35 potential nuclides





Sum energy spectrum of both electrons

Signal: Peak at the Q-value of the nuclear transition
Measured observable: Half-life

Double beta decay – Basic equations

Observable is a half-life (limit), depending on the number of observed (excluded) events in the peak region

$$N_{\beta\beta} = N_0 e^{-\ln 2 t / T_{1/2}}$$

Experimental sensitivity depends on

$$T_{1/2}^{-1} \propto a\varepsilon \sqrt{\frac{Mt}{\Delta E B}}$$ (BG limited)

$$T_{1/2}^{-1} \propto a\varepsilon M t$$ (BG free)

Half- life can be converted into effective Majorana neutrino mass

$$T_{1/2}^{-1} = PS^{0\nu} \left| M_{GT}^{0\nu} - M_F^{0\nu} \right|^2 \frac{\langle m_\nu \rangle^2}{m_e^2} \longrightarrow m_\nu \propto \sqrt[4]{\frac{\Delta E B}{Mt}}$$

From the theory point of view you try to maximise this

$$\langle m_\nu \rangle = \left| \sum U_{ei}^2 m_i \right| = \left| m_1 U_{e1}{}^2 + m_2 U_{e2}{}^2 e^{i\alpha_1} + m_3 U_{e3}{}^2 e^{i\alpha_2} \right|$$

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Experimental approaches

0νββ decay rate scales with Q^5 → only those with Q>2000 keV

Isotope	*Q-Value (keV)*	*Nat. abund. (%)*	
Ca 48	4271	0.187	Candles
Ge 76	2039	7.8	GERDA, Majorana — Talk by S. Schoenert
Se 82	2995	9.2	SuperNEMO (?)
Zr 96	3350	2.8	
Mo 100	3034	9.6	MOON
Pd 110	2013	11.8	
Cd 116	2809	7.5	COBRA
Sn 124	2288	5.64	
Te 130	2529	34.5	CUORE
Xe 136	2479	8.9	EXO, KamLAND, NEXT, XMASS
Nd 150	3367	5.6	SNO+, „LNGS“, DCBA, SuperNEMO(?)

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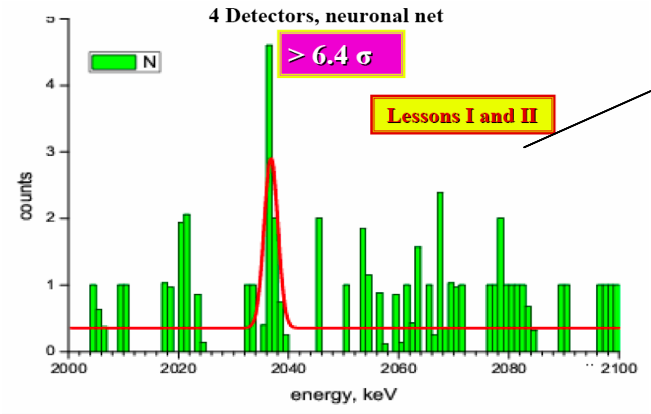
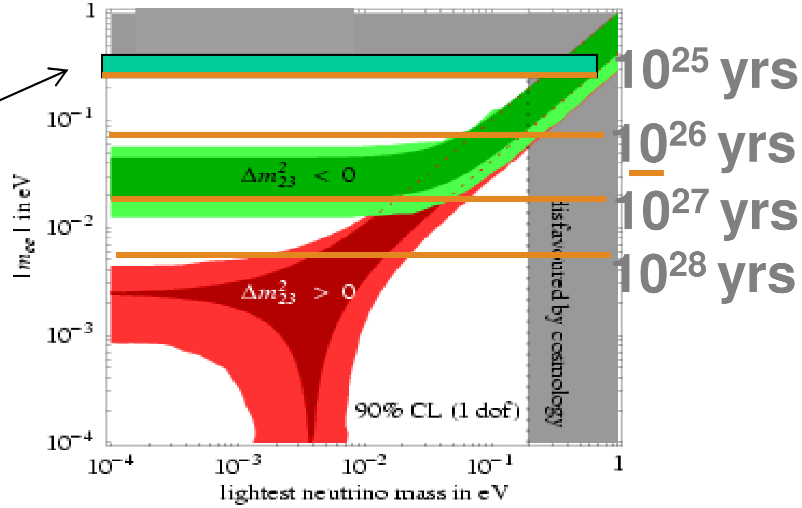
Present situation

claim of evidence



H.V. Klapdor-Kleingrothaus et al., Mod.Phys.Lett.A21:1547-1566,2006

$T_{1/2} = 2.23 \pm\ 0.4 \times 10^{25}$ yr



Strategy

- ★ Is there a peak?
- ★ If not do a more sensitive experiment
  - If yes, check with several other isotopes
  - If not confirmed
- ★ If confirmed, disentangle physics mechanism

Back of an envelope

This is the 50 meV option, just add 0's to moles and kgs if you want smaller neutrino masses

$$T_{1/2} = \ln 2 \cdot a \cdot N_A \cdot M \cdot t \,/\, N_{\beta\beta} \quad (\tau \gg T) \quad \text{(Background free)}$$

For half-life measurements of $10^{26\text{-}27}$ yrs

1 event/yr you need $10^{26\text{-}27}$ source atoms

This is about 1000 moles of isotope, implying about 100 kg

Now you only can loose: nat. abundance, efficiency, background, .

The ultimate experiment

There are 11(35) potential double beta emitters, you have to stay with these isotopes

Number of source atoms : ∞

Measuring time: ∞ ✓

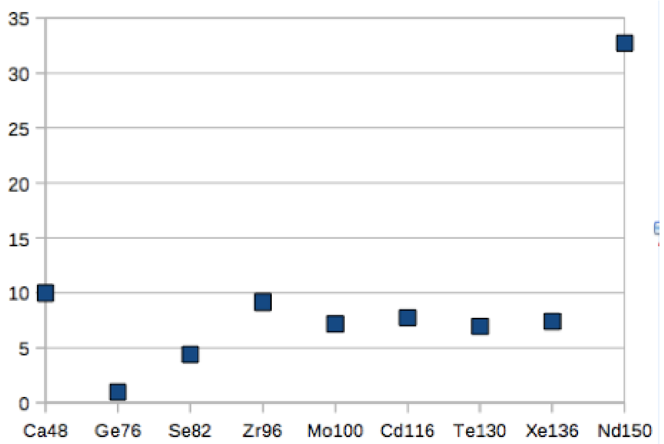
Background : 0

Energy resolution: δ –function

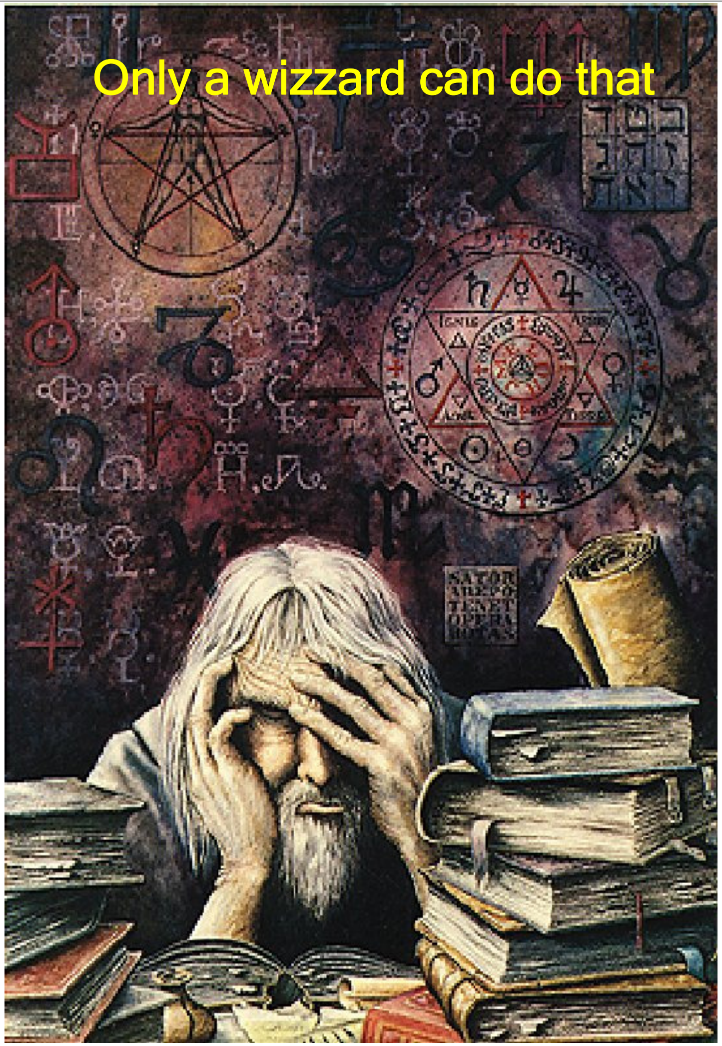
Efficiency: 100% ✓

Nuclear matrix elements: precisely known

Phase space incl. Coulomb correction: as large as possible

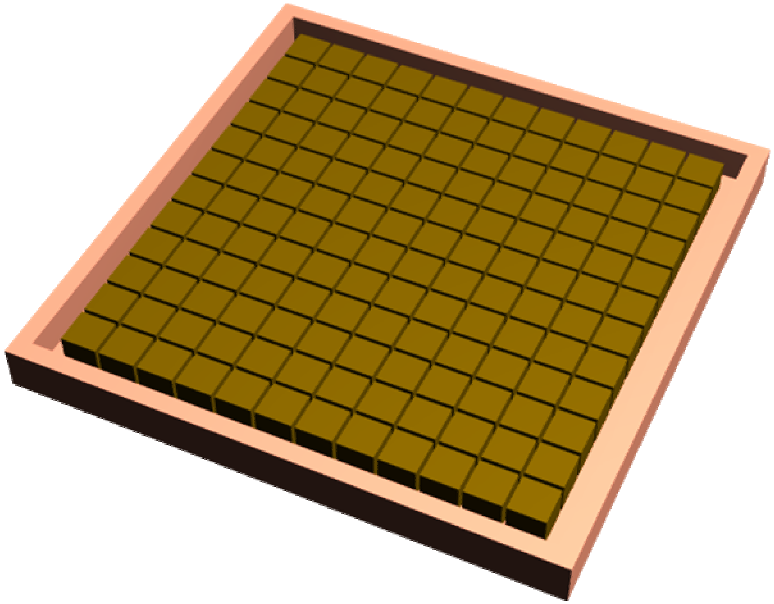


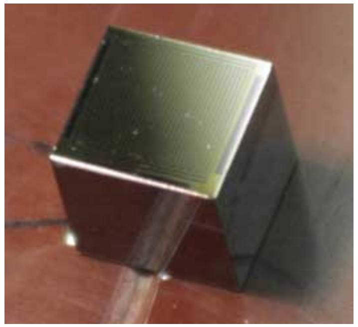
From Boehm,Vogel, Physics of massive neutrinos 1992



COBRA

Use large amount of CdZnTe Semiconductor Detectors





Focus on ^{116}Cd

K. Zuber, Phys. Lett. B 519,1 (2001)

COBRA collaboration

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Technical University Dresden
Technical University Dortmund
Material Res. Centre Freiburg
University of Erlangen-Nürnberg
University of Hamburg

Laboratori Nazionali del Gran Sasso

Washington University at St. Louis

University of Bratislava

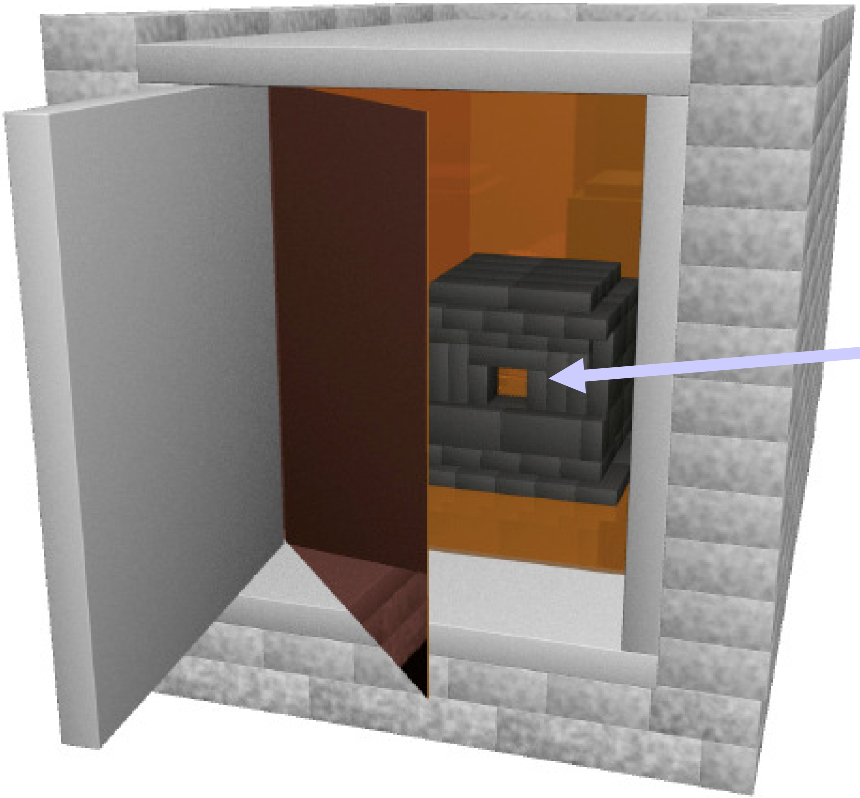
University of Jyvaskyla

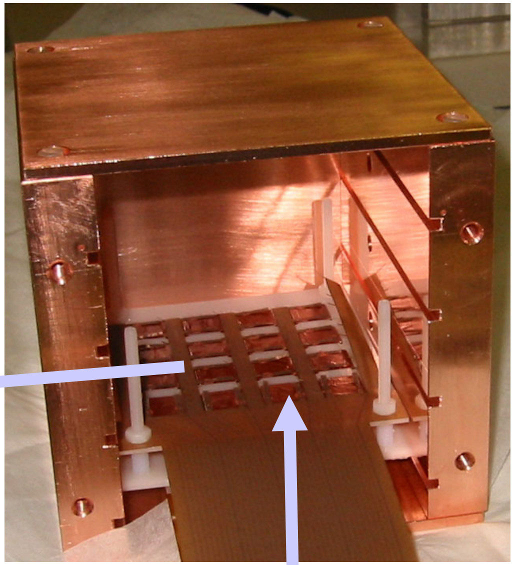
University of La Plata

Czech Technical University Prague

JINR Dubna

Setup at Gran Sasso Lab

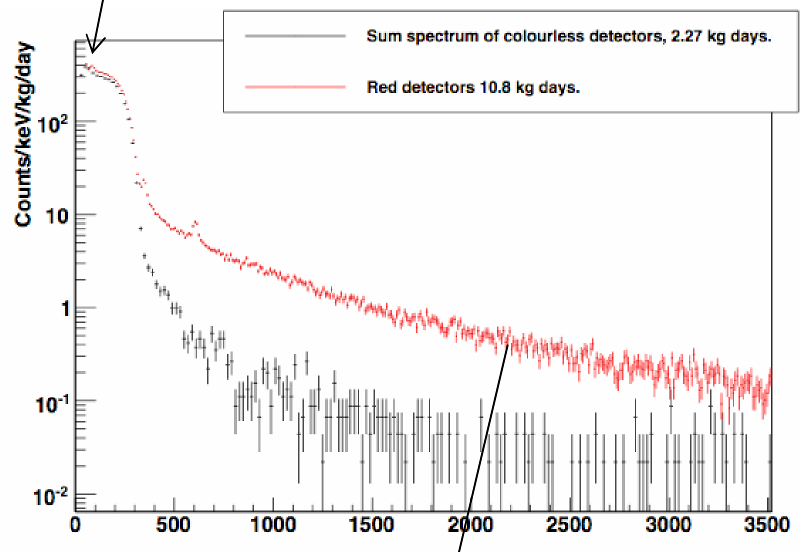




COBRA

4-fold forbidden non-unique beta decay of Cd-113
half-life about 8 x 10^{15} years

C. Goessling et al., PRC 72:064328 (2005)
J. V. Dawson et al., Nucl. Phys. A 818,264 (2009)

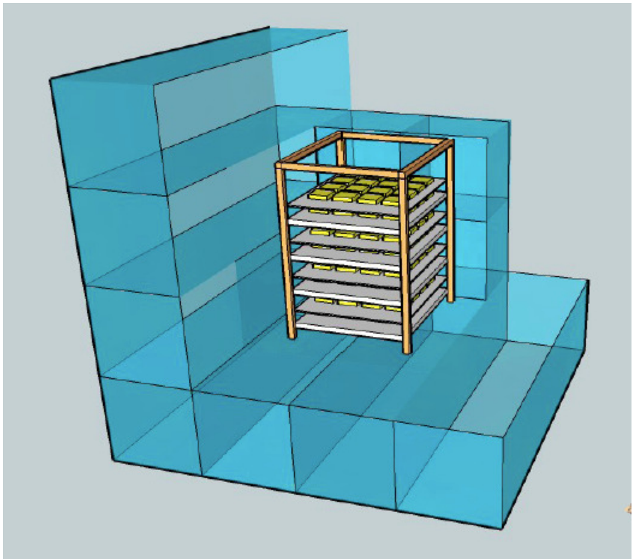


Double beta limits

J.V. Dawson et al., Phys. Rev. C 80,025502 (2009)

Major upgrade 2010

- Upgrade to 64 detectors
- New DAQ system
- Active Veto and shielding improvement
- Enriched CdZnTe detectors



COBRA - Pixel

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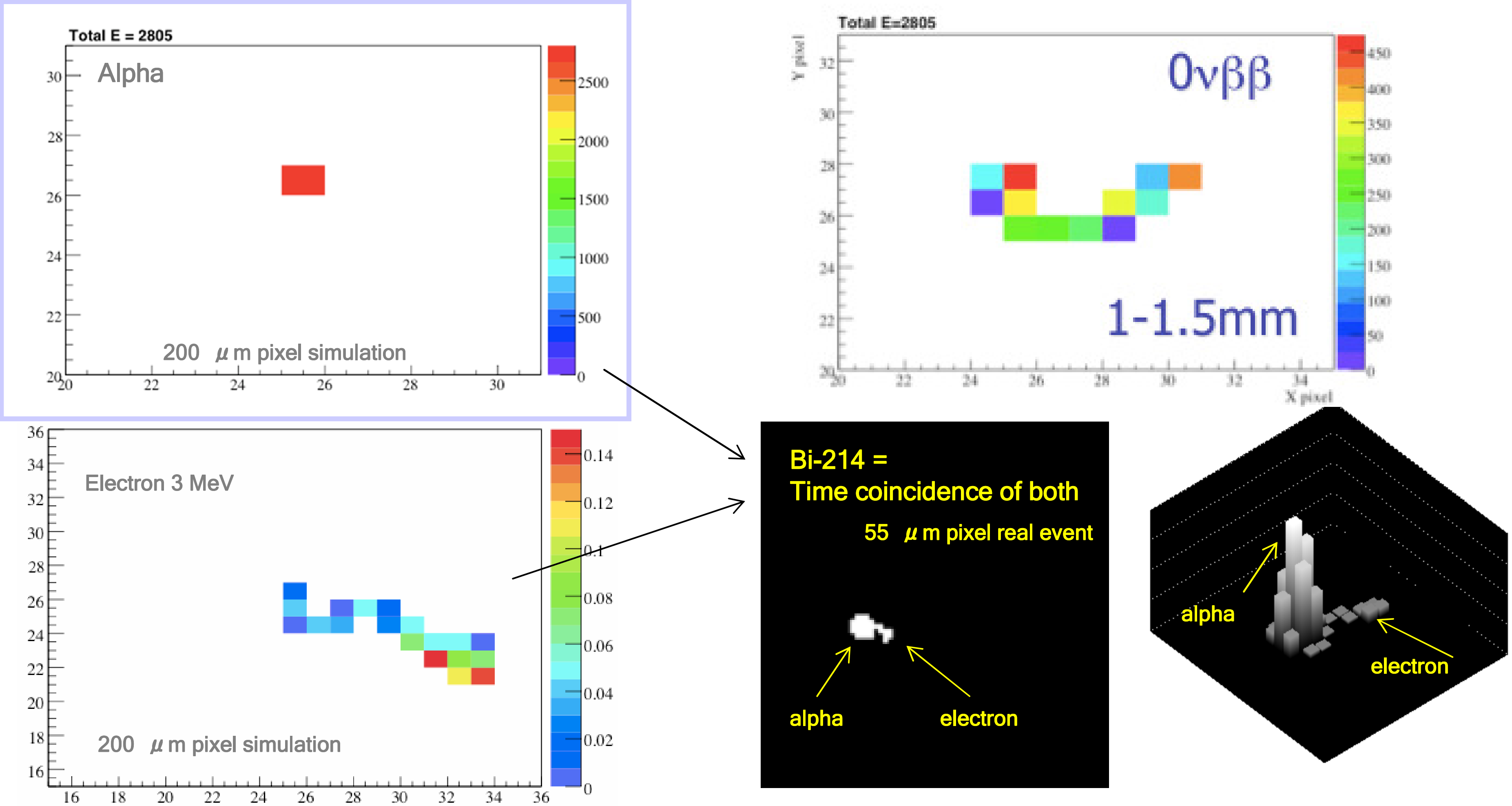
Idea: Massive background reduction by particle identification



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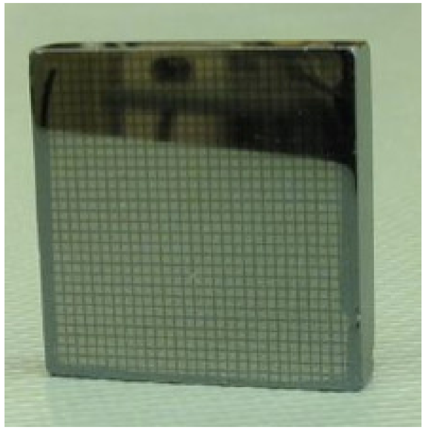
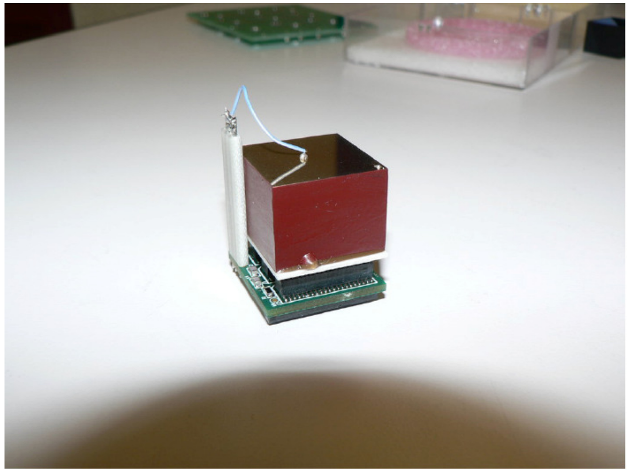
COBRA – Pixel CZT

Solid state TPC - Semiconductor tracker



$20x20x5 mm^3$ systems
8x8 pixels (running at LNGS since Jan. 2010)
32x32 pixel system
100x100 pixel system

World largest CZT detector = 36 grams
collaboration with Zhong He (Univ. of Michigan)



$20x20x15 mm^3$
11x11 pixel system
Up to 40 slices in z by pulse information
Running at LNGS from Sep. 2009-Jan. 2010

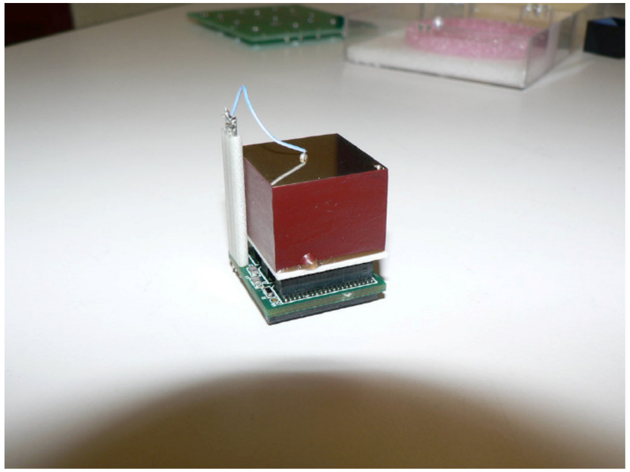
Timepix system:
$14x14x0.3 mm^3$ Si (2 systems)
$14x14x1 mm^3$ CdTe (2 systems)
256x256 systems
128x128 systems

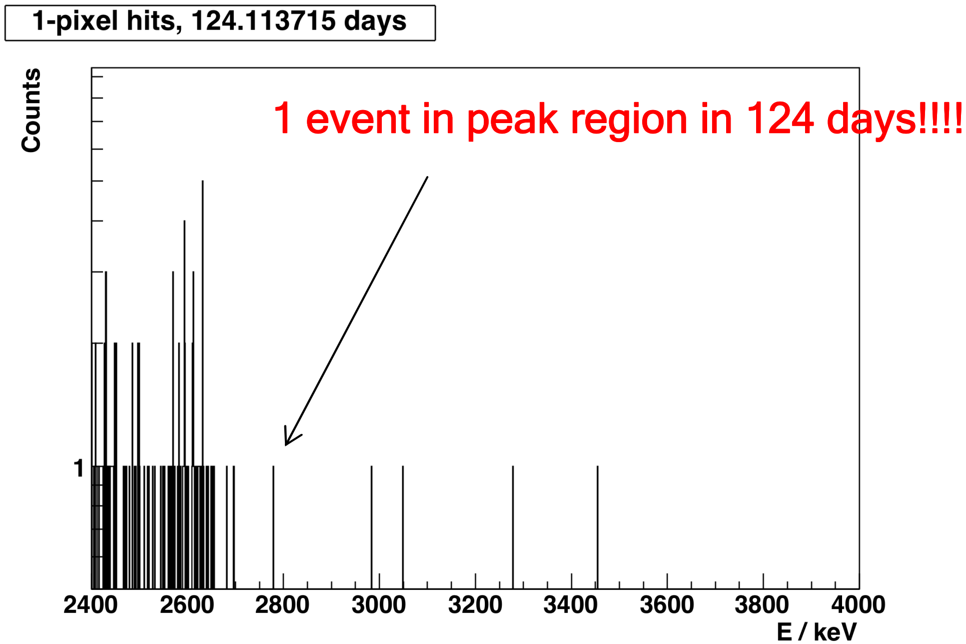
One system running in Felsenkeller Lab
since Sep. 2009

COBRA – Polaris

Preliminary

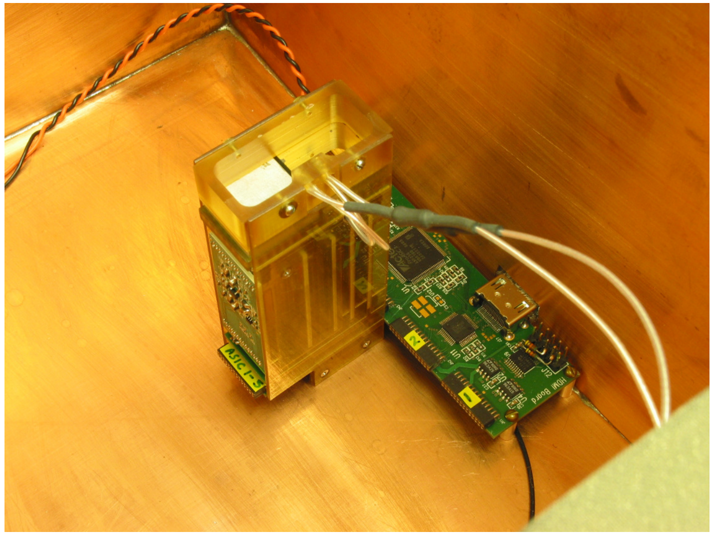
The power of pixels!

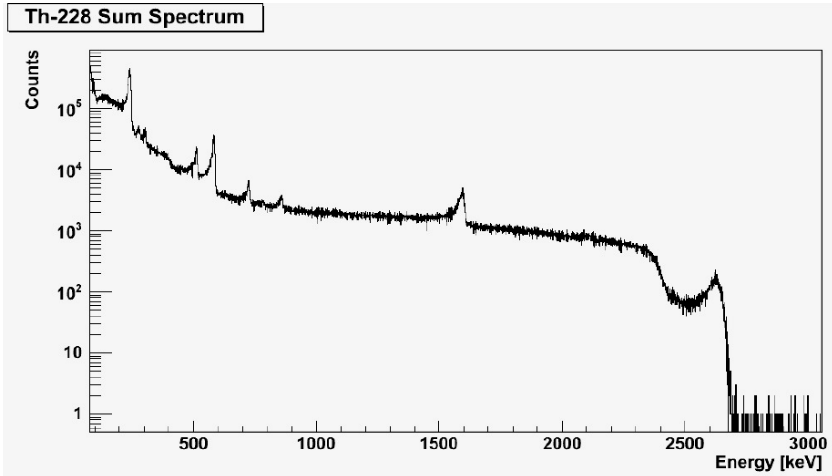


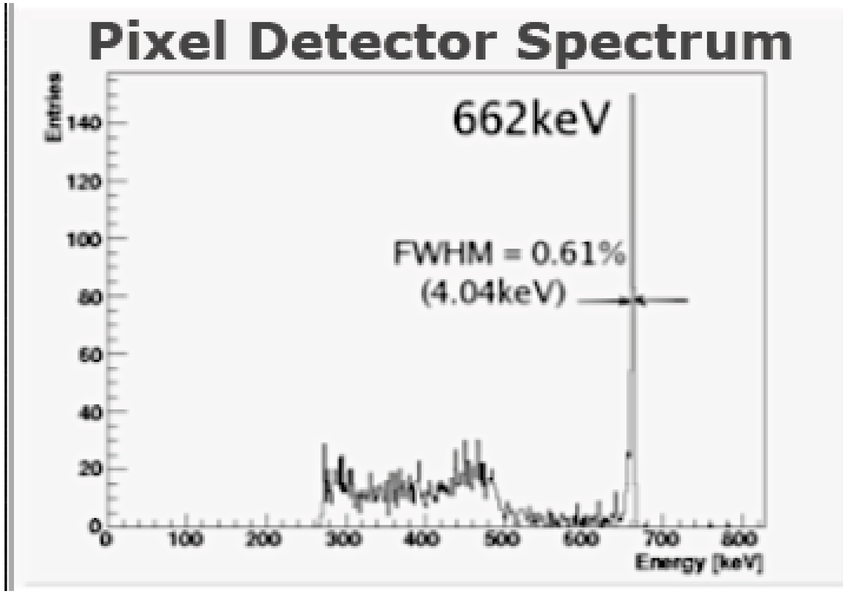


125 days one event only!!!, no z-analysis,
Detector not even low background,
No sophisticated shielding
event at 2.8 MeV close to corner
coordinates (10,1)

COBRA – St. Louis system

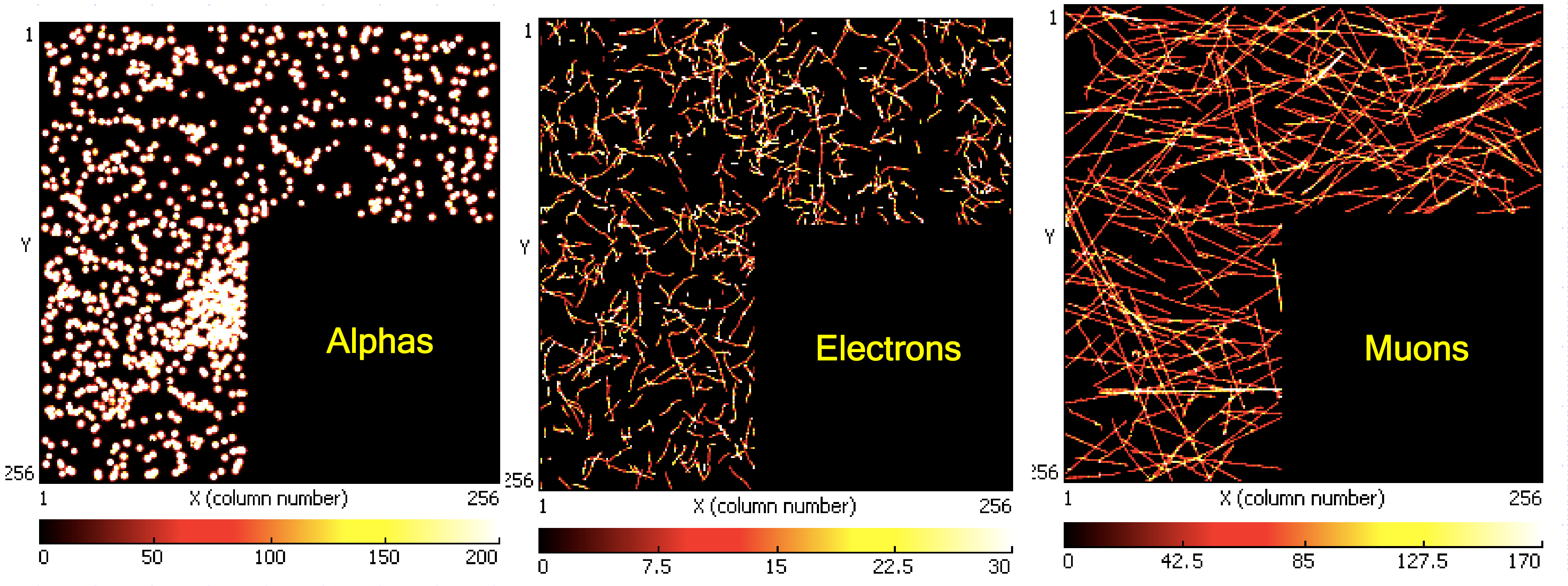






COBRA – Timepix

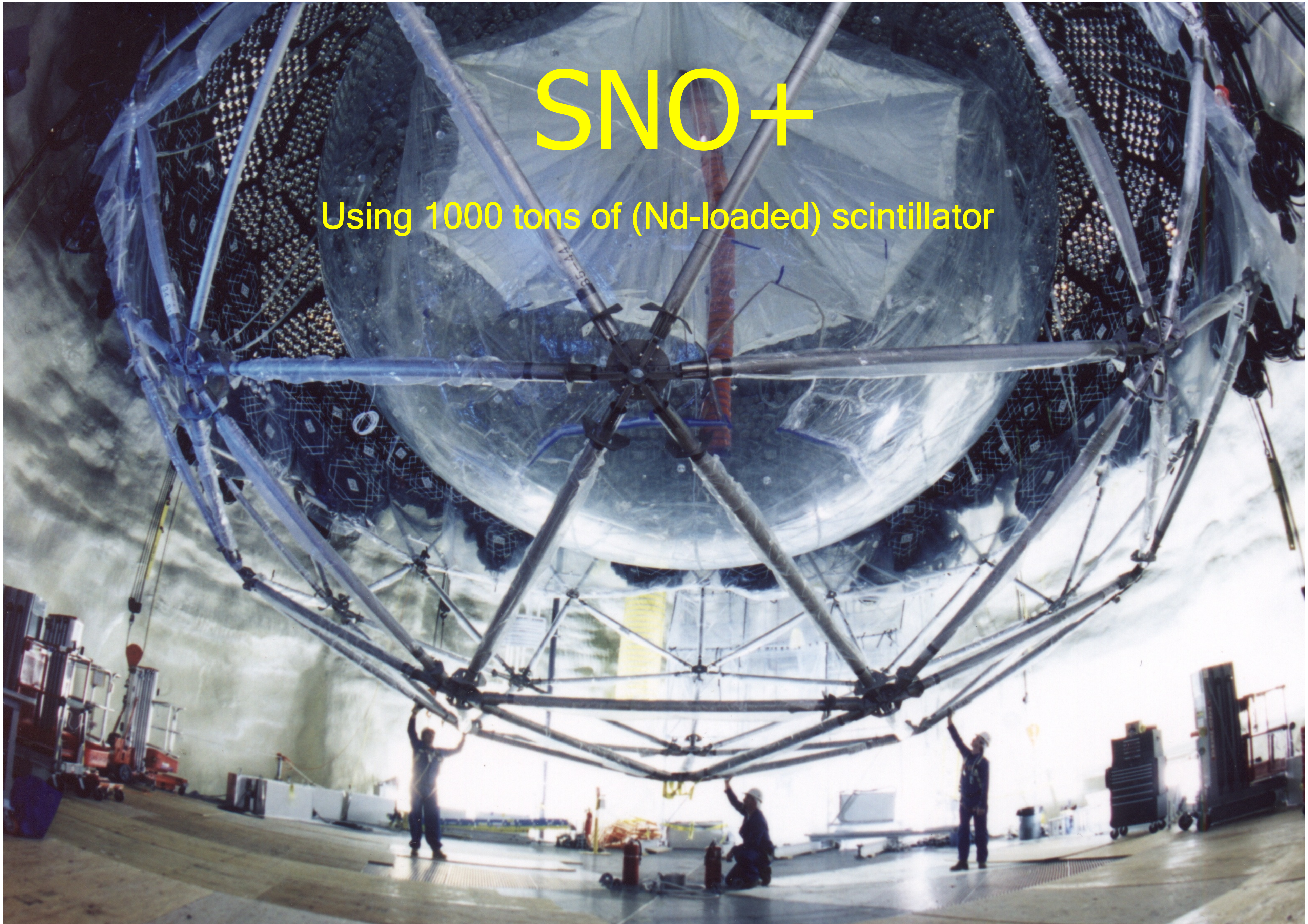
256x256 pixels, 55µm



Plan: Technical Design Report for large scale experiment ready in 2012

SNO+

Using 1000 tons of (Nd-loaded) scintillator



Solar neutrinos, reactor neutrinos, geoneutrinos, supernova neutrinos, double beta decay

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SNO+ collaboration

Queen's, **Alberta**, **Laurentian**, **SNOLAB**: 24 members

Brookhaven National Lab: R. Hahn, Y. Williamson, M. Yeh
Idaho State University: J. Heise, K. Keeter, J. Popp, E. Tatar, C. Taylor

University of Pennsylvania: E. Beier, H. Deng, B. Heintzelman, J. Secrest, T. Shokair, J. Klein
University of Washington: N. Tolich, J. Wilkerson, W. Tsung

Oxford University: S. Biller, A. Reichhold, J. Wilson
University of Sussex: E. Falk Harris, S. Peeters, J. Hartnell
University of Leeds: : J. Rose, S. Bradbury

LIP Lisbon: S. Andringa, N. Barros, J. Maneira, J. Rodelo

TU Dresden: K. Zuber, F. Krueger, P. Schrock

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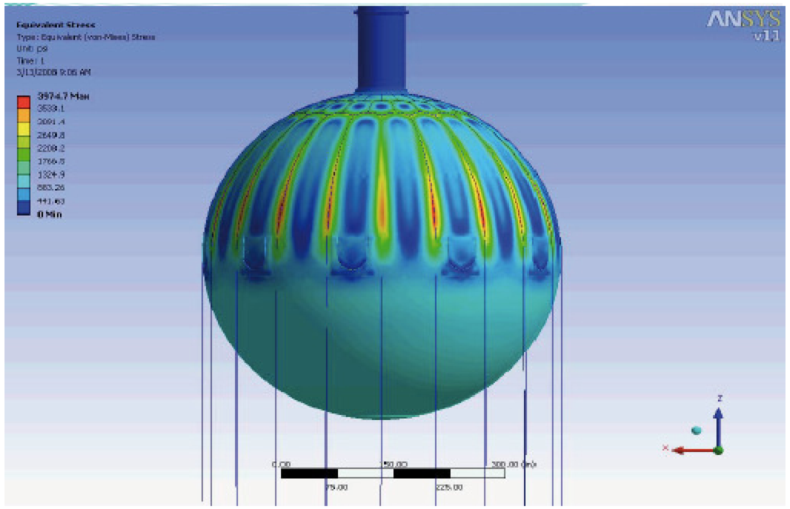
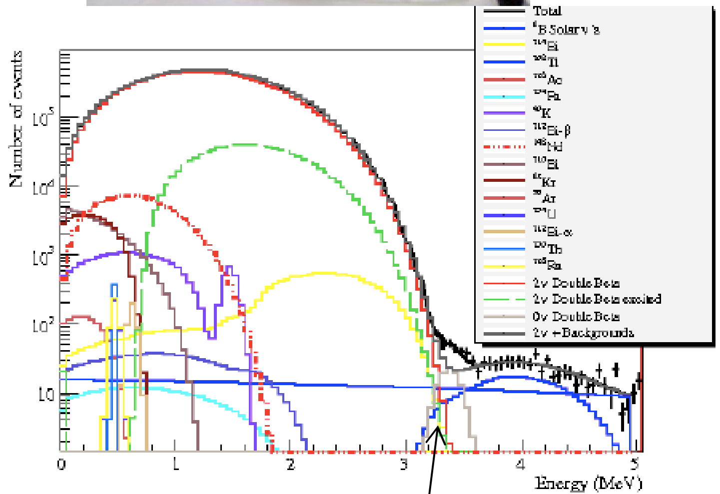
SNO+ impressions

Nd-loaded LAB with PPO





Peak range

SNO+ time planning

- Oct. 2010:	Installation of various slow control items, Installation of ropes
- Feb 2011:	System ready for temporary filling
Feb – May 2011:	Work on the AV
Jun - Aug 2011:	Temporary drain
Aug – Nov 2011:	Final filling with water
Nov 11 – Feb 2012:	Replacing water with scintillator
201?:	Adding Nd

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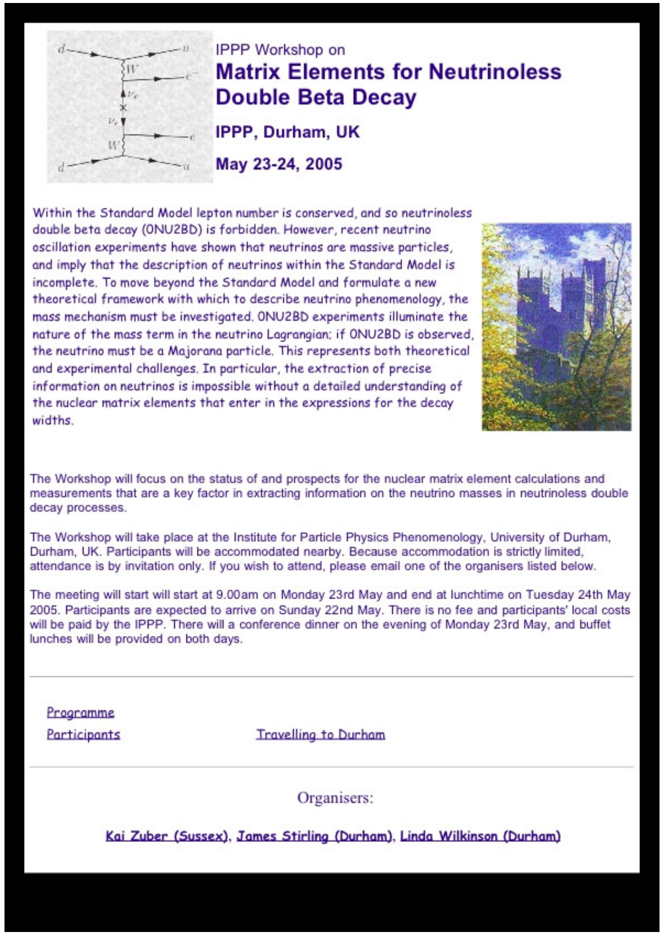
NME + Experiments


IPPP Workshop on

Matrix Elements for Neutrinoless Double Beta Decay

IPPP, Durham, UK

May 23-24, 2005

Within the Standard Model lepton number is conserved, and so neutrinoless double beta decay (0NU2BD) is forbidden. However, recent neutrino oscillation experiments have shown that neutrinos are massive particles, and imply that the description of neutrinos within the Standard Model is incomplete. To move beyond the Standard Model and formulate a new theoretical framework with which to describe neutrino phenomenology, the mass mechanism must be investigated. 0NU2BD experiments illuminate the nature of the mass term in the neutrino Lagrangian; if 0NU2BD is observed, the neutrino must be a Majorana particle. This represents both theoretical and experimental challenges. In particular, the extraction of precise information on neutrinos is impossible without a detailed understanding of the nuclear matrix elements that enter in the expressions for the decay widths.

The Workshop will focus on the status of and prospects for the nuclear matrix element calculations and measurements that are a key factor in extracting information on the neutrino masses in neutrinoless double decay processes.

The Workshop will take place at the Institute for Particle Physics Phenomenology, University of Durham, Durham, UK. Participants will be accommodated nearby. Because accommodation is strictly limited, attendance is by invitation only. If you wish to attend, please email one of the organisers listed below.

The meeting will start will start at 9.00am on Monday 23rd May and end at lunchtime on Tuesday 24th May 2005. Participants are expected to arrive on Sunday 22nd May. There is no fee and participants' local costs will be paid by the IPPP. There will a conference dinner on the evening of Monday 23rd May, and buffet lunches will be provided on both days.

Programme

Participants

Travelling to Durham

Organisers:

Kai Zuber (Sussex), James Stirling (Durham), Linda Wilkinson (Durham)

Consensus Report: K. Zuber, nucl-ex/0511009

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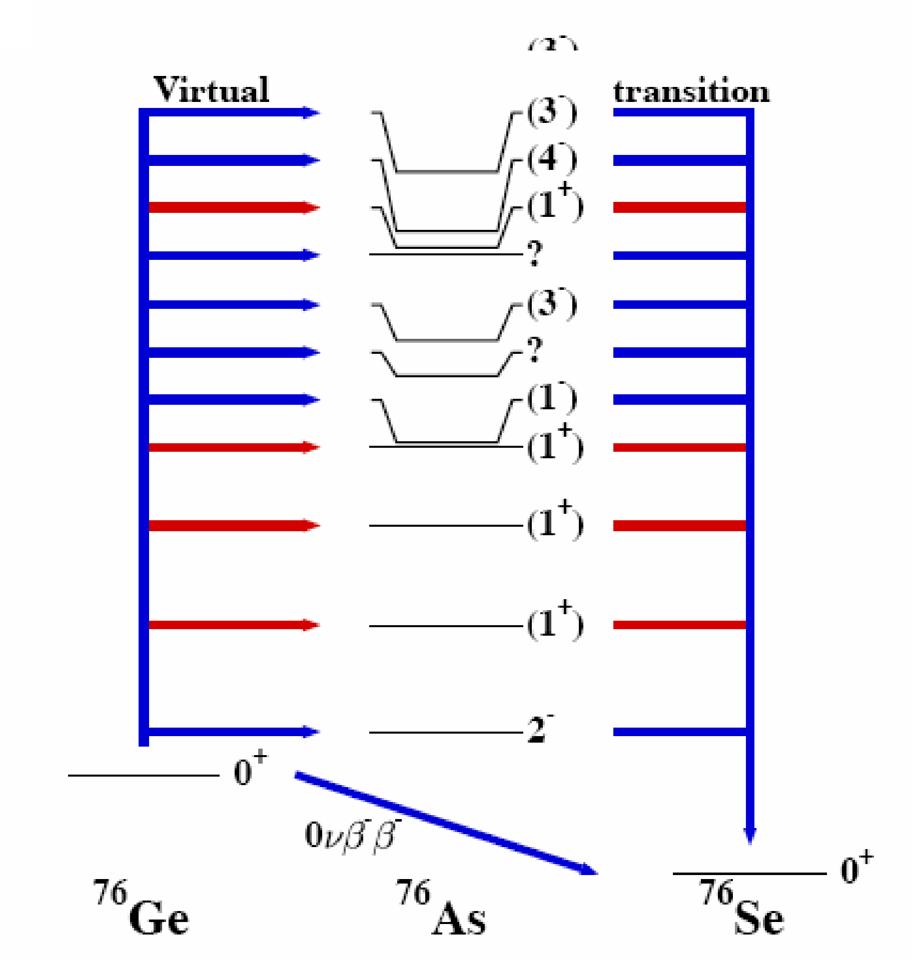
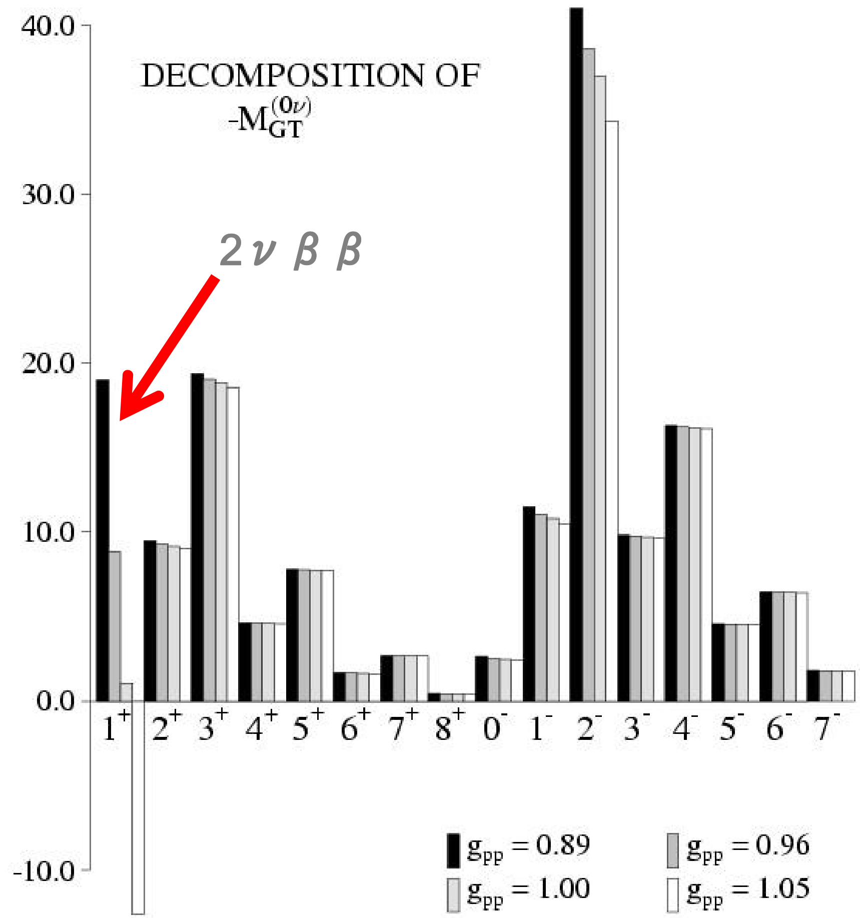
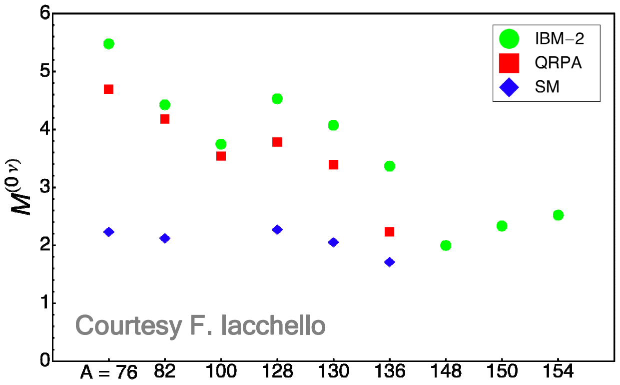
NME – Intermediate states



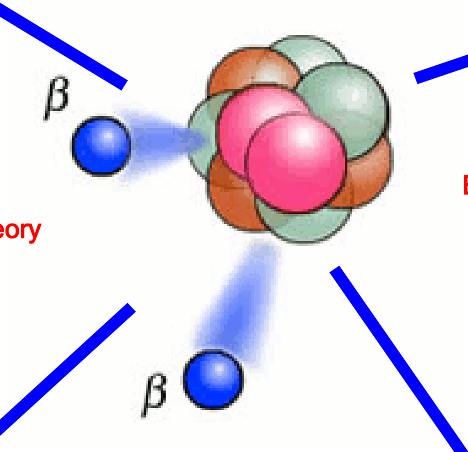


Nuclear matrix elements

Most important: Short range correlations



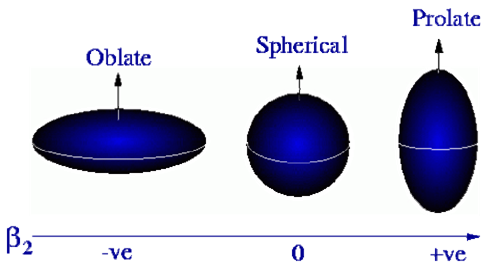
Atomic traps:
Ft-values,
Q-values



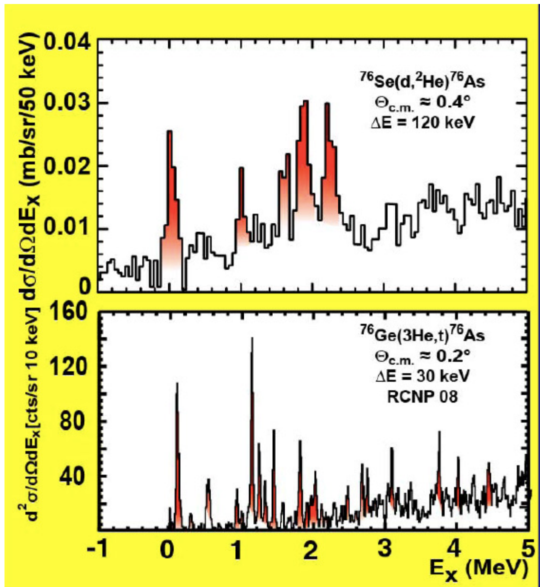
Theory

Experiment

Nuclear deformation



Charge exchange and
nucleon transfer reactions



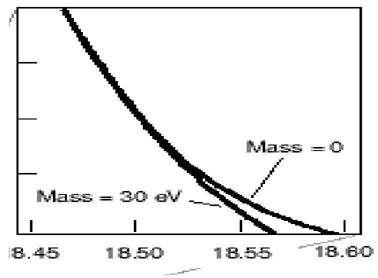
Measure properties of
11 isotope pairs in as
much detail as possible!!!

Double beta decay and neutrino masses

Also other neutrino physics matters

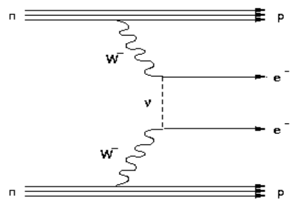
Beta decay:

$$m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$



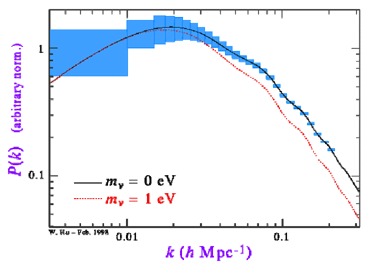
Double beta decay:

$$m_{\beta\beta} = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$



Cosmology:

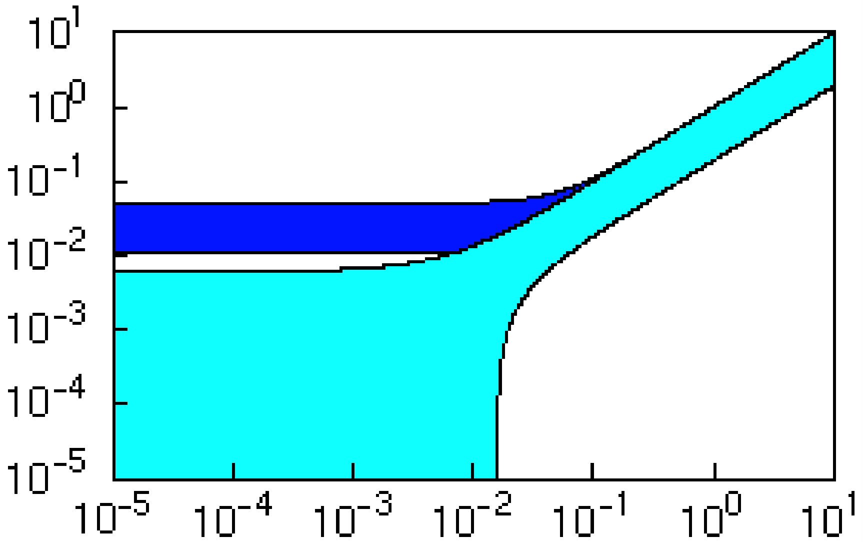
$$\Sigma = m_1 + m_2 + m_3$$

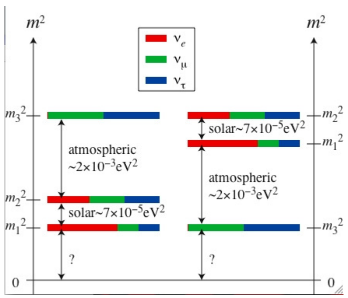


+ oscillation parameters

DBD and oscillation physics

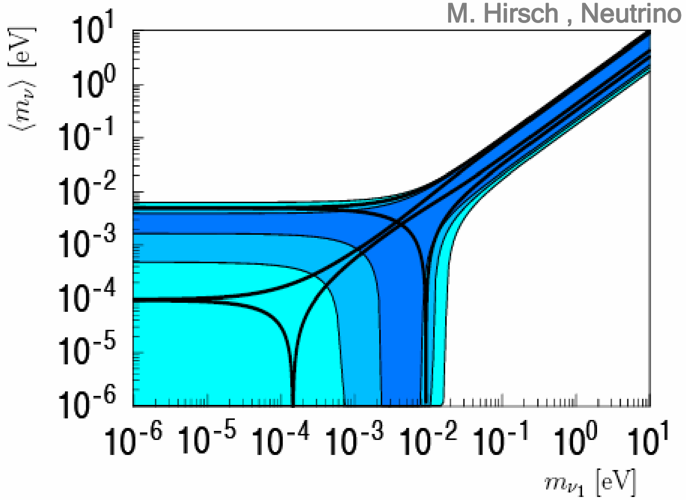
Latest oscillation parameters
from Gonzalez-Garcia et al.
arXiv:1001.4524





Impact of improving θ_{13}

M. Hirsch , Neutrino 2006

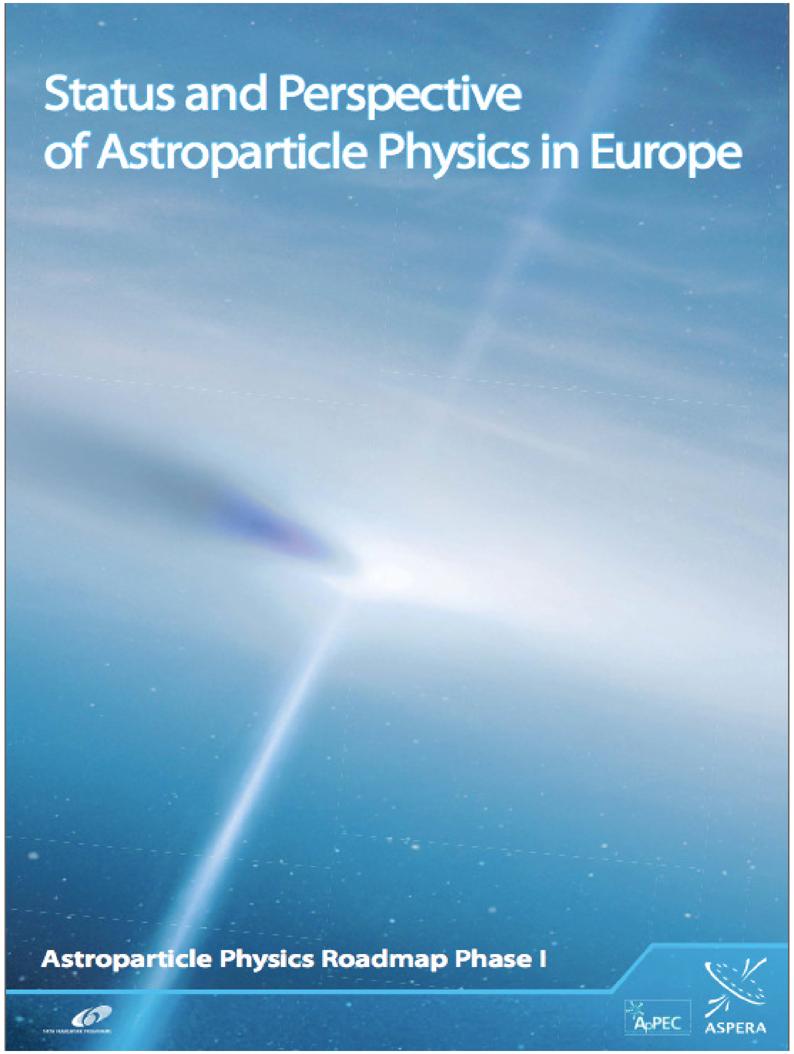


$\sin^2\theta_R =$
$[0, 5.1\cdot 10^{-2}]$
$[0, 2.5\cdot 10^{-2}]$
$[0, 5.1\cdot 10^{-3}]$

$\Delta m^2_{Atm} = [1.4, 3.3]\cdot 10^{-3}$ eV^2, $\Delta m^2_{\odot} = [7.2, 9.1]\cdot 10^{-5}$ eV^2,
$\sin^2\theta_{\odot} = [0.23, 0.38]$

No matrix element uncertainties included

Astroparticle Physics Roadmap



The KKGH claim

A subgroup of the HM collaboration (Klapdor-Kleingrothaus et al., KKGH in what follows) has claimed a positive effect from a re-analysis of their data, with $T_{1/2} \sim 1.2 \cdot 10^{25}$ y and $m_{\beta\beta} \sim 0.2$ -0.6 eV. Although this claim remains controversial, it provides an additional motivation for experiments with sensitivities in this mass range.

Running experiments

The largest running experiments are CUORICINO and NEMO-3. CUORICINO (Gran Sasso Lab) uses ^{130}Te as the double beta parent nucleus. It is an array of cryogenic bolometers of Tellurite crystals with a total mass of 41 kg (33.8% ^{130}Te) and is a first stage for CUORE conceived with a total mass of 740 kg. The main isotopes in NEMO-3 are ^{100}Mo (7kg) and ^{82}Se (1kg). NEMO-3 is a cylindrical detector with a central source foil sandwiched by tracking detectors and surrounded by a calorimeter in a 25 Gauss magnetic field and is located in the Fréjus laboratory. NEMO-3 is a stage on the way to the Super-NEMO detector, currently conceived to contain 100 kg ^{150}Nd or ^{82}Se. The sensitivities of both experiments are in the 0.5 eV range. These experiments could possibly confirm, but not fully disprove the KKGH claim.

Coming soon...

The European next-stage detectors are GERDA, CUORE and Super-NEMO. GERDA is being set-up in Gran Sasso and uses Germanium detectors enriched in ^{76}Ge, 18 kg in a first and about 40 kg in a second phase. They will scrutinize the KKGH claim starting in 2008, and will reach a sensitivity $T_{1/2} > 2 \cdot 10^{26}$ y and $m_{\beta\beta} < 0.1$-0.3 eV targeted for 2010. Depending on the physics results, a third phase using 500 to 1000 kg of enriched germanium detectors is planned merging GERDA with the US lead Majorana collaboration. The start of CUORE operation is scheduled for 2011, reaching a final sensitivity of 0.05-0.1 eV. Super-NEMO will finish a phase of design study in 2008 and projects the completion of the full detector in 2012 with 100 kg of ^{150}Nd or ^{82}Se. Its final sensitivity will be in the range 0.05–0.2 eV. All three experiments can prove or disprove the KKGH claim. Their motivation, as well as ultimate goal is to start the exploration of the parameter range predicted by the inverted mass hierarchy. This endeavour will commence at the beginning of the next decade.

R&D on Cadmium

It is not excluded at this point that an innovative European approach, COBRA, will join the competition. COBRA uses dominantly ^{116}Cd and ^{130}Te isotopes. A detector array of 64 CdZnTe semiconductor devices with a mass of about 0.5 kg has been installed in the Gran Sasso laboratory. Work towards a large scale detector is ongoing, and a Conceptual Design Study is expected in 2010.

Outside Europe

At this point, two large experiments located in the USA with similar sensitivity and a fourth innovative European approach have to be mentioned: EXO will use ^{136}Xe isotopes in a Time Projection Chamber filled with liquid enriched Xenon, 200 kg in a first stage. Neuchatel is the one European EXO collaborator. EXO-200 would address a similar mass range as CUORICINO and NEMO-3. For a later one-ton version, a 0.03 eV sensitivity

Time schedules

2010: GERDA (talk by S. Schoenert)
EXO 200 kg enriched Xe

2012: CUORE with 750 kg TeO_2

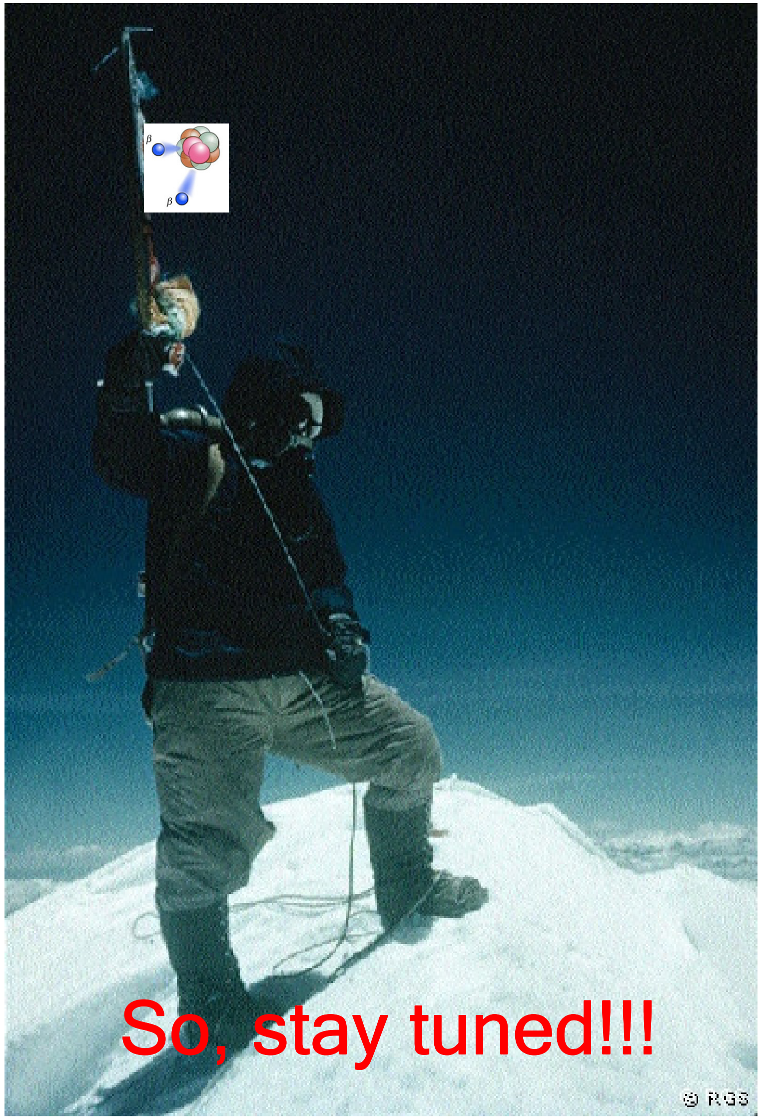
2013: KamLAND (300 kg enriched Xe)

2014(?) : SNO+, SuperNEMO

2015(?) : EXO (1t enriched Xe), COBRA

Conclusion

- **Double beta decay is the gold plated channel to probe the fundamental character of neutrinos**
- **Near term experimental goals are driven by the claim of a peak in Ge-76, GERDA is well on its way to prove it**
- **COBRA is a promising next generation experiment to explore double beta decay in Cd116. Unique option would be the semiconductor tracker**
- **SNO+ is under construction, relying on a well understood infrastructure, scintillator filling foreseen in 2012**
- **To support matrix element calculations as much experimental input as possible is desired! We are only talking about 11 isotope pairs!!!**
- **Germany has a long history in double beta decay and good reputation. It is strongly involved in several experiments and take a leading role the field**


So, stay tuned!!!
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