False starts
in history of searches for 2β decay
or
Discoverless double beta decay

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EVIDENCE FOR NEUTRINOLESS DOUBLE BETA DECAY

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The data of the Heidelberg–Moscow double beta decay experiment for the measuring period August 1990–May 2000 (54.9813 kg y or 723.44 molyears), published recently, are analyzed using the potential of the Bayesian method for low counting rates. First evidence for neutrinoless double beta decay is observed giving first evidence for lepton number violation. The evidence for this decay mode is 97% (2.2σ) with the Bayesian method, and 99.8% c.l. (3.1σ) with the method recommended by the Particle Data Group. The half-life of the process is found with the Bayesian method to be $T^{0\nu}_{1/2} = (0.8\text{–}18.3) \times 10^{25}$ y (95% c.l.) with a best value of 1.5×10^{25} y. The deduced value of the effective neutrino mass is, with the nuclear matrix elements from Ref. 1, $\langle m \rangle = (0.11\text{–}0.56)$ eV (95% c.l.), with a best value of 0.39 eV. Uncertainties in the nuclear matrix elements may widen the range given for the effective neutrino mass by at most a factor 2. Our observation which at the same time means evidence that the neutrino is a Majorana particle, will be of fundamental importance for neutrino physics.

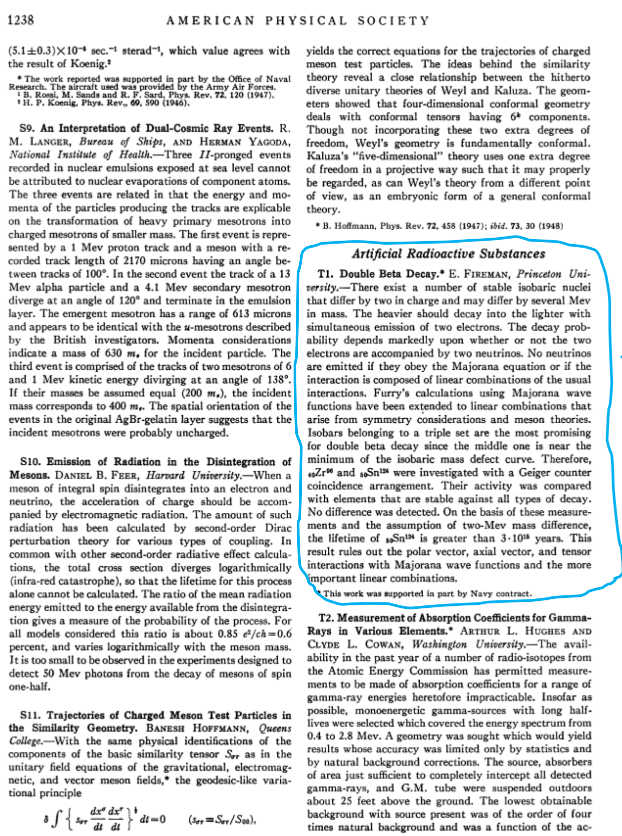
!

In fact, it was not the first time in history of 2β searches when observation of the effect was declared …

V.R. Lazarenko, Phys. Uspekhi 90 (1966) 601:
"… Double beta decay was "observed" more than once, however all these discoveries were disproved by subsequent experiments or raised doubts for some reasons …"

In the following, I will list
– in chronological order –
all previous declarations for observation of 2β decay
(including neutrinoless!)

First experimental article on 2β decay:
E. Fireman,
Phys. Rev. 74 (1948) 1248



$(5.1\pm0.3)\times10^{-6}$ sec.$^{-1}$ sterad^{-1}, which value agrees with the result of Koenig.[2]

* The work reported was supported in part by the Office of Naval Research. The aircraft used was provided by the Army Air Forces.
[1] B. Rossi, M. Sands and R. F. Sard, Phys. Rev. **72**, 120 (1947).
[2] H. P. Koenig, Phys. Rev., **69**, 590 (1946).

S9. **An Interpretation of Dual-Cosmic Ray Events.** R. M. Langer, *Bureau of Ships*, and Herman Yagoda, *National Institute of Health.*—Three *II*-pronged events recorded in nuclear emulsions exposed at sea level cannot be attributed to nuclear evaporations of component atoms. The three events are related in that the energy and momenta of the particles producing the tracks are explicable on the transformation of heavy primary mesotrons into charged mesotrons of smaller mass. The first event is represented by a 1 Mev proton track and a meson with a recorded track length of 2170 microns having an angle between tracks of 100°. In the second event the track of a 13 Mev alpha particle and a 4.1 Mev secondary mesotron diverge at an angle of 120° and terminate in the emulsion layer. The emergent mesotron has a range of 613 microns and appears to be identical with the *u*-mesotrons described by the British investigators. Momenta considerations indicate a mass of 630 m_e for the incident particle. The third event is comprised of the tracks of two mesotrons of 6 and 1 Mev kinetic energy divirging at an angle of 138°. If their masses be assumed equal (200 m_e), the incident mass corresponds to 400 m_e. The spatial orientation of the events in the original AgBr-gelatin layer suggests that the incident mesotrons were probably uncharged.

S10. **Emission of Radiation in the Disintegration of Mesons.** Daniel B. Feer, *Harvard University.*—When a meson of integral spin disintegrates into an electron and neutrino, the acceleration of charge should be accompanied by electromagnetic radiation. The amount of such radiation has been calculated by second-order Dirac perturbation theory for various types of coupling. In common with other second-order radiative effect calculations, the total cross section diverges logarithmically (infra-red catastrophe), so that the lifetime for this process alone cannot be calculated. The ratio of the mean radiation energy emitted to the energy available from the disintegration gives a measure of the probability of the process. For all models considered this ratio is about 0.85 $e^2/ch=0.6$ percent, and varies logarithmically with the meson mass. It is too small to be observed in the experiments designed to detect 50 Mev photons from the decay of mesons of spin one-half.

S11. **Trajectories of Charged Meson Test Particles in the Similarity Geometry.** Banesh Hoffmann, *Queens College.*—With the same physical identifications of the components of the basic similarity tensor $S_{\sigma\tau}$ as in the unitary field equations of the gravitational, electromagnetic, and vector meson fields,* the geodesic-like variational principle

$$\delta\int\left\{s_{\sigma\tau}\frac{dx^\sigma}{dt}\frac{dx^\tau}{dt}\right\}^{\frac{1}{2}}dt=0\qquad(s_{\sigma\tau}=S_{\sigma\tau}/S_{00}),$$

yields the correct equations for the trajectories of charged meson test particles. The ideas behind the similarity theory reveal a close relationship between the hitherto diverse unitary theories of Weyl and Kaluza. The geometers showed that four-dimensional conformal geometry deals with conformal tensors having 6^4 components. Though not incorporating these two extra degrees of freedom, Weyl's geometry is fundamentally conformal. Kaluza's "five-dimensional" theory uses one extra degree of freedom in a projective way such that it may properly be regarded, as can Weyl's theory from a different point of view, as an embryonic form of a general conformal theory.

* B. Hoffmann, Phys. Rev. **72**, 458 (1947); *ibid*. **73**, 30 (1948)

Artificial Radioactive Substances

T1. Double Beta Decay.* E. Fireman, *Princeton University.*—There exist a number of stable isobaric nuclei that differ by two in charge and may differ by several Mev in mass. The heavier should decay into the lighter with simultaneous emission of two electrons. The decay probability depends markedly upon whether or not the two electrons are accompanied by two neutrinos. No neutrinos are emitted if they obey the Majorana equation or if the interaction is composed of linear combinations of the usual interactions. Furry's calculations using Majorana wave functions have been extended to linear combinations that arise from symmetry considerations and meson theories. Isobars belonging to a triple set are the most promising for double beta decay since the middle one is near the minimum of the isobaric mass defect curve. Therefore, $_{40}Zr^{96}$ and $_{50}Sn^{124}$ were investigated with a Geiger counter coincidence arrangement. Their activity was compared with elements that are stable against all types of decay. No difference was detected. On the basis of these measurements and the assumption of two-Mev mass difference, the lifetime of $_{50}Sn^{124}$ is greater than $3\cdot10^{15}$ years. This result rules out the polar vector, axial vector, and tensor interactions with Majorana wave functions and the more important linear combinations.

* This work was supported in part by Navy contract.

T2. Measurement of Absorption Coefficients for Gamma-Rays in Various Elements.* Arthur L. Hughes and Clyde L. Cowan, *Washington University.*—The availability in the past year of a number of radio-isotopes from the Atomic Energy Commission has permitted measurements to be made of absorption coefficients for a range of gamma-ray energies heretofore impracticable. Insofar as possible, monoenergetic gamma-sources with long half-lives were selected which covered the energy spectrum from 0.4 to 2.8 Mev. A geometry was sought which would yield results whose accuracy was limited only by statistics and by natural background corrections. The source, absorbers of area just sufficient to completely intercept all detected gamma-rays, and G.M. tube were suspended outdoors about 25 feet above the ground. The lowest obtainable background with source present was of the order of four times natural background and was a function of the ac-

Artificial Radioactive Substances

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And already in the second article the effect was observed! **1949 - ^{124}Sn**

E. Fireman, Phys. Rev. 75 (1949) 323

2 samples of Sn, 25 g each:
sample A enriched in ^{124}Sn to 54% (natural abundance of ^{124}Sn is 5.79%)
sample B depleted in ^{124}Sn to 0.4%

2 proportional counters for each Sn sample (with and without coincidence), periodic change (rotation) of samples relatively to counters

Result: **rate A – rate B = 0.0±0.4 counts/min without coincidence**
= 2.0±0.2(stat.) counts/hr in coincidence (10σ effect)

Absorption curve with Al absorber: "is similar to that of electrons from a spectrum with an energy end point between 1.0 Mev and 1.5 Mev" (for ^{124}Sn $Q_{2\beta}$=2.288 MeV).

Conclusion:

counts/min. If one interprets this effect as double beta-decay from Sn^{124}, one obtains a half-life between $0.4\cdot10^{16}$ yr. and $0.9\cdot10^{16}$ yr. Other alternative explanations for these observations have been considered but none have been found to be plausible. This result would indicate that double beta-decay is unaccompanied by neutrinos. A

So, 2β0ν decay at the first time was "observed" in 1949 with 2.6σ significance!

In subsequent work (M.I. Kalkstein, W.F. Libby, Phys. Rev. 85 (1952) 368) only limit was obtained as:

$T_{1/2}(^{124}Sn, 0\nu)>2.4\times10^{17}$ yr

and recently (M.J. Hwang et al., Astropart. Phys. 31 (2009) 412) as:

$T_{1/2}(^{124}Sn, 0\nu)>2.0\times10^{19}$ yr

Reanalysis of 1952 data in A.S. Barabash, preprint ITEP 56 (Moscow, 1987):

$T_{1/2}(^{124}Sn, 2\nu)>1.0\times10^{17}$ yr

So, what E. Fireman observed in 1949 was contamination of Sn sample A by some radioactive element(s)

Comment 1: while during last few years big progress was achieved in searches for 2β transitions of ^{124}Sn to excited levels of ^{124}Te (with HP Ge detectors: $T_{1/2}>\sim10^{21}$ yr), there is still not very big progress for 2β decay to the ^{124}Te ground state

Comment 2: ^{124}Sn enriched (54%) and depleted (0.4%) samples of Sn (25 g each) – very nice, especially for 1949; many 2β people would be very glad to have such sources now

Possible effect in ^{100}Mo:

J.H. Fremlin, M.C. Walters, Proc. Phys. Soc. A 65 (1952) 911

Photoemulsion sensitive to β and α particles

Underground measurements (1860 ft = 567 m depth) – first in history of 2β search

Steel and lead shieldings

Results:

Table 2

Sample		Count in loaded area: Electrons	Count in loaded area: α-particles	Background (β/mm^2)	Exposure (days)	Sample activity (β/mm^2/day)	Min. half-life $T_{1/2}/\eta$ (years)
$CaCO_3$	a	86·0±4·5	none	75·5±1·6	56	0·19±0·07	7×10^{16}
Chromium	a	66·0±4·0	4·3±0·6	66·0±3·0	27	0·00±0·15	$2·2\times10^{17}$
Iron sponge	a	76·5±4·3	1·0±0·4	75·5±1·6	56	0·18±0·07	$1·3\times10^{17}$
Nickel	b	52·0±1·6	0·5±0·1	52·5±1·6	27	0·00±0·07	$3·2\times10^{17}$
Zinc	a	44·8±1·8	0·3±0·1	47·5±1·3	27	0·00±0·12	2×10^{17}
Germanium	a	50·0±1·7	none	52·5±1·6	27	0·00±0·08	$2·8\times10^{17}$
Molybdenum	a	87·5±2·1	none	54·1±1·2	27	1·24±0·09	$1·5\times10^{16}$
$SrCO_3$	a	79·1±3·4	none	63·8±1·5	56	0·27±0·07	$3·4\times10^{16}$
Cadmium 99·99		86 0±4·6	4·5±1·0	75·5±1·6	56	0·19±0·09	10^{17}
SnO	a	94·0±4·8	1·5±0·5	63·8±1·5	56	0·56±0·09	$1·4\times10^{16}$
^{124}Sn	*	138±7	20·6±1·4	46·4±2·3	15	6·1 ±0·5	2×10^{15}
Tellurium	a	77·5±5·0	none	63·8±1·5	56	0·24±0·11	$1·3\times10^{16}$
$BaCO_3$	a	115±5	7±1	47·2±2·4	15	4·5 ±0·4	$1·8\times10^{15}$
Tungsten	b	53·5±1·4	0·95±0·10	39·1±0·9	27	0·54±0·06	2×10^{16}
Osmium	a	311±20	51±10	75·5±1·6	56	40±3·6	$2·3\times10^{14}$
Platinum	b	67·2±3·3	3·0±1·0	52 5±1·6	27	0·55±0·13	$1·7\times10^{16}$

Excessive (on the level of 6σ-12σ) β activity is observed for Sn, ^{124}Sn, Ba, W, Os samples – however, for all of them also α activity is observed. Thus, both of them probably are related with U/Th contaninations

However, for Mo excessive β activity (13σ) is not accompanied by α activity!

No strong conclusion on 2β decay of ^{100}Mo was made by authors ("… work on other samples … is desirable …").

Today $T_{1/2}$ values for ^{100}Mo 2β decay: 2ν = $(7.11\pm0.54)\times10^{18}$ 0ν > 4.6×10^{23} yr

(R. Arnold et al., Phys. Rev. Lett. 95 (2005) 182302)

Possible effect in ^{96}Zr: **1953 - ^{96}Zr**

J.A. McCarthy, Phys. Rev. 90 (1953) 853

Two trans-stilbene scintillators able to work in coincidence and without coincidence
Active shielding, passive shielding of steel, Pb, Cd, B

Samples (ZrO_2 powder): **^{96}Zr, enrichment 89.5% (nat. abundance 2.80%), 52 mg**
^{94}Zr, enrichment 97.9% (nat. abundance 17.38%), 52 mg

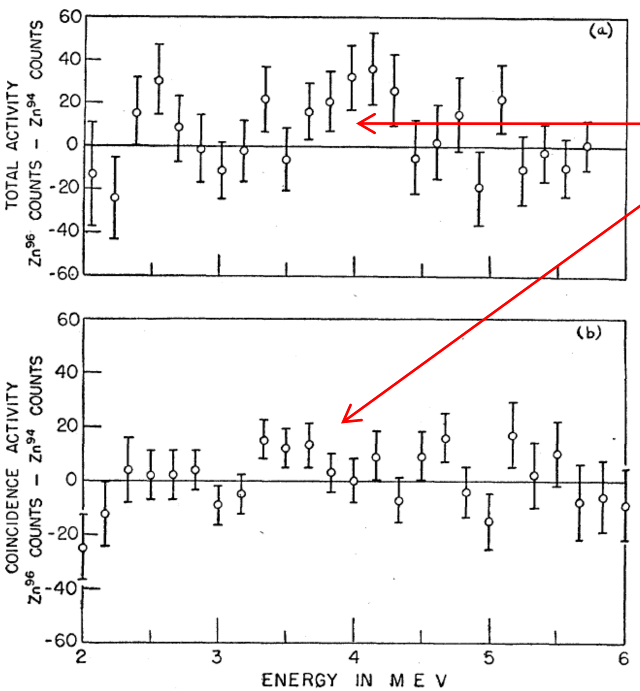


FIG. 9. Difference between activity with Zr^{96} sample and with Zr^{94} sample. The difference in the total activity in 218 hours is shown in the upper diagram; the difference in the coincidence activity in 212 hours is shown in the lower diagram. The energy scale is the same for both. Each error is the square root of the sum of the Zr^{96} and the Zr^{94} counts in the interval.

^{96}Zr–^{94}Zr	**(^{96}Zr $Q_{2\beta}$=3347.7 keV – today value)**	
3.3–4.3 MeV	**total**	**0.67±0.18 count/h**
3.3–4.3 MeV	**coincidence**	**0.25±0.09 count/h**

Thus, from this part of the experiment we have four possibilities for the 3.8-Mev peak:

1. A statistical effect. The probability of such an effect is less than 1 percent.
2. Internal conversion of a 3.8-Mev gamma-ray with an extraordinarily large internal conversion coefficient.
3. Internal pair production.
4. Double beta-decay with a lifetime of 0.6±0.2 ×10^{17} years.

In view of the coincidence data presented below, the author considers the fourth hypothesis (double beta-decay) the most likely one.

2σ effect

No strong conclusion:

feels that the results presented here indicate, but do not prove, that double beta-decay may occur in Zr^{96} without the emission of neutrinos. Further experimentation is clearly necessary.

Today values:
2ν = ~2×10^{19} yr
0ν > ~9×10^{21} yr

Evidence of 2β0ν decay of ^{48}Ca: **1955 - ^{48}Ca**

J.A. McCarthy, Phys. Rev. 97 (1955) 1234

Two plastic scintillators able to work in coincidence and without coincidence
Active shielding, passive shielding of steel, Pb, Cd, B

Samples ($CaCO_3$): **^{48}Ca, enrichment 84.3% (nat. abundance 0.187%), 78 mg**
^{44}Ca, enrichment 97.9% (nat. abundance 2.086%)

the John Hancock building, the sample identifications were coded by Professor J. W. Rosengren and the key to the code was withheld from the author until the conclusion of the experiment to eliminate possible (but carefully guarded against) "bias effects."

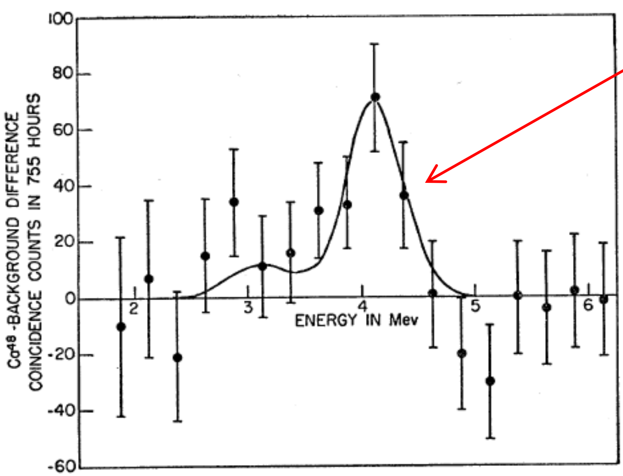


FIG. 2. Difference between coincidence activity with the Ca48 sample in position and with the Ca44 sample in position in 755 hours of counting with each sample. The curve drawn in indicates the predicted curve if ββ decay occurs with a lifetime of 1.6 ×10^17 years.

^{48}Ca–^{44}Ca **(^{48}Ca $Q_{2\beta}$=4274 keV)**
3.75–4.50 MeV **coincidence 0.19±0.06 c/h**

Strong conclusion:

The author believes this to be evidence for double beta decay without neutrino emission unless the observed counts are due to an unusual phenomenon of unknown origin.

$T_{1/2}=(1.6\pm0.7)\times10^{17}$ yr – 2.3σ significance

Today values:
2ν = ~4×10^{19} yr **0ν > ~4×10^{22} yr**

2β2ν decay of ^{82}Se: **1980 – ^{82}Se**

M.K. Moe, D.D. Lowenthal, Phys. Rev. C 22 (1980) 2186

13.75 g of Se (enriched in ^{82}Se to 97%) in form of foils of 5.6 mg/cm^2 (7.5 mg/cm^2 with Mylar), preliminary selection of all materials with NaI detector, cloud chamber with magnetic field (1 kG) + multiwire proportional counter, measurements at the Earth surface, shield of iron (>38 cm) and lead (15 cm).

Very detailed article (18 pages) with thorough analysis of all possible sources of mimicking events. Measurements of energies of each e$^-$ and angle between them.

Result: 20 events of 2e$^-$ (5 were caused by ^{214}Bi); good agreement between expected and measured spectra for energies of single electrons, sum of their energies and opening angle

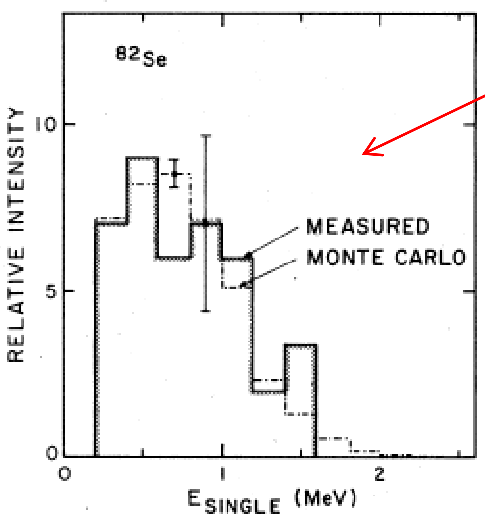


FIG. 12. The predicted and measured single electron energy spectra for negatron pairs from ^{82}Se.

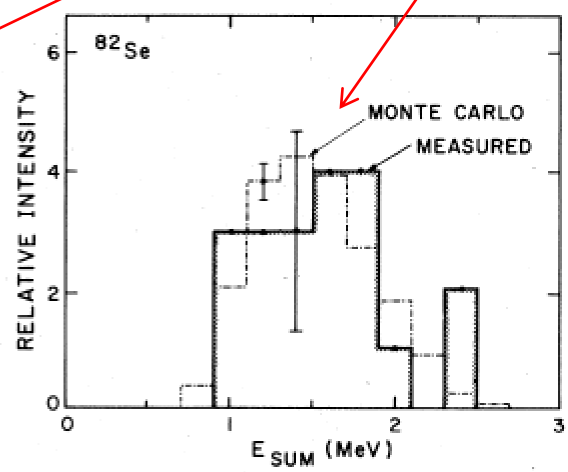
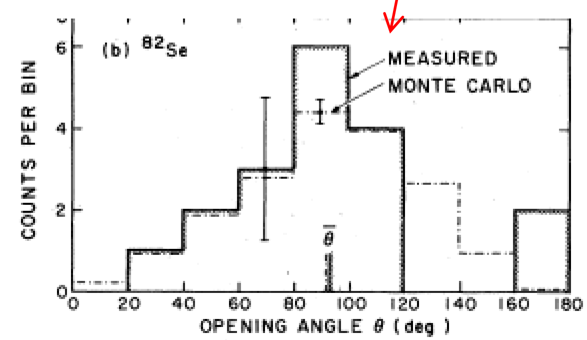


FIG. 13. The predicted and measured electron sum energy spectra for negatron pairs from ^{82}Se.



Abstract:

Pairs of negative beta particles have been observed originating from a ^{82}Se source during a cloud-chamber search for double beta decay. Backgrounds recognized in previous experiments were suppressed to well below the observed event rate, and no other significant backgrounds are apparent. Within the limited statistics of the small data sample, the observed single-electron energy spectrum, the two-electron sum energy spectrum, and the opening angle distribution are consistent with expectation for neutrino-accompanied double beta decay of ^{82}Se. The tentative assignment of the observed events to double beta decay, results in a ^{82}Se half-life of $(1.0\pm0.4)\times10^{19}$ years, in good agreement with some very recent theoretical predictions. However, the result is in serious disagreement with the much longer half-lives measured in geochemical experiments. A planned follow-up experiment is described.

Agreement for single-electron spectrum, two-electron spectrum, opening angle and (some) theoretical predictions … The dream of experimentalist …
Only one drawback: inconsistency with geochemical 2β $T_{1/2}$~10^{20} yr.

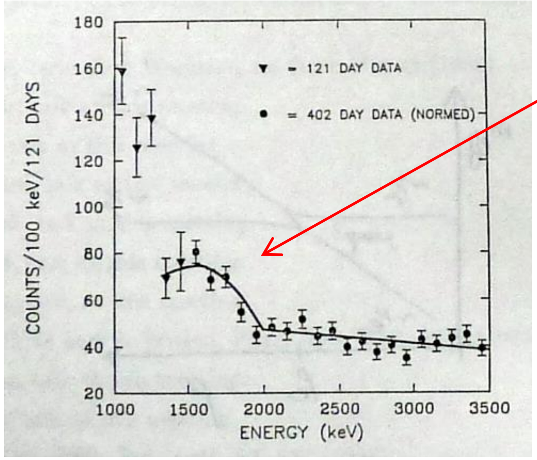
Next measurements of S.R. Elliott, A.A. Hahn, M.K. Moe with new apparatus – TPC with magnetic field – gave $T_{1/2}=(1.1^{+0.8}_{-0.3})\times10^{20}$ yr [Phys. Rev. Lett. 59 (1987) 2020]. This work is the first direct laboratory observation of 2β2ν decay (35 events during 7960 h).

Today value (NEMO-3, ~1 kg of ^{82}Se, 2750 events during 389 d, PRL 95 (2005) 182302): $T_{1/2}=(9.6\pm0.3)\times10^{19}$ yr

Neutrinoless 2β decay of ^{76}Ge with emission of Majoron: **1987 – ^{76}Ge**

F.T. Avignone et al., Proc. Ann. APS Meeting, Salt Lake City, 1987, World Sci., 1987, p. 359; Proc. IV Telemark Conf., Ashland, 1987, World Sci., 1987, p. 248

HP Ge detector 135 cm^3, shield of Cu, Pb (>40 cm, in particular, 448 y old), Cd, B, …, 402 d, Homestake gold mine: bump resembling 2β0νM decay of ^{76}Ge



2β0νM decay of ^{76}Ge, $T_{1/2}=6\times10^{20}$ y

However, statement was not strong:
"… If these events are in fact due to this exotic decay process, the half-life is $(6\pm1)\times10^{20}$ yr … We cannot at this point claim to have observed 0ν ββ-decay resulting in two electrons and a Majoron …"

Today limit for 2β0νM decay of ^{76}Ge : >7.9×10^{21} yr

Probably, this was the first observation of 2β2ν decay of ^{76}Ge (prior to the first announcements of its observation in 1990 with ^{76}Ge detectors), however it was not recognized as 2β2ν effect

The New York Times, 14 Jan 1987:
"Experiments conducted deep in a South Dakota gold mine have reportedly produced evidence for an extremely rare form of radioactive decay whose existence, if proved, would overthrow one of the basic laws of physics"

Science 235 (1987) 534:

Possible First Hints of Double Beta Decay

Nature 331 (1988) 392:

Northwest Laboratory (USC–PNL) reported* the observation of double β-decay with majoron emission.

As the existence of the majoron would represent a new particle which could not be accommodated in the standard model, these reports attracted great attention.

Observation of $2\beta0\nu$ decay of ^{76}Ge to excited 2_1^+ level of ^{76}Se: 1988 – ^{76}Ge

J. Busto et al. (French & Spanish groups), Proc. Int. Workshop on Neutrino Phys., Heidelberg, 20-22.10.1987 – Springer, 1988, p. 220

4 HP Ge detectors (~100 cm^3 each), 4π active shielding of 19 NaI, Cu and Pb passive shielding, Modane Underground Laboratory (4500 m w.e.), 6207 h

$E_{exc}(2_1^+, {}^{76}Se) = 559.1$ keV
Search for coincidence signal: 2041-559=1482 keV in Ge and 559 keV in NaI

When energy window in NaI is set to 559±31 keV, peak appears in Ge data, S=13±5 counts (2.6σ), $T_{1/2} = 1\times10^{22}$ yr
Time distribution of events – in accordance with Poisson, geometrical distribution – all Ge and NaI detectors

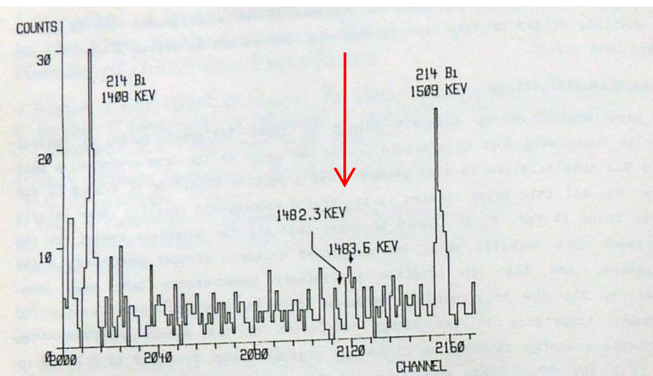


Fig. 2. Partial Ge spectrum obtained in coincidence with the NaI halo. The NaI window is centered at 560 keV and has width of 70 keV. The energy calibration is strictly 0.7 keV/channel (0.0 keV intercept).

Conclusion:

decay experiment which has been running for app...
underground facility. We have observed a coincidence cascade of ≃ 13 ± 5 counts between a 1483.6 ± 0.5 keV Ge energy deposition and a 559 ± 15 keV NaI energy deposition, in agreement with the expected energies of 1482.3 ± 0.5 keV and 559.1 ± 0.1 keV. No other unidentified cascade was seen in the full Ge-NaI matrix and no explaination within our background analysis has been found. All these features suggest the possibility of neutrinoless double beta decay of ^{76}Ge to the first excited state of ^{76}Se with a half-life $T_{1/2} \simeq 10^{22}$ y. Such a half-life based on a ... does not appear, at the present time, in contradiction

Today limit: >8.2×10^{23} yr

A. Morales et al. (only Spanish group), Nuovo Cim. A 100 (1988) 525

4 HP Ge detectors (total volume of 456 cm^3), 4π active shielding of 19 NaI, Modane Underground Laboratory (4000 m w.e.), 6122 h

$E_{exc}(2_1^+, {}^{76}Se)$=559.1 keV
Search for coincidence signal: 2041-559=1482 keV in Ge and 559 keV in NaI

When energy window in NaI is set to 559±31 keV, peak appears in Ge data:

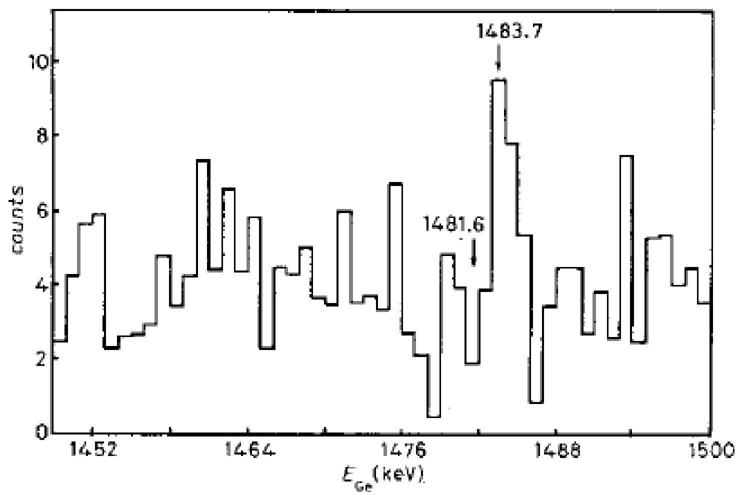


Fig. 6. – Enlarged energy region of the Ge coincidence spectrum when gated by a NaI windown of $2.68\sigma(\pm 35\,\text{keV})$ around 560 keV. $t = 6122$ h, $\Delta E_{NaI} = \pm 35$ keV.

S=13.3±5.3 counts (2.5σ)
$T_{1/2}=(1.1\pm0.5)\times10^{22}$ yr

Not very strong conclusion:
"… might be hypothetically attributed to a neutrinoless double beta effect …
rather questionable to positively conclude that we are seeing a double beta effect"
(abstract: > 6×10^{22} yr)

Comments: J. Busto et al. (only French group), Nuovo Cim. A 102 (1989) 937:

It cames as a real surprise to read in one of the latest issues of this journal (Vol. 100, No. 4, p. 525) a paper entitled: *Results of a search on the neutrinoless double beta decay of* ^{76}Ge *to the excited states of* ^{76}Se, signed only by the Zaragoza group of Professor A. Morales. It is of a public notoriety among the Nuclear Physics community that this experiment has been carried out at the Frejus underground laboratory, in collaboration with two other groups from the Centre d'Etudes Nucléaires de Bordeaux-Gradignan (C.E.N.B.G.) and Centre de Recherches Nucléaires de Strasbourg (C.R.N.), both members of the French Institut National de Physique Nucléaire et de Physique des Particules (IN2P3). Several preliminary results have been already published in common at various conferences (International Symposium on Nuclear Beta Decay and Neutrino, Osaka, 1986; International Conference on High Energy Physics, Berkeley, 1986; International Workshop on Neutrino Physics, Heidelberg, 1987).

While there was an agreement between both groups on existence of the peak, the French group would prefer more thorough analysis before publication.

all the experimental details had to be exposed clearly. The Bordeaux-Strasbourg groups had adopted the usual position that no definitive publication of the results would be attempted until these differences were resolved within the collaboration.

Apparently the group of Prof. A. Morales has preferred to abandon any further scientific discussion and to publish, as their own, the main results of a joint experiment. This group did not even send us a preprint of the article in question. The present authors think this action constitutes a serious breach of scientific ethics which should be largely explained, through the present comment, to the community of nuclear and particle physicists.

Reply: A. Morales et al. (only Spanish group), Nuovo Cim. A 102 (1989) 939:

"… We conclude not to make any claim of having positively found a neutrinoless double beta decay …"

On the contrary, the group of Prof. Mennrath wanted to present the results of their analysis as *an indication* of a double beta decay. Our discrepancies were not a mere difference of opinions—as said in the Comment—but were based on two different analyses and interpretations. That situation evolved into two deeply opposite attitudes with respect to our understanding of what a well-established scientific claim should be. We have tried to resolve the differences within the Collaboration, but after very long discussions no agreement was reached. So in January 1988, at the Moriond Neutrino Workshop, we communicated to Prof. Mennrath, with disappointment, that both groups should publish independently their analysis and conclusions. After that, a preprint FANZ 9/87—essentially the version we had sent to Bordeaux for our last round of discussions—was widely distributed in February 1988, and then sent for publication to *Nuovo Cimento*. Moreover, we requested from the Rapporteurs of

The Spanish group says that in fact it was the French colleagues who made the final decision without continuing further scientific discussion:

However, the title and the content of the transparencies presented by Prof. Mennrath at Heidelberg and previously agreed, were modified in the published version by our Bordeaux colleagues, without our knowledge nor our consent to sign the paper, which appeared as «Indication of neutrinoless 2β…» in *Proc. Int. Workshop on Neutrino Physics* (Springer-Verlag, 1988), p. 220. This assertion

Background peak at 2527 keV and $2\beta0\nu$ decay of ^{130}Te: 1992-1994 – ^{130}Te

In background data collected with 8 HP Ge detectors (total volume of 1095 cm^3) at St. Gotthard underground Laboratory (3000 m w.e.) during 15058 h (D. Reusser et al., Phys. Rev. D 45 (1992) 2548) small peak at 2527 keV was observed. This has extraordinary importance for calorimetric searches for $2\beta0\nu$ decay of ^{130}Te because $Q_{2\beta}(^{130}Te)=2527.01\pm0.32$ keV.

A. Alessandrello et al., Phys. Lett. B 335 (1994) 519: "Due to relevance that this peak would have in the present and future experiment on ^{130}Te, we have re-analized this spectrum in collaboration with the Neuchatel group … We found unambiguously that a peak at 2527 keV was generated by the early saturation of amplifier number six, which was defective in the last part of the experiment."

M. Moe, P. Vogel, Annu. Rev. Nucl. Part. Sci. 44 (1994) 247: →

operated several years ago in the St. Gotthard Laboratory. The existence of a background γ ray so close to the 2528.8 ± 1.2 keV (98a) expected for 0ν in ^{130}Te would be a disaster for the tellurium bolometric experiments. After three months of intense effort to identify the peak, the Milan and St. Gotthard groups working together determined conclusively that the Gotthard feature was an artifact produced by a malfunctioning amplifier.

With the nightmare of a 2527-keV γ ray behind them, the Milan group is proceeding with the tellurium experiments. However, the discovery of a spurious peak within a 0ν search region is a sobering reminder of the need to confirm any future claim of 0ν observation in a calorimeter or bolometer with evidence from more than one isotope.

Indication on 2β0νM decays of ^{82}Se, ^{100}Mo, ^{150}Nd: **1993 – ^{82}Se, ^{100}Mo, ^{150}Nd**

S.R. Elliott et al., Nucl. Phys. B (Proc. Suppl.) 31 (1993) 68

TPC in magnetic field, thin foils of enriched 2β isotopes (^{82}Se, ^{100}Mo, ^{150}Nd)

Two-electron events resembling double beta decay are being observed at energies beyond the die-off of the spectrum predicted for the two-neutrino mode. The anomaly appears in three isotopes having different half lives and Q-values. Tests are now underway to determine its origin.

The measured spectra with no subtraction of background are shown in Figure 3 for 20 244 hours with 13.4 g of ^{82}Se, 6 327 hours with 5.5 g of ^{100}Mo, and 2 534 hours with 11.2 g of ^{150}Nd.

2β2ν

2β0νM ?

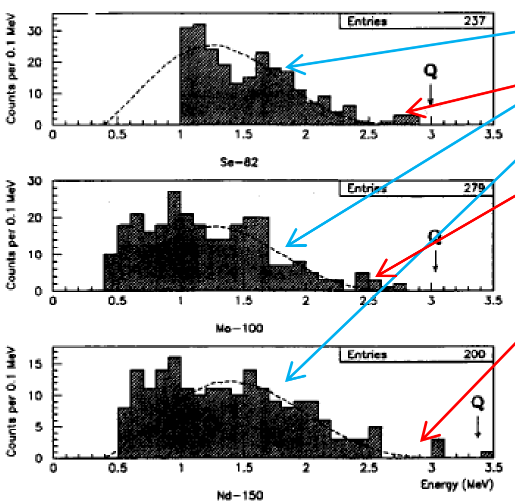


Figure 3. The measured sum-energy spectra of double beta decay candidates from the three isotopes. A 200 keV threshold has been imposed on each electron, and in the case of ^{82}Se, a sum-energy threshold of 1 MeV has also been applied. The dashed curves are the theoretical $\beta\beta_{2\nu}$ spectra with the experimental thresholds and resolution folded in.

"All three spectra show excess activity where the two-neutrino spectrum has all but died away."

Single electron spectra are similar in shape and activity for Se and Mo; however rate of high energy 2e events for Mo is 3 times higher. $Q_{2\beta}$ value for ^{150}Nd is higher, and energies of 2e events are higher too!

This apparent shift of the anomalous counts with $Q_{\beta\beta}$ is quite startling. There is no indication in the neodymium lone-electron spectrum of any additional activity at high energy. The molyb-

Effect disappeared after increase of strength of magnetic field

Earlier indication on $2\beta0\nu$ decay of ^{76}Ge in the H-M experiment: **1994 – ^{76}Ge**

B. Maier (for the Heidelberg-Moscow collaboration),
Nucl. Phys. B (Proc. Suppl.) 35 (1994) 358

3 HP Ge detectors (total mass of 6.92 kg, enriched in ^{76}Ge to 86%), Gran Sasso laboratory (3500 m w.e.)

3σ interval of a hypothetical $0\nu\beta\beta$-peak we seem to observe a systematic excess of events. In Fig. 3 the

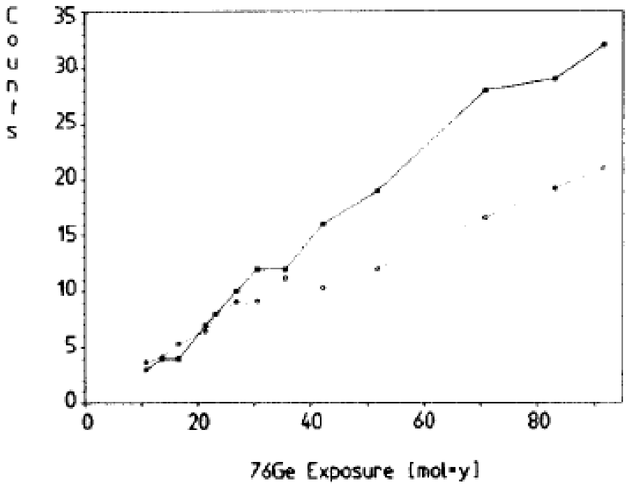


Fig. 3. Number of expected (dashed line) and measured counts (solid line) in the 3σ energy range of the $0\nu\beta\beta$-peak ($0^+ \rightarrow 0^+$) as a function of measuring time.

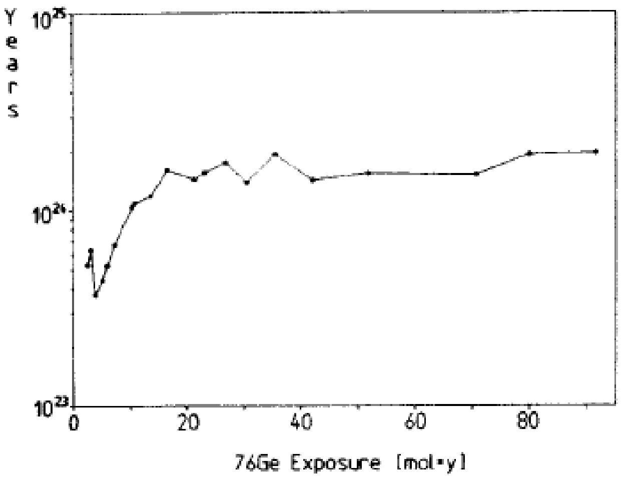


Fig. 4. Deduced half life limit for the $0\nu\beta\beta$-decay ($0^+ \rightarrow 0^+$) as a function of measuring time.

Saturation at lim $T_{1/2}(0\nu) \sim 1.6\times10^{24}$ yr

However, no strong conclusion

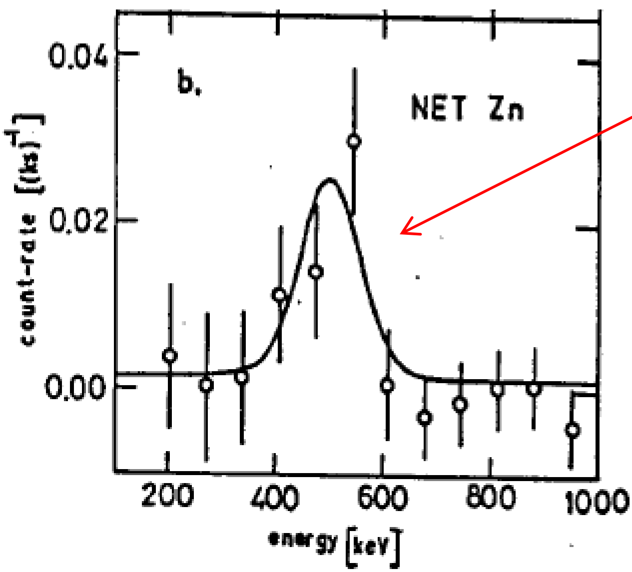
Indication on $\varepsilon\beta^+$ decay of ^{64}Zn: 1995 – ^{64}Zn

I. Bikit et al., Appl. Radiat. Isot. 46 (1995) 455

NaI(Tl) + HP Ge detector in coincidence
Active shielding, passive shielding of iron, Pb, Cd, B

Samples: Zn cylinder ∅7×2.5 cm (^{64}Zn nat. abundance 48.268%)
Fe, Cu cylinders and nothing as blank samples

Detection of two 511 keV γ's (after annihilation of positron) in coincidence



Difference Zn–blanc = $(6\pm4)\times10^{-5}$ counts/s
$T_{1/2}(0\nu+2\nu) = (1.1\pm0.9)\times10^{19}$ yr

Conclusion (not strong):

life of the electron-positron conversion decay of ^{64}Zn at 99.7% confidence level. If not caused by some unidentified and highly unlikely contamination of our Zn sample (the p.a. grade Zn pellets have been compressed to form the cylindric sample without melting), this result will be the first experimental evidence for the electron positron conversion process.

Today limits: $0\nu > 4.3\times10^{20}$ yr $2\nu > 7.0\times10^{20}$ yr

The effect was probably caused by some radioactive contamination (β^+ decay or $\gamma \to e^+e^-$ conversion, f.e. from 1461 keV line of ^{40}K)

2β⁺/εβ⁺/2ε decay of ^{130}Ba and 2ε decay of ^{132}Ba: 2001 – ^{130}Ba, ^{132}Ba

A.P. Meshik et al., Phys. Rev. C 64 (2001) 035205

Geochemical measurements: search for excess of ^{130}Xe and ^{132}Xe daughters in natural barite $BaSO_4$ samples
(other sources: cosmogenic production; spontaneous fission of U/Th; 2β decay of ^{130}Te)

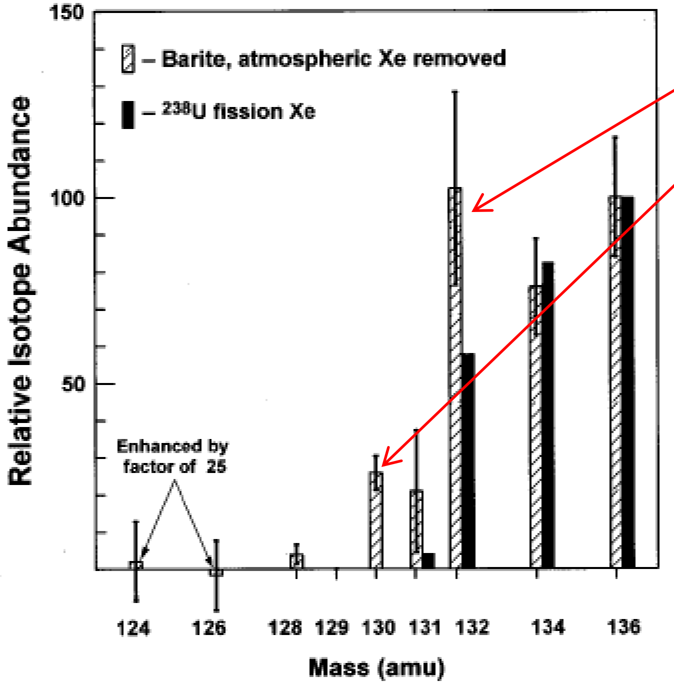


FIG. 2. Xe from Belorechenskoe barite (second run) after sub-

2β decay of ^{132}Ba: $T_{1/2}=(1.3\pm0.9)\times10^{21}$ yr
2β decay of ^{130}Ba: $T_{1/2}=(2.2\pm0.5)\times10^{21}$ yr
(finally only limit for ^{132}Ba as $>2.2\times10^{21}$ yr)

Theoretical expectations for 2K capture:
^{130}Ba – 10^{21}-10^{24} yr
^{132}Ba – 10^{23}-10^{26} yr

Result for ^{130}Ba is often considered as the first observation of the 2K2ν processes

In my opinion, it is better to consider it as indication: in fact, 5 $BaSO_4$ samples were investigated, all recovered from depths of at least 100 m; however "four of them had clear signatures of spallation-produced Xe".
Also: some dependence of authors decision on theoretical expectations …

To be checked in future!

Indication of $\varepsilon\beta^+$ decay of ^{112}Sn: **2008 – ^{112}Sn**

J. Dawson et al., Nucl. Phys. A 799 (2008) 167

1.24 kg of natural Sn, 72 cm^3 Ge detector, passive shielding of Cu and Pb, measurements at the Earth surface during 831 h

Number of events in the 511 keV annihilation peak: 1849±37 with Sn, and 1579±34 without Sn; excess is 270±50 counts (5.4σ). It is not related with U/Th contamination in Sn sample because no excess was found for other peaks (352, 583, 609 keV; but ^{40}K ?).

intensity increase of the 511 keV line cannot be attributed to uranium or thorium contamination in the tin.

Assuming the observed events are all due to the double beta decay of ^{112}Sn, a half-life of

$$T_{1/2}^{0(2)\nu\beta^+/EC}(0^+ \to 0^+_{\text{g.s.}}) = 5.09^{+1.17}_{-0.79} \times 10^{17}\ \text{yr} \quad (18)$$

can be derived, given the efficiency for observing 511 keV gammas = 1.175%.

However, authors gave conservatively only limit of >4.1×10^{17} yr.

No excess in the 511 keV peak in underground experiments:

>9.1×10^{17} yr **H.J. Kim et al., Nucl. Phys. A 793 (2007) 171**

>1.2×10^{19} yr **A.S. Barabash et al., Nucl. Phys. A 807 (2008) 269**

Remember ^{64}Zn … also surface measurements … ^{40}K ? …

Heidelberg-Moscow experiment:
5 HP Ge detectors (11 kg), 86-88% enriched in ^{76}Ge, Gran Sasso Underground Laboratory (3600 m w.e.), passive shielding, many years of measurements (start in 1990)

There are few articles on this subject:

0) H.V. Klapdor-Kleingrothaus et al. (HM collaboration, 14 persons),
Eur. Phys. J. A 12 (2001) 147 (received 2001.08.22)
53.9 kg×y full statistics (35.5 kg×y with PSA for single site events):
$T_{1/2}(0\nu) > 1.3(1.9)\times10^{25}$ yr at 90% C.L.

1) H.V. Klapdor-Kleingrothaus, A. Dietz, H.L. Harney, I.V. Krivosheina,
Mod. Phys. Lett. A 16 (2001) 2409 (received 2001.12.05)
55.0 kg×y full statistics (no PSA), $T_{1/2}(0\nu) = 1.6\times10^{25}$ yr [(0.8-35.1)×10^{25} yr at 95% C.L.]
46.5 kg×y part of statistics (no PSA), $T_{1/2}(0\nu) = 1.5\times10^{25}$ yr [(0.8-18.3)×10^{25} yr]
2.2-3.1σ effect

Criticized in number of works:
F. Feruglio et al., Nucl. Phys. B 637 (2002) 345 |
C.E. Aalseth et al., Mod. Phys. Lett. A 17 (2002) 1475 |
Yu.G. Zdesenko et al., Phys. Lett. B 546 (2002) 206 | no effect or ~1.5σ effect
A. Ianni, Nucl. Instrum. Meth. A 516 (2004) 184 |

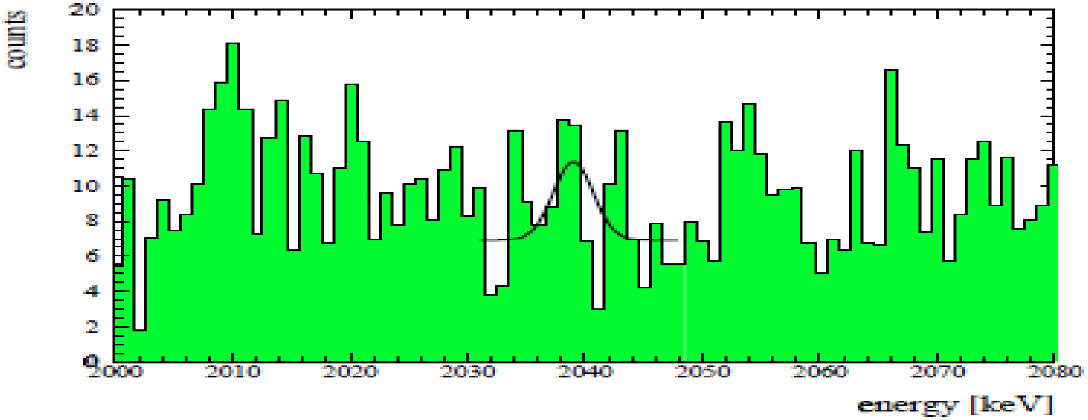
Also, Moscow part of the H-M collaboration derived only limit:
$T_{1/2}(0\nu) > 1.6\times10^{25}$ yr at 90% C.L.
A.M. Bakalyarov et al., Phys. Part. Nucl. Lett. 2 (2005) 21

2) H.V. Klapdor-Kleingrothaus, I.V. Krivosheina, A. Dietz, O. Chkvorets,
Phys. Lett. B 586 (2004) 198
71.7 kg×y full statistics (no PSA), $T_{1/2}(0\nu) = 1.2\times10^{25}$ yr [(0.7-4.2)×10^{25} yr at 95% C.L.]
4.2σ effect

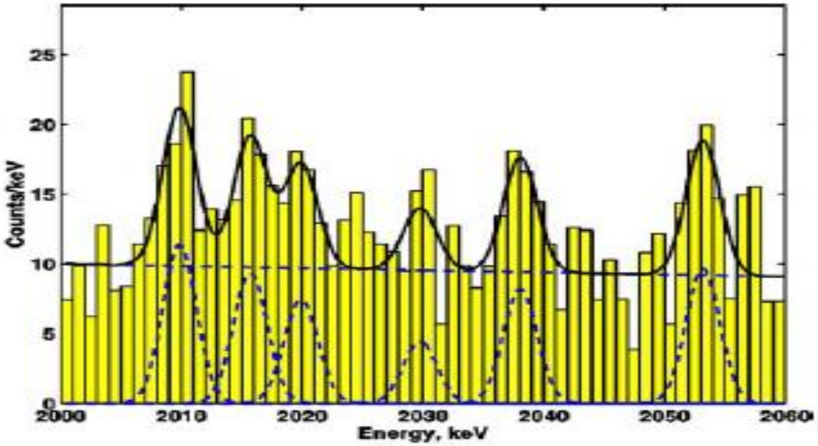
Not only statistics was bigger; also summing procedure was improved:
Final spectrum = sum of 9570 individual spectra
360 calibration spectra for each of 5 detectors, FWHM(2615 keV)=3.27 keV for sum of 1800 calibration spectra

3) H.V. Klapdor-Kleingrothaus, I.V. Krivosheina, Mod. Phys. Lett. A 21 (2006) 1547
? kg×y, PSA – 2 methods (pulse shapes were written since 1995)
$T_{1/2}(0\nu) = 2.23^{+0.44}_{-0.31}\times10^{25}$ yr – final result
6.2σ effect

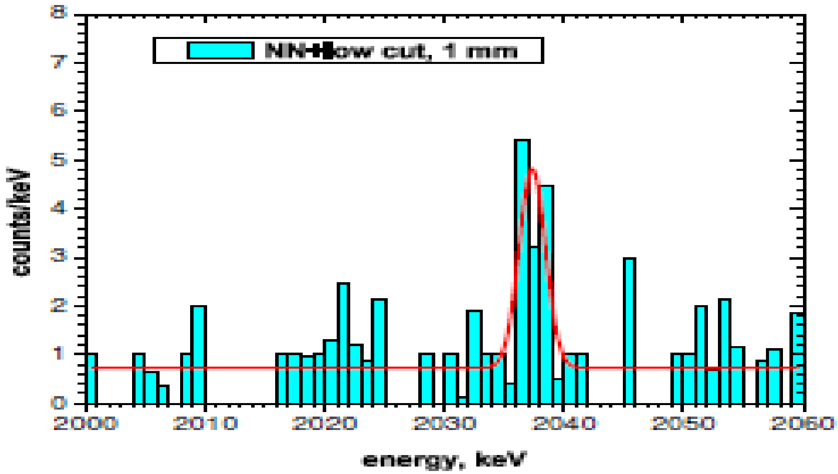
MPLA 16(2001)2409:
5 HP Ge, 1990.08-2000.05,
55.0 kg×y, no PSA, 2.2-3.1σ effect



PLB 586(2004)198:
5 HP Ge, 1990.08-2003.05,
71.7 kg×y, no PSA, 4.2σ effect



MPLA 21(2006)1547:
4 HP Ge, 1995-2003,
? kg×y, PSA – 2 methods, 6.2σ effect



It is impossible to reject the ^{76}Ge 2β0ν claim, however, it should be independently confirmed. Two BIG experiments are now under construction: GERDA and Majorana; ~100-1000 kg of ^{76}Ge, sensitivity 10^{26} – 10^{27} yr (on different stages).

Conclusions

V.R. Lazarenko, Phys. Uspekhi 90 (1966) 601:
"… Double beta decay was "observed" more than once, however all these discoveries were disproved by subsequent experiments or raised doubts for some reasons …"

History of searches for double beta is a history of studies of backgrounds and fighting with them. My personal involvement in this field started in 1982 – when only limits existed for both 2β0ν and 2β2ν decays (47 yr after prediction in 1935). After the first few years of my work, I believed that 2β decay does not exist (even 2ν). However: in 1987 – first direct laboratory observation of 2β2ν in ^{82}Se, and to-date it is observed in 10 isotopes (and probably in ^{130}Ba too) – and seen sometimes with great statistics of ~10^6 events of ^{100}Mo 2β2ν decay in NEMO-3.

So, even if we are skeptical now for some new observations, we still have a chance to see 2β0ν decay in our life.

Thank you for attention!

Thanks to Stefano Scopel for the second title of this talk.

Double beta decay

Allowed in SM:

$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\nu_e$ – two-neutrino 2β decay

Forbidden in SM, $\Delta L=2$:

$(A,Z) \rightarrow (A,Z+2) + 2e^-$ – neutrinoless 2β decay

$(A,Z) \rightarrow (A,Z+2) + 2e^- + M$ – 2β0ν decay with Majoron emission

2β0ν requires: $\nu_e=\nu_e$ (Majorana particle)
$m(\nu_e)\neq 0$ (or right-handed admixtures)

Many extensions of the SM predict $m(\nu_e)\neq 0$ and, as a result, 2β0ν processes. Experimental observation of this exotic phenomenon would be an unambiguous signal of new physics which lies beyond the SM.

Current day status:

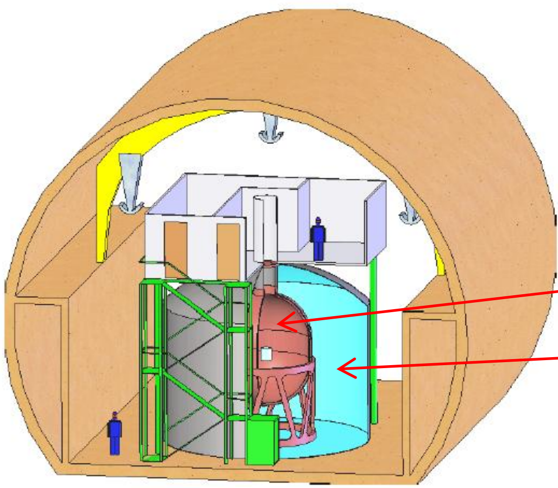
69 nuclei-candidates;
prediction in 1935, experiments since 1948;
2β2ν - first direct observation in 1987 (^{82}Se, 35 events); to-date observed at 10 nuclei (^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{150}Nd, ^{238}U, probably also in ^{130}Ba; $T_{1/2}=10^{18}–10^{24}$ yr – rarest observed decays to-date);
2β0ν - current one positive claim on observation (^{76}Ge)

It is impossible to reject the ^{76}Ge 2β0ν claim, however, it should be independently confirmed. Two BIG experiments are now under construction: GERDA and Majorana; ~100-1000 kg of ^{76}Ge, sensitivity $10^{26} – 10^{27}$ yr (on different stages).

GERDA:

inherited enriched in ^{76}Ge detectors from HM (5 det., 11 kg) and IGEX (3 det., 6 kg);
bought 35.5 kg GeO_2 enriched in ^{76}Ge (to 87-88%);
in future – use of 18-fold segmented HP Ge detectors (tracking)

Progress in Gran Sasso National Laboratories:



Proposal
September 2004

cryostat
April 2008

water tank
October 2008