Project
Lithium Detector of Solar Neutrinos.
I. Physical motivation
II. Methodical justification

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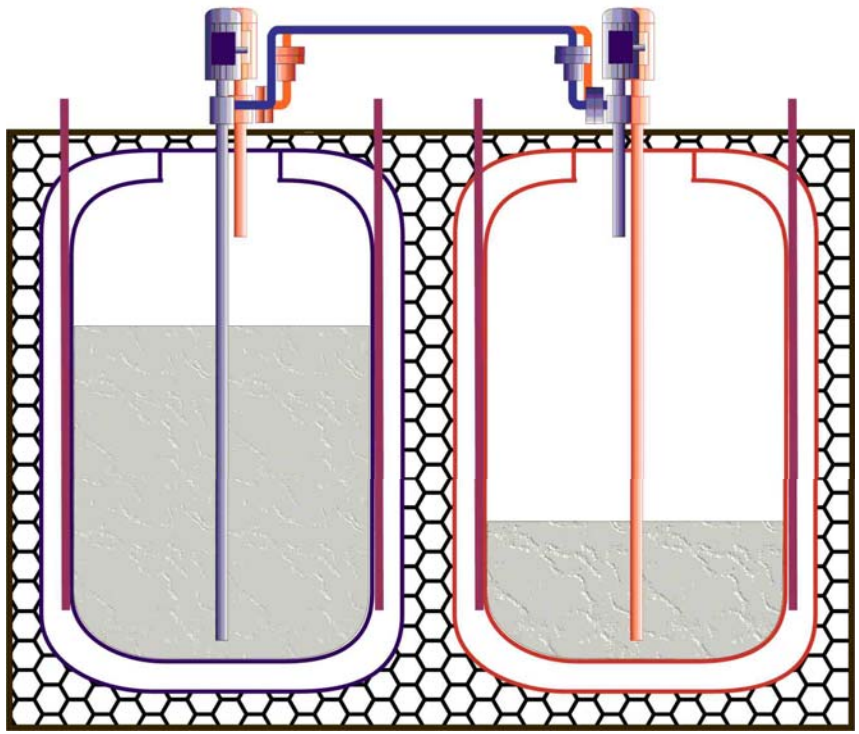


A Lithium Detector

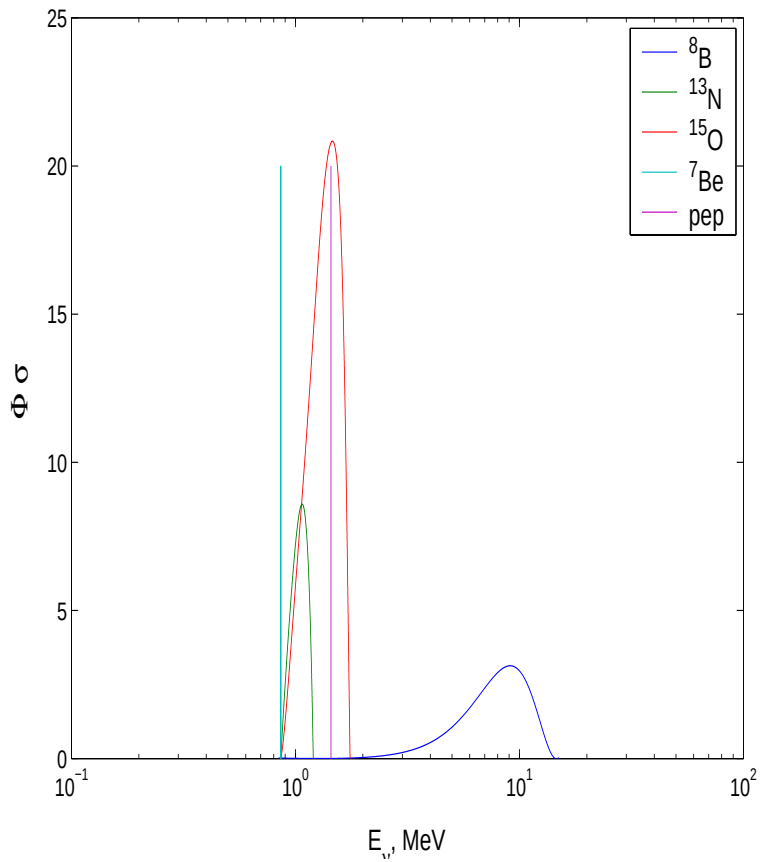


Fig.1 from : A.Kopylov, V.Petukhov, Physics Letters, B 544(2002)11-15

$^{7}Li + \nu_e > {}^{7}Be + e^-$

Both initial and final states are mirror nuclei. The transition is super-allowed. The cross-section is high and can be calculated with very good accuracy, better than 1%.

The abundance of ^{7}Li in natural lithium is high (93%), the mass of the target is small (~10 tons).

The threshold is 0.86 MeV, I.e. very high sensitivity to neutrinos of medium energy

(^{7}Be, pep, CNO)

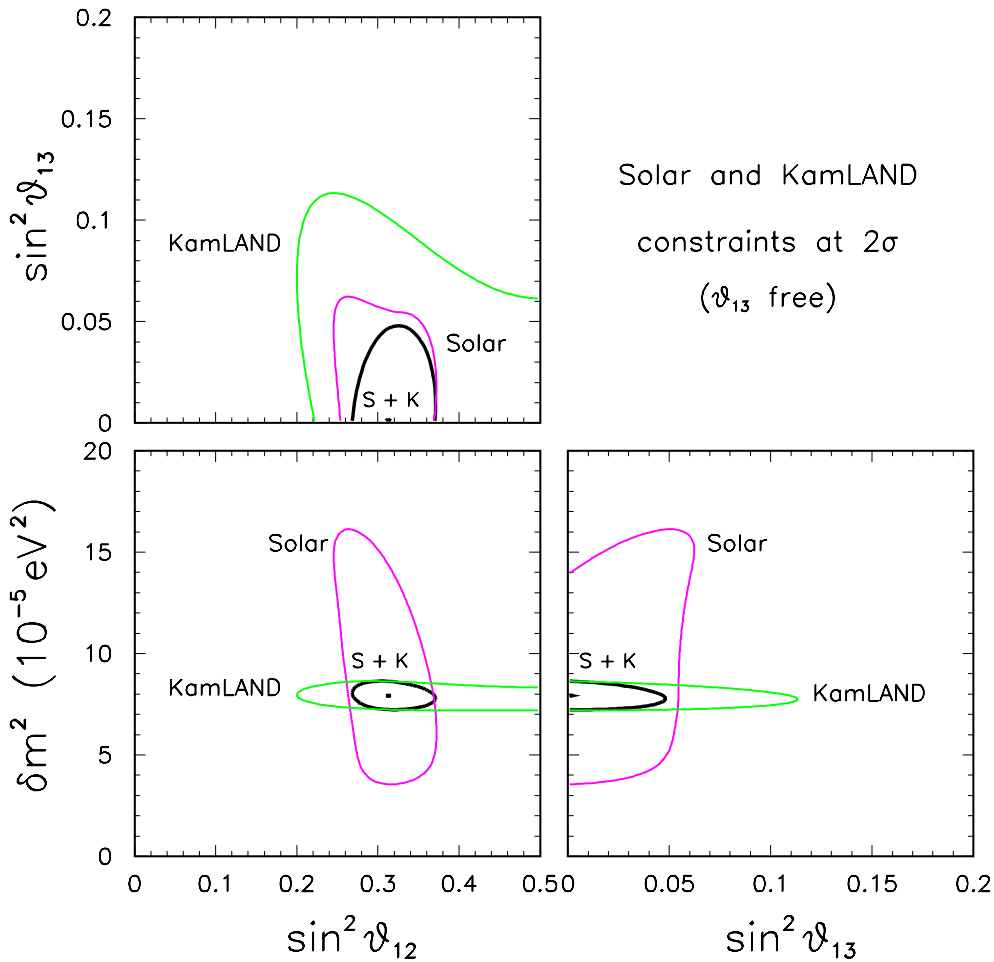
V.A.Kuzmin and G.Zatsepin

On the neutrino spectroscopy of the Sun, in Proceedings of 9th International Cosmic Ray Conference, London, 1965, p.1024

J.N.Bahcall Phys.Lett. **13** (1964) 332

J.N.Bahcall Phys.Rev.Lett. **23** (1969) 251

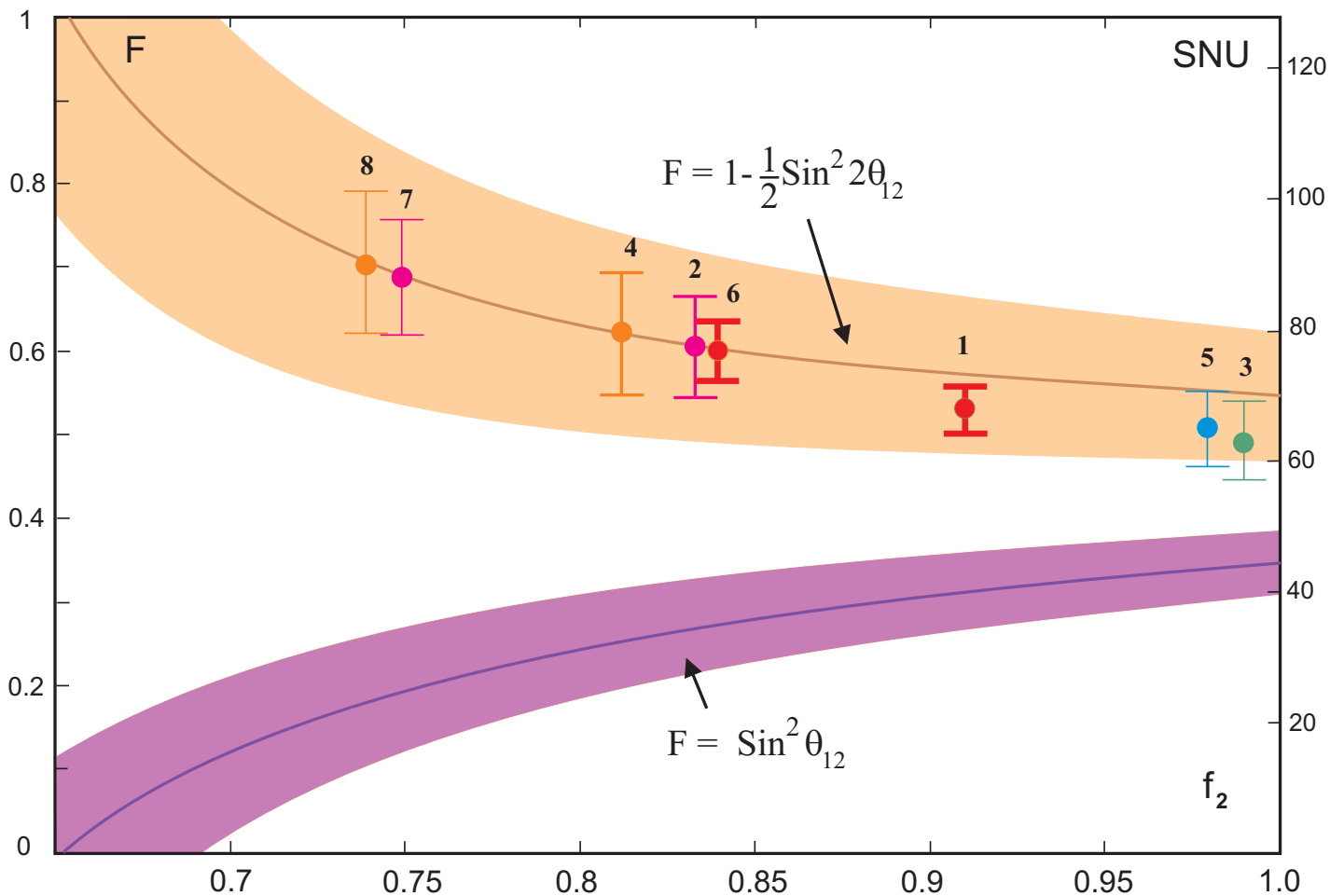
Present status including the latest results of KamLAND (G.L.Fogli et al., arXiv:hep-ph/0506307)



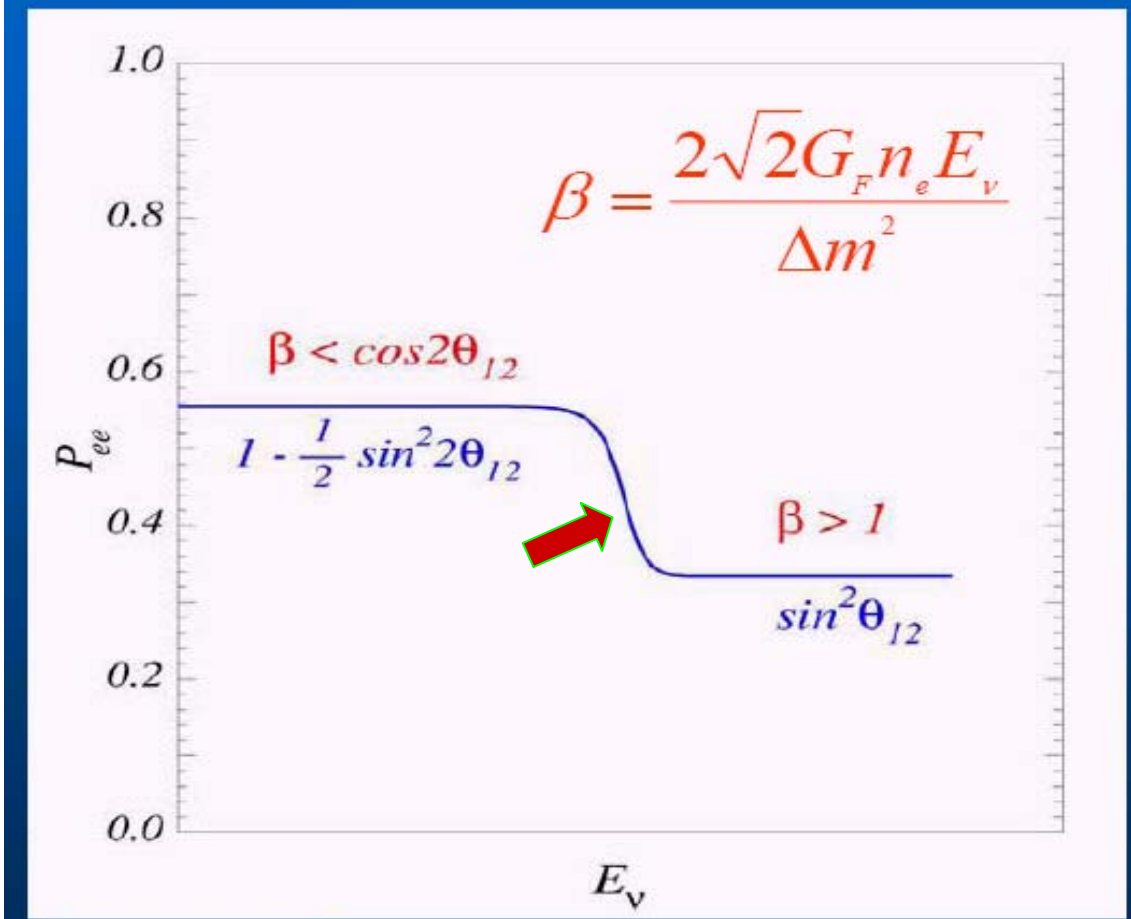
Experimental limit on a mixing angle upon the results of gallium experiments (SAGE, GALLEX, GNO) and SNO:

$CC/NC = (1-f_2)\cos^2\theta_{sol} + f_2\sin^2\theta_{sol} = 0.347 \pm 0.038.$

(A.Kopylov, V.Petukhov hep-ph/0608149.)



The energy dependence of the attenuation factor (not tested experimentally)



$E_{crit}(^8\mathrm{B}) = 1.8\ \mathrm{MeV}$

$E_{crit}(^7\mathrm{Be}) = 2.2\ \mathrm{MeV}$

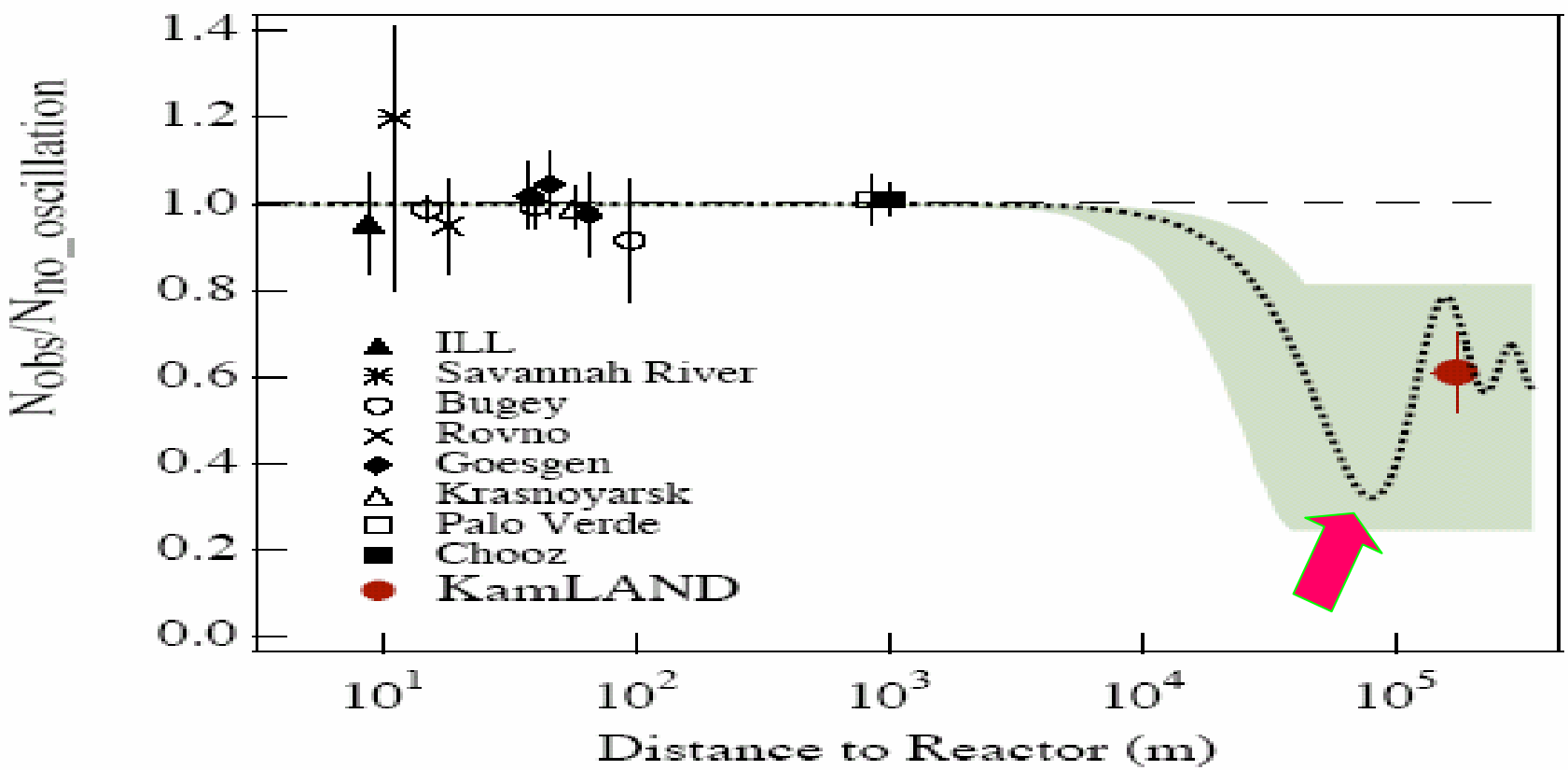
$E_{crit}(\mathrm{pp}) = 3.3\ \mathrm{MeV}$

To determine precisely a mixing angle θ_{12} from vacuum oscillations.

To see the minimum of the oscillation curve.

(at the distance of about 50 km from a reactor,

S.Choubey hep-ph/0402288, Y.Minakata et al. hep-ph/0407326)



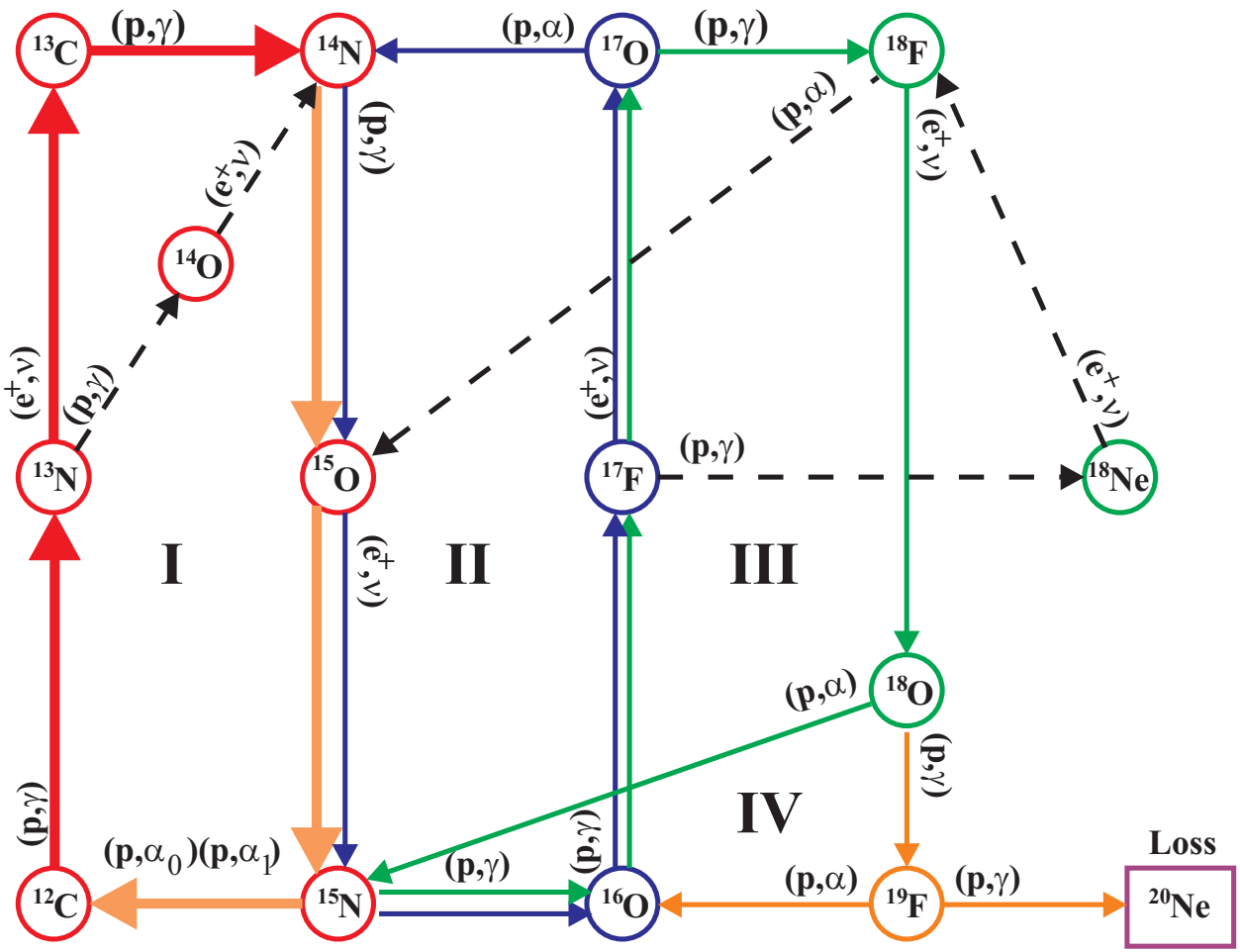
Under the sign "plus" of Δm^2_{12}

The fundamental result gained from the solar neutrino experiments, that a mass state with a larger electron neutrino component has a smaller mass ($m_2 > m_1$ or $\Delta m_{12}^2 > 0$).
Will it be confirmed by a direct experiment?
KamLAND allows both signs for Δm_{12}^2, although the module was determined with a high precision: $(7.9 + 0.6/-0.5)\cdot 10^{-5}$ eV^2.
Important: to measure precisely (~3%) a mixing angle θ_{12} by a dedicated reactor experiment (H. Minakata et al. hep-ph/0407326) and in solar neutrino experiment (M.Nakahata Report at NOW-2004, JAPAN, 2004).
If the mixing angles are different, may be interpreted as:

1. Something omitted in MSW;
2. Some New Physics (NSI of O.G.Miranda, M.A.Tortola and J.W.F.Valle hep-ph/0406280 etc);
3. CPT violation;
4. Something new in the generation of the solar energy;

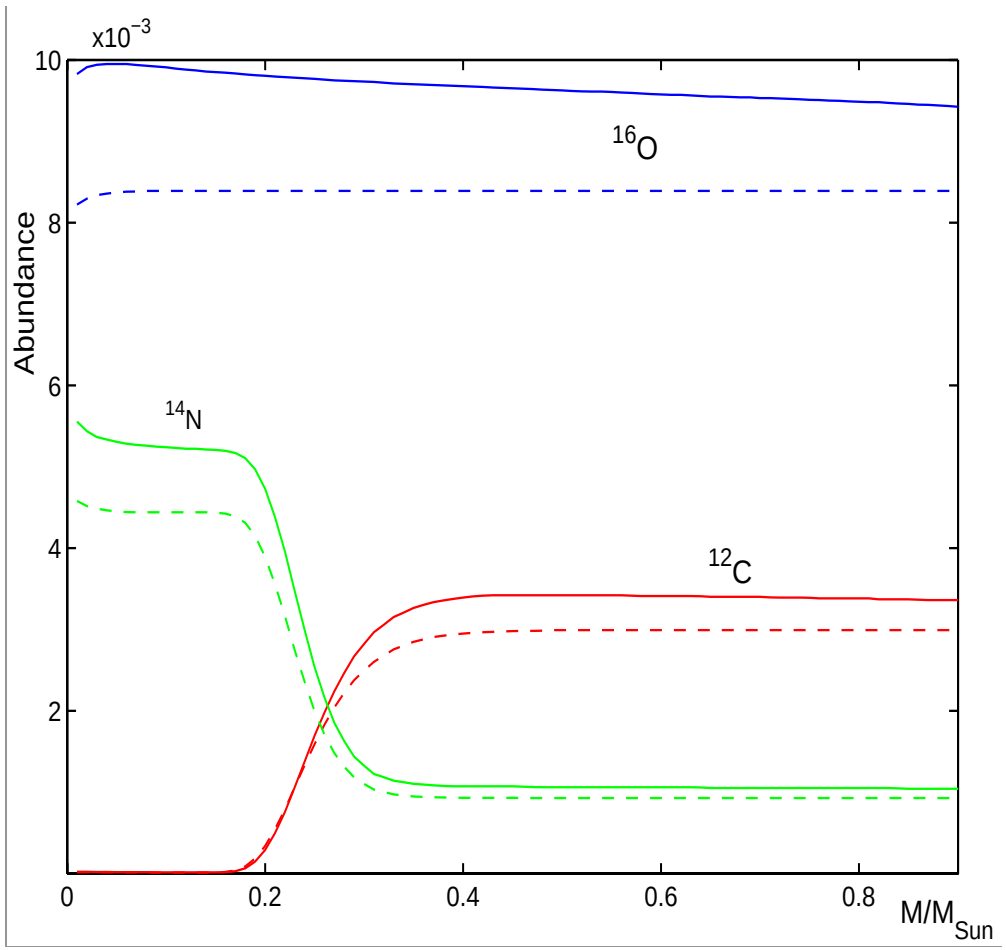
On the schedule:
To measure the energy spectrum of pp-neutrinos;
To measure the fluxes of non-pp neutrinos (^{7}Be- and CNO-);

The task not solved yet – to measure the flux of neutrino from CNO cycle

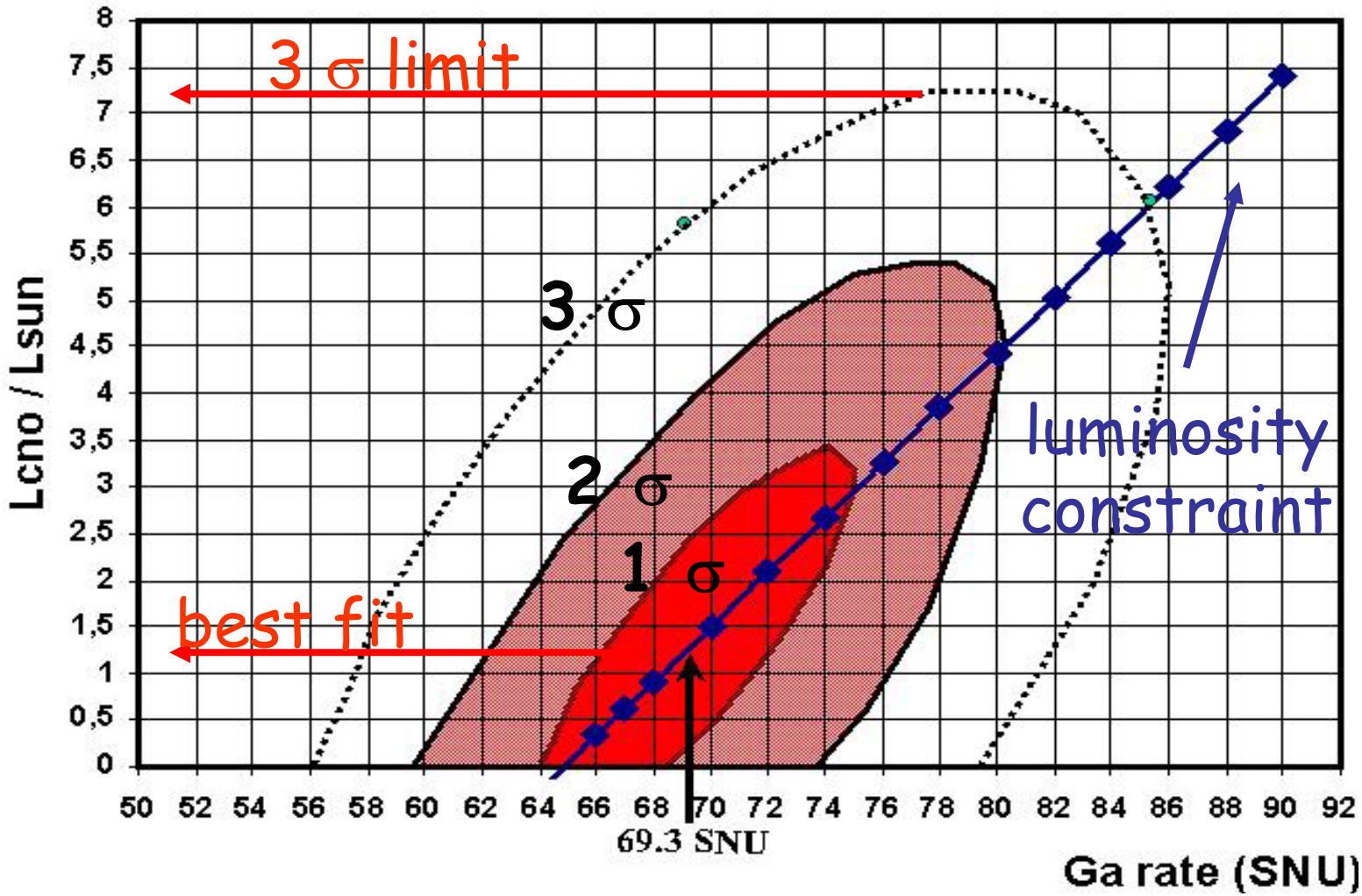


The abundances of ^{12}C and ^{14}N along the profile of the Sun suggested by Standard Solar Model.

- J.N.Bahcall, 1989, *Neutrino Astrophysics*
- But so far – no experimental evidence that CNO does exist, no information on such peculiar distribution of abundances of ^{12}C and ^{14}N
- The energy produced in CNOI and CNOII are very close while the effect in a lithium detector is very different: 1/5 for neutrinos from ^{13}N to ^{15}O
- If all the effect due to ^{13}N neutrinos this will increase the energy produced in CNOI by a factor of 6, what will decrease the energy produced in pp-chain and will give theta solar conflicting with the present result. Depends upon the result of measurements in Li exp.



Important! Here the solar model N14 (Bahcall nomenclature) is used as reference, i.e. the unity on the Y axis take already into account the reduced flux due to new $S_0(^{14}N)$ measurement



The solar ν fluxes

- Bahcall and Pinsonneault hep-ph/0402114

Table 1: Predicted solar neutrino fluxes from solar models. The table presents the predicted fluxes, in units of $10^{10}(pp)$, $10^{9}(^{7}\mathrm{Be})$, $10^{8}(pep, ^{13}\mathrm{N}, ^{15}\mathrm{O})$, $10^{6}(^{8}\mathrm{B}, ^{17}\mathrm{F})$, and $10^{3}(hep)$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Columns 2-4 show BP04, BP04+, and our previous best model BP00. Columns 5-7 present the calculated fluxes for solar models that differ from BP00 by an improvement in one set of input data: nuclear fusion cross sections (column 5), equation of state for the solar interior (column 6), and surface chemical composition for the Sun (column 7). Column 8 uses the same input data as for BP04 except for a recent report of the $^{14}\mathrm{N}$ + p fusion cross section. References to the improved input data are given in the text. We use OPAL radiative opacities calculated for each chemical composition. The last two rows ignore neutrino oscillations and present for the chlorine and gallium solar neutrino experiments the capture rates in SNU (1 SNU equals 10^{-36} events per target atom per sec). Due to oscillations, the measured rates are smaller: 2.6 ± 0.2 and 69 ± 4, respectively.

Source	BP04	BP04+	BP00	Nucl	EOS	Comp	^{14}N
pp	$5.94(1 \pm 0.01)$	5.99	5.95	5.94	5.95	6.00	5.98
pep	$1.40(1 \pm 0.02)$	1.42	1.40	1.40	1.40	1.42	1.42
hep	$7.88(1 \pm 0.16)$	8.04	9.24	7.88	9.23	9.44	7.93
^{7}Be	$4.86(1 \pm 0.12)$	4.65	4.77	4.84	4.79	4.56	4.86
^{8}B	$5.82(1 \pm 0.23)$	5.28	5.05	5.79	5.08	4.62	5.77
^{13}N	$5.71(1\ ^{+0.37}_{-0.35})$	4.06	5.48	5.69	5.51	3.88	3.23
^{15}O	$5.03(1\ ^{+0.43}_{-0.39})$	3.54	4.80	5.01	4.82	3.36	2.54
^{17}F	$5.91(1\ ^{+0.44}_{-0.44})$	3.97	5.63	5.88	5.66	3.77	5.85
Cl	$8.5^{+1.8}_{-1.8}$	7.7	7.6	8.5	7.6	6.9	8.2
Ga	131^{+12}_{-10}	126	128	130	129	123	127

The production rates.

Table 1. Standard Model Predictions (BP2000): solar neutrino fluxes and neutrino capture rates, with 1σ uncertainties from all sources (combined quadratically).

Source	Flux (10^{10} cm^{-2}s^{-1})	Cl (SNU)	Ga (SNU)	Li (SNU)
Pp	$5.95(1.00^{+0.01}_{-0.01})$	0.0	69.7	0.0
Pep	$1.40\times10^{-2}(1.00^{+0.015}_{-0.015})$	0.22	2.8	9.2
Hep	9.3×10^{-7}	0.04	0.1	0.1
^{7}Be	$4.77\times10^{-1}(1.00^{+0.10}_{-0.10})$	1.15	34.2	9.1
^{8}B	$5.05\times10^{-4}(1.00^{+0.20}_{-0.16})$	5.76	12.1	19.7
^{13}N	$5.48\times10^{-2}(1.00^{+0.21}_{-0.17})$	0.09	3.4	2.3
^{15}O	$4.80\times10^{-2}(1.00^{+0.25}_{-0.19})$	0.33	5.5	11.8
^{17}F	$5.63\times10^{-4}(1.00^{+0.25}_{-0.25})$	0.0	0.1	0.1
Total		$7.6^{+1.3}_{-1.1}$	128^{+9}_{-7}	$52.3^{+6.5}_{-6.0}$

The expected rate from solar neutrinos is 25 SNU, of this 8 SNU – from CNO neutrinos, i.e. approx. 30% while the energy produced in CNO cycle is only 1.5%

The task for a lithium detector

- To measure the contribution of CNO-cycle to the solar luminosity and to test a current theory of the evolution of the stars.
- To measure the attenuation factor for neutrinos of intermediate energies and to test a currently accepted separation of the regions of vacuum oscillations and MSW in a matter of the Sun.
- To measure precisely a mixing angle and to test that nothing has been omitted in the current understanding of the neutrino propagation through the matter of the Sun.
- If to determine the fluxes of CNO neutrinos with the accuracy 30% (10% uncertainty in a lithium experiment), the total flux of pp-neutrinos will be found with the uncertainty less than 1% [A.Kopylov, I.Orekhov, V.Petukhov, A.Solomatin, A.Arnoldov hep-ph/0601091]

$$0.913f_{pp} + 0.002f_{pep} + 0.07f_{Be} + 0.015f_{CNO} = 1$$

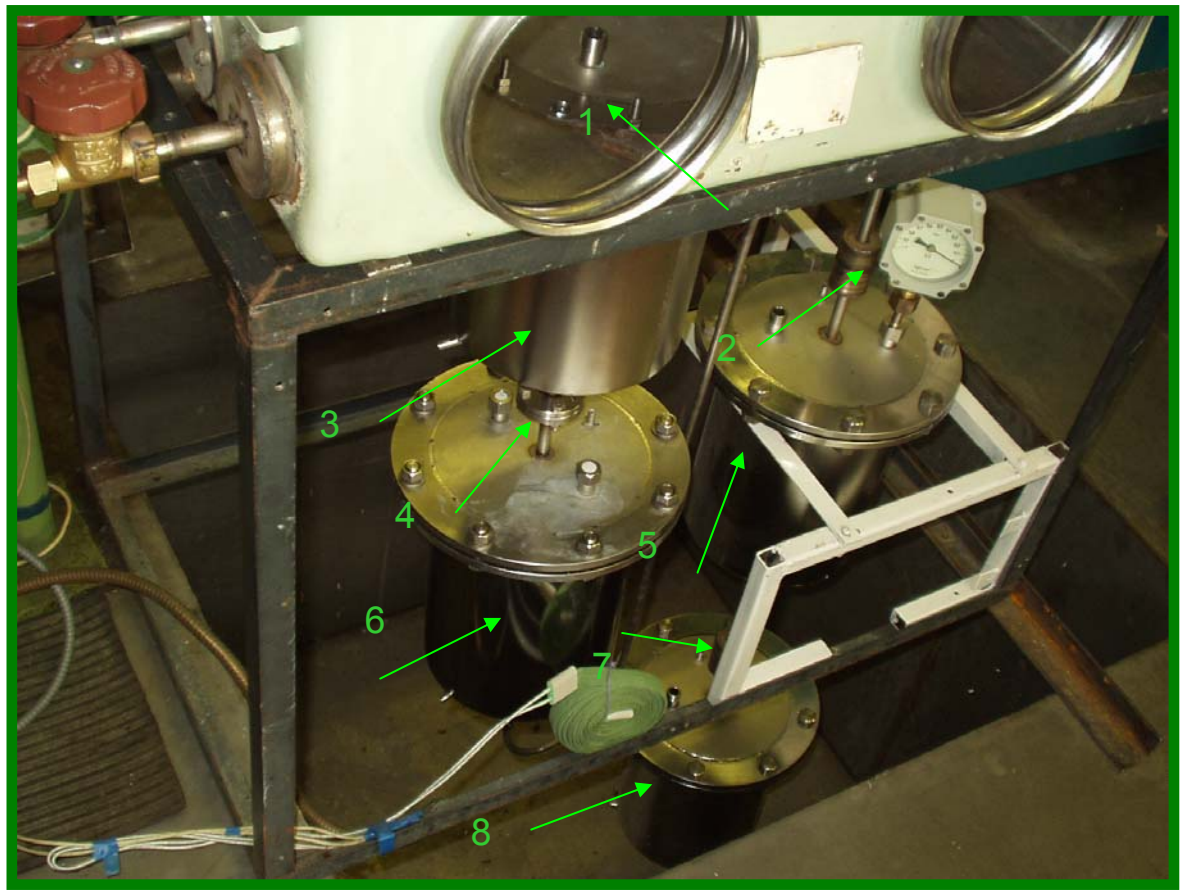
The constant of the solar luminosity has not been changed within a few decimal fractions of a percent.

A Laboratory Stand (without a thermal insulation and heaters)

1. A lithium loading in argon for melting.
2. A filter element
3. A melting cylinder
4. Introduction of the radioactive sample.
5. Receiver 2
6. Receiver 1
7. A filter element
8. Receiver 3.

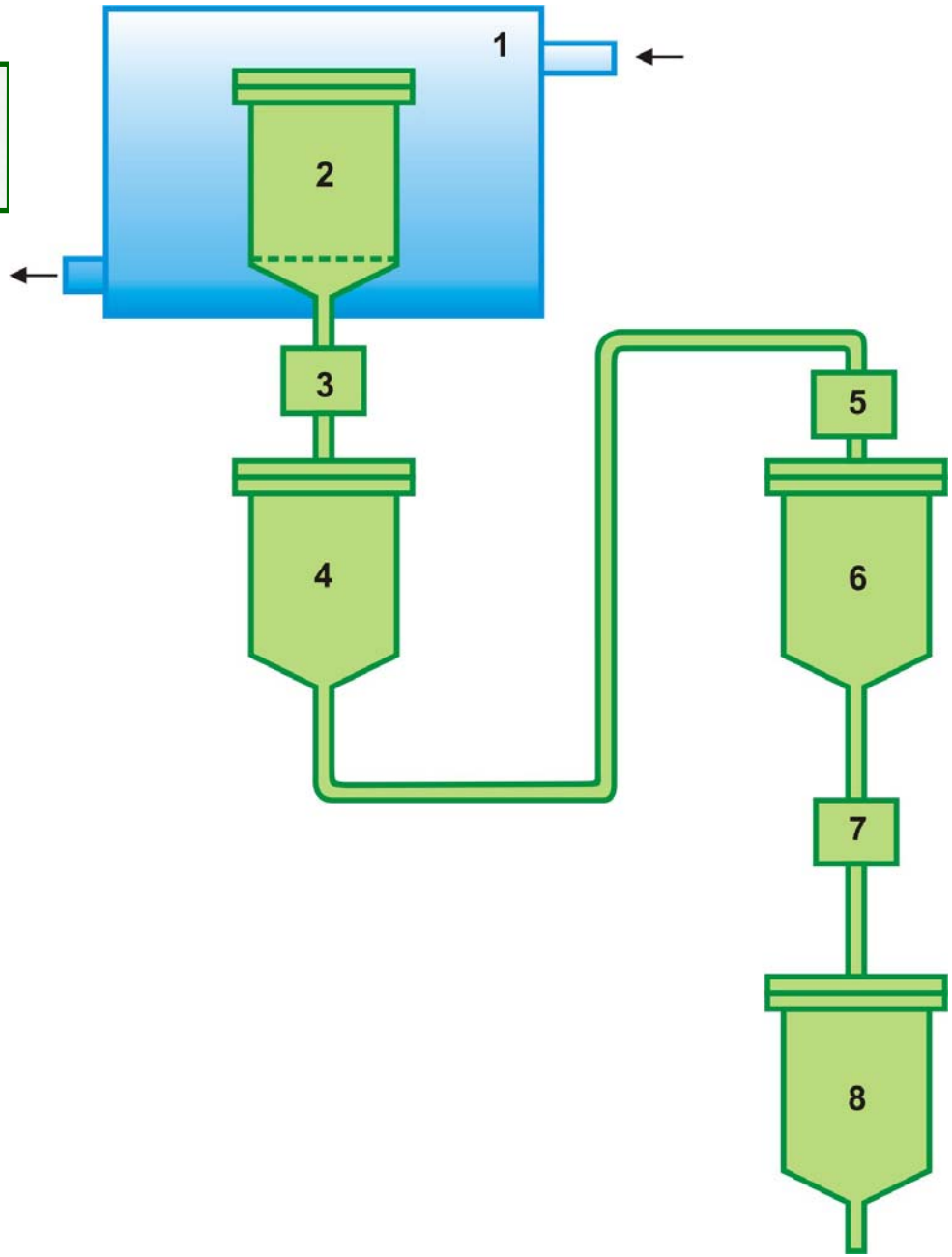
After the operation the system gets disassembled by cutting in pieces, the activity of each part is measured by HPGe detector

Then: the receiver 3 and a melting cylinder get swapped



The scheme of the installation

1. The argon box
2. A melting cylinder
3. Introduction of the radioactive sample
4. Receiver 1
5. A filter element 1
6. Receiver 2
7. A filter element 2
8. Receiver 3



Li

METALLIC LITHIUM
«батарейный» сорт

Внешний вид Металл серебристо-белого цвета
Плотность 0,543 г/см^3
Температура плавления 180 °С
Физико-химические свойства Бурно реагирует с водой. При нагревании на воздухе загорается.
Область применения Анодный материал в производстве химических источников тока.
Форма продукта Слитки цилиндрической формы, диаметром 100-200 мм, высотой 200-400 мм. и др., предназначенные для последующего прессования ленты и фольги
Химический состав
*Массовая доля **лития**, %* 99,9 min
*Массовая доля **примесей**, %*

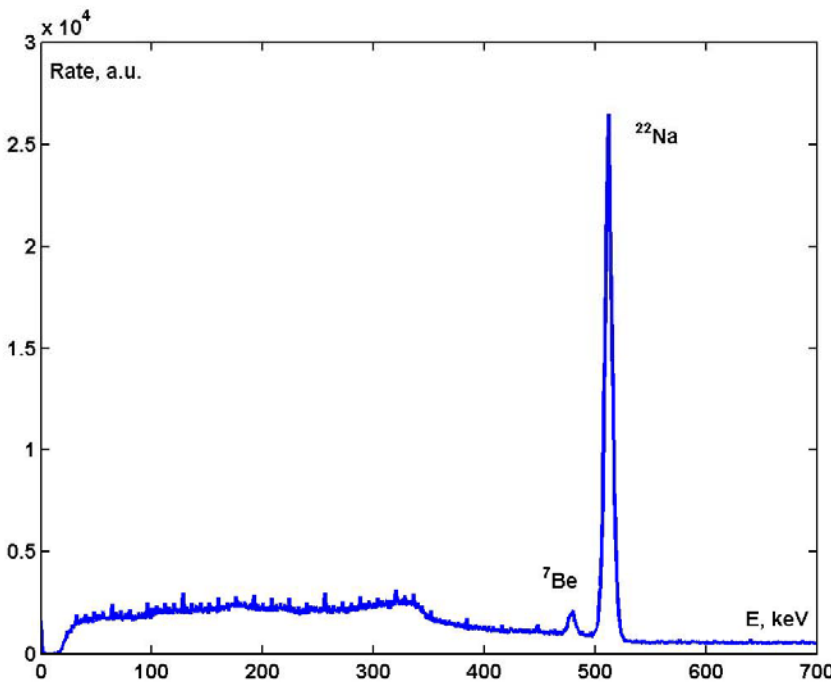
Натрий (Na)	0,02 max
Калий (K)	0,003 max
Кальций (Ca)	0,02 max
Железо (Fe)	0,003 max
Алюминий (Al)	0,003 max
Кремний (Si)	0,01 max
Азот (N)	0,03 max
Хлор (Cl)	0,005 max

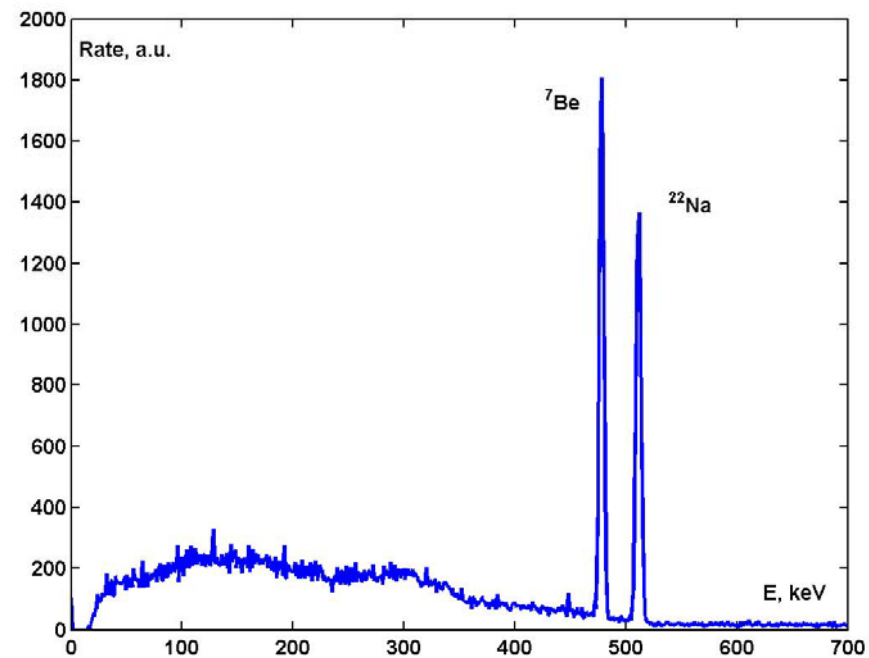
Имеется возможность изготовления продукции по спецификации заказчика.
Упаковка продукта Слитки с обезжиренной поверхностью упаковывают в пакеты из ламинированного алюминием полиэтилена, герметизированные сваркой в среде осушенного аргона и вложенные в пакеты из пузырчатого полиэтилена. Пакеты со слитками укладывают в бочки объемом 210 литров. Предварительно в бочку укладывают охранный полиэтиленовый мешок

Aluminum (30 mg) as a carrier of ^{7}Be.

$^{27}Al(p,X)^{7}Be$ $^{27}Al(p,X)^{22}Na$ $E_p \approx 100$ MeV $t_{exp}=1200$ μA·h

Left – a gamma-spectrum of the aluminum sample (t=1 min) after the irradiation by protons, right – the same after the distillation of sodium during 2 hours at 800 °C in a graphite crucible and a subsequent etching in the hydrofluoric acid. The measurement of the activity of ^{7}Be before and after etching proves that beryllium do not get absorbed by the film of aluminum oxides. This guarantees that beryllium is introduced in a melted lithium homogenously.





In the study it has been found:

The isotope ^{22}Na was found to be completely in lithium in a cylinder №4.

No traces of ^{7}Be were found in lithium in a cylinder №4, i.e. beryllium has been completely extracted from lithium.

No traces of ^{7}Be were found on the walls of cylinder №3, neither in the filters №1 и №2. The overshoot of beryllium through a receiver N1 was less than 1%.

Practically all the activity of ^{7}Be has been precipitated on the film of oxides, trapped by the walls of a receiver №1. A small diameter on the output of a receiver N1 effectively provided it.

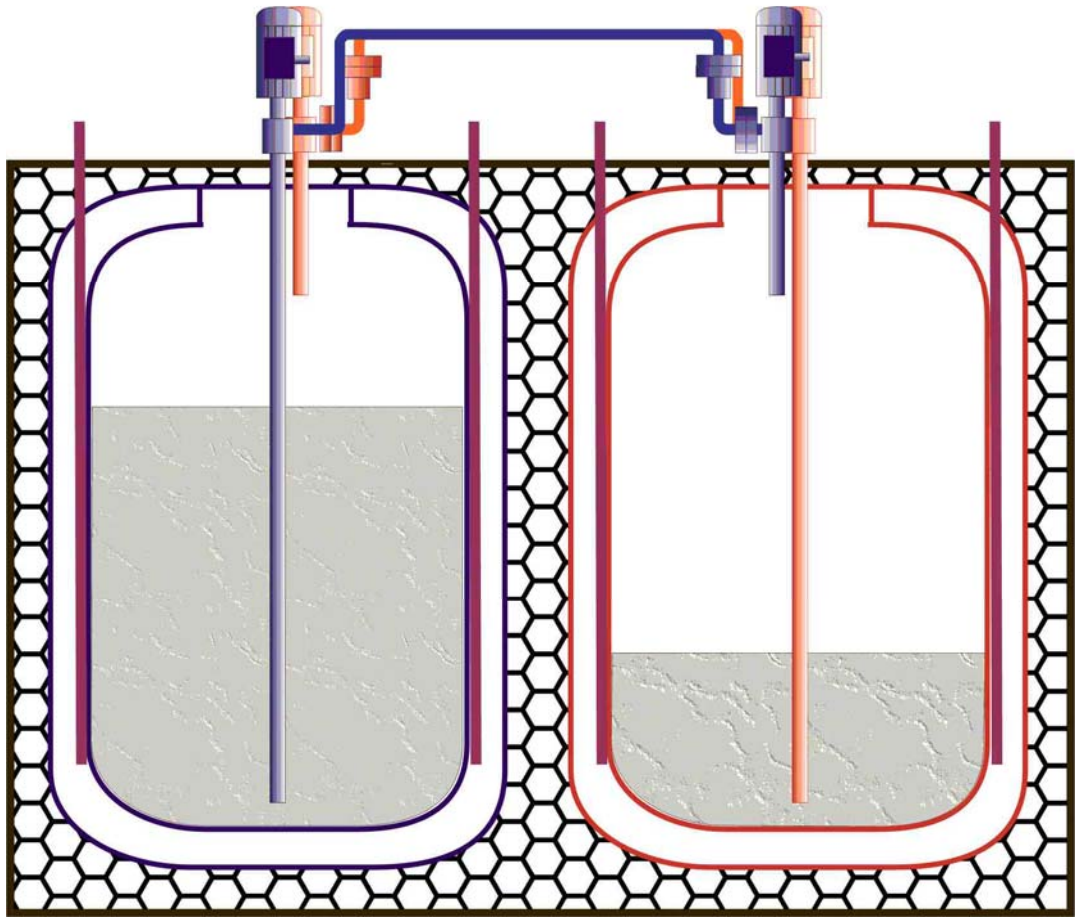
The fact, that all the activity of 7Be was precipitated on the surface, facilitates effective collection of the activity, because it is far more easier to do from the surface than from the volume of the filter and the losses of lithium are minimal in this case. The activity of ^{7}Be was collected from the surface by means of several flushes of the portions of a distilled water onto the surface of a cylinder N1. Each portion of water after the flush passed through a paper filter, and we've got on the output a portion of activity of ^{7}Be in an unsolved residue and a portion – in a solution after the filter. Five flushes 100 ml each has been made. The measurement of the activity has shown that in the first 4 flushes has been collected 96.4% of the activity of ^{7}Be. From this: 61.4% was contained in an unsolved precipitate and 35% - in a solution. The yield of 96.4% is quite good for the realization of a lithium experiment. Then ashless filters were burned and it was shown, by comparing the activity before and after burning procedure that the activity of ^{7}Be has not been lost. This can be explained by the fact that beryllium has no volatile compounds. In this way the efficiency of the extraction of beryllium from a metallic lithium was demonstrated. The further concentration of beryllium has been conducted by the earlier developed technique [30]. The losses of beryllium were minimal (less than 1% in the overall). The analyses of a lithium content in the solutions has shown that losses of lithium during the extraction were less than 1%, this is quite satisfactory for the realization of a lithium experiment.

Upon the results of the study the technical guidelines were formulated:

1. A thermostatic mode should be implemented.
2. The optimal lay-out is a modular structure of the installation (20 modules, each module contains 500 kg of lithium).
3. To use a cross-flow design of the lithium tanks. Each module is composed of two tanks with a thermal insulation in a common housing. Lithium is transported from one tank to another and vice versa.
4. After lithium gets transferred from a tank, beryllium in the lithium films gets washed out from the walls by means of several portions of a distilled water.
5. Filtration of a solution with a precipitate through ashless filters. The solution and a dry residue – on the output.
6. Concentration of the solution till a dry sample.

These technical guidelines is a basis for the design of a pilot installation on one lithium module.

Module on 500 kg of lithium (a pilot installation).
1400x2800 mm, h=2.5m

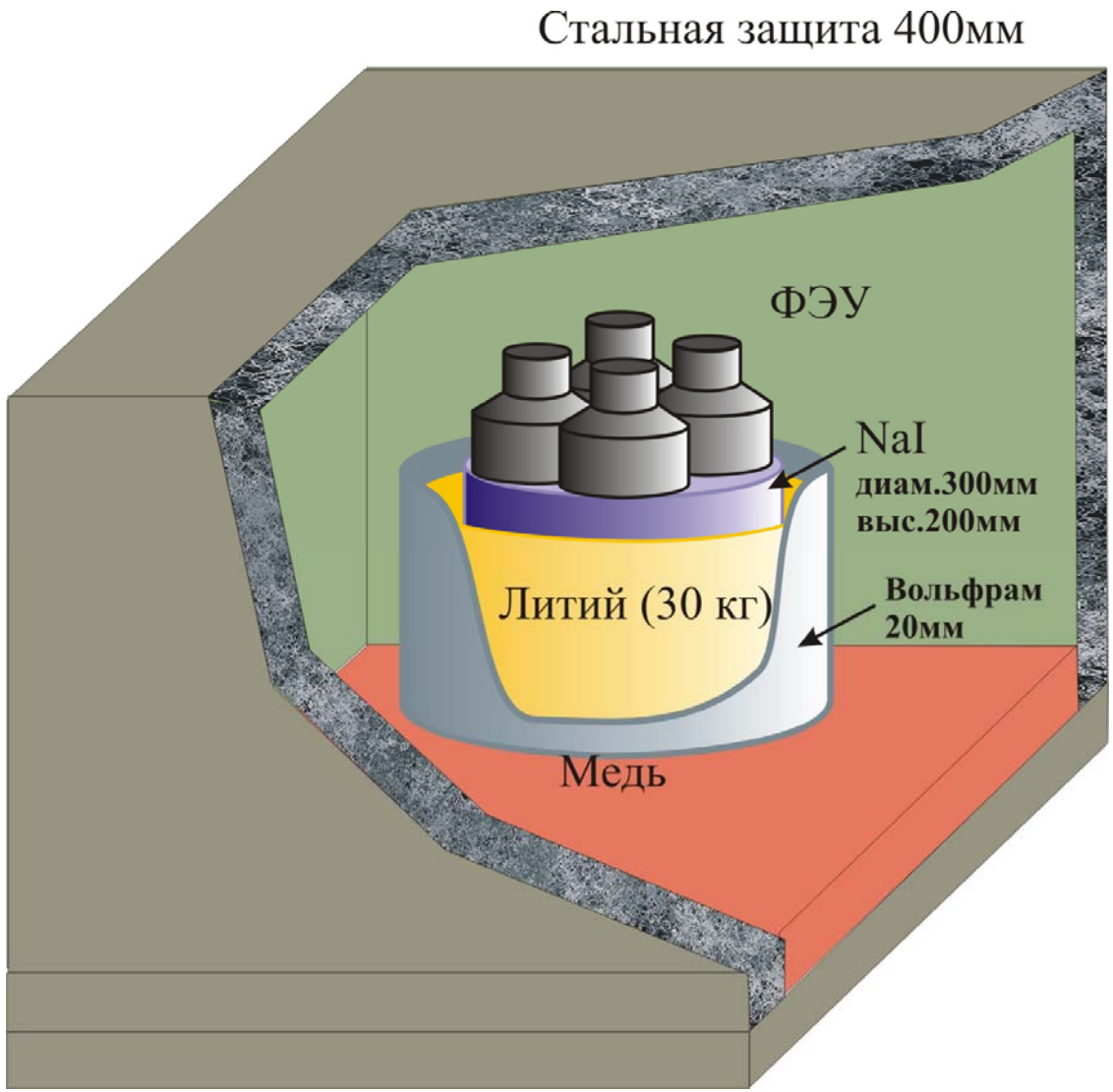


The advantages of a modular structure.

- Each module after the exposure at the site on a surface will be brought to an underground chamber and ^{7}Be generated at the surface by a nucleonic component of CR will be extracted from lithium. This will provide statistics (20 measurements) adequate to determine the scattering of the points relative to a medium value and will enable to compare the results of measurements with the coefficients found from the ratio of the extracted to inserted beryllium sample as a carrier of ^{7}Be.
- The modular structure is useful also to extrapolate the yield of ^{7}Be by CR placing the modules at several shallow depths and measuring the depth curve of the yield as it has been done in a chlorine experiment.

- The work will be done with one module after another. Lithium (500 kg) will be melted, after this beryllium will be extracted and the activity of ^{7}Be will be counted by HPGe detector. For the power of electric heaters minus thermal loss 5 kW, the time needed for heating lithium from 20°C till a melting point, for melting lithium and heating lithium till 200°C will be approximately 2 days. The time needed to complete all procedures with one module including all chemistry and counting of ^{7}Be will take approximately a week. So in half a year starting from the beginning of transportation of lithium modules underground the full scale lithium installation on 10 tons of lithium will be ready for first exposure. The measured coefficients of extraction will show how many cycles of extractions are needed to remove all cosmogenic ^{7}Be from lithium.

The measurement of the concentration of ^{232}Th (on ^{208}Tl) and ^{238}U (on ^{214}Bi) using a gamma spectrometer NaI(Tl)



$$W = \frac{\sqrt{N}}{mtq\ \eta\varepsilon}$$

The measurement of the upper limit of the conc. of 238U/232Th

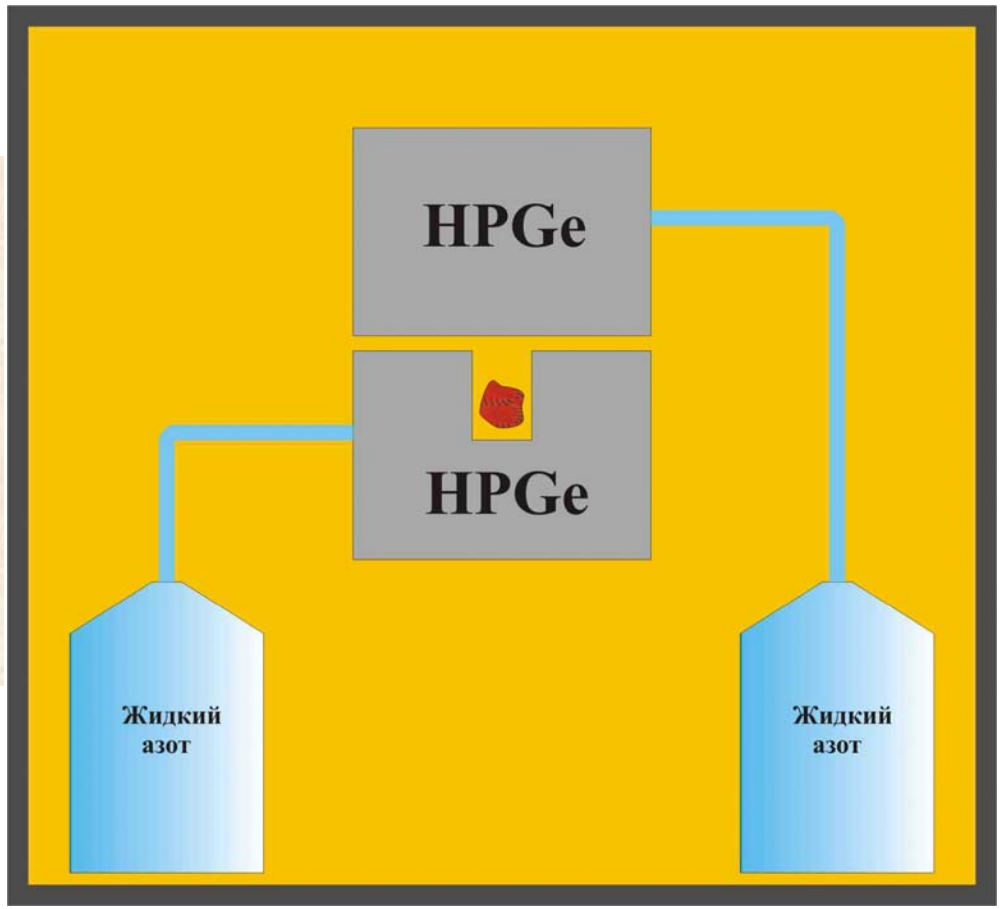
N – number of pulses within FWHM of the peak , m = $3x10^4$ г – mass of the sample, t – time of measurement, q – specific activity of the nuclide (decays/g/sec), η – quantum yield, ε – efficiency of the counting .
Calibration has been done by ^{22}Na , peaks 511 and 1275 keV (511 and 1275 channels).
Resolution on 511 кэВ about 22% (file *Cal_comp511.agr*).

Time of measurement of background – 60,7 days, of lithium – 48,1 days.

E, KeV	R, %%	Region of the peak, chann.	t, sec (days)	√N/t, сек$^{-1}$	q, decays/g/sec	η	ε	W 10^{-9} g/g
511	22							
1275	*14*							
1461	13				$2.6x10^5$	0.11 ^{40}K	0.014	
The measurement of the background (22.04.05 – 1.07.05)								
1765	*12*	*1553-1977*	5243711 (60.7)	0,000463	$1.2x10^4$ ^{238}U	0,18 ^{214}Bi	*0.014*	0.5
2615	*10*	*2354 2877*	5243711 (60.7)	0,000357	$0.3x10^4$ ^{232}Th	1 ^{208}Tl	*0.016*	0.25
The measurement of lithium (7.02.05 – 28.03.05)								
1765	*12*	*1553-1977*	4158961 (48.1)	0,000506	$1.2x10^4$ ^{238}U	0,18 ^{214}Bi	*0.014*	0.56
2615	*10*	*2354 2877*	4158961 (48.1)	0,000397	$0.3x10^4$ ^{232}Th	1 ^{208}Tl	*0.016*	0.28
The measurement of lithium (22.07.04 – 28.09.04)								
1765		*395-470*	3402894 (39.4)	0,000524	$1.2x10^4$ ^{238}U	0,18 ^{214}Bi	*0.014*	0.58
2615		*550-718*	3402894 (39.4)	0,000513	$0.3x10^4$ ^{232}Th	1 ^{208}Tl	*0.016*	0.36
The measurement of lithium (total)								
1765			7561855 (87.5)	0,000365	$1.2x10^4$ ^{238}U	0,18 ^{214}Bi	*0.014*	**0.4**
2615			7561855 (87.5)	0,000318	$0.3x10^4$ ^{232}Th	1 ^{208}Tl	*0.016*	**0.22**

The counting of ^{7}Be by the HPGe detectors.

- The line 478 KeV in 10% of ^{7}Be decay
- The background from 511 keV
- To discriminate background of 511 kev one needs very high resolution → HPGe detectors



Background spectrum taken with 2 twin HPGe detectors (1116 g and 1105 g)

R.L.Brodzinski et al (NIM A292 (1990) 337-342

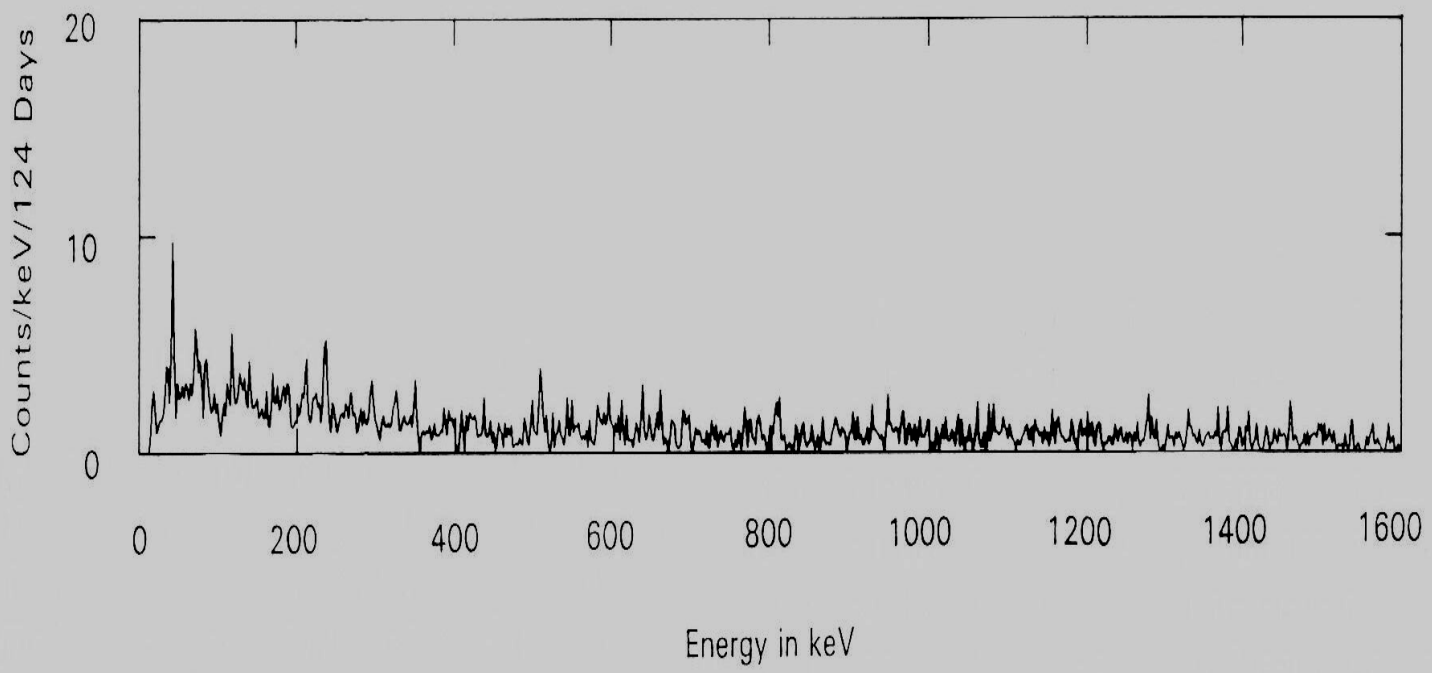
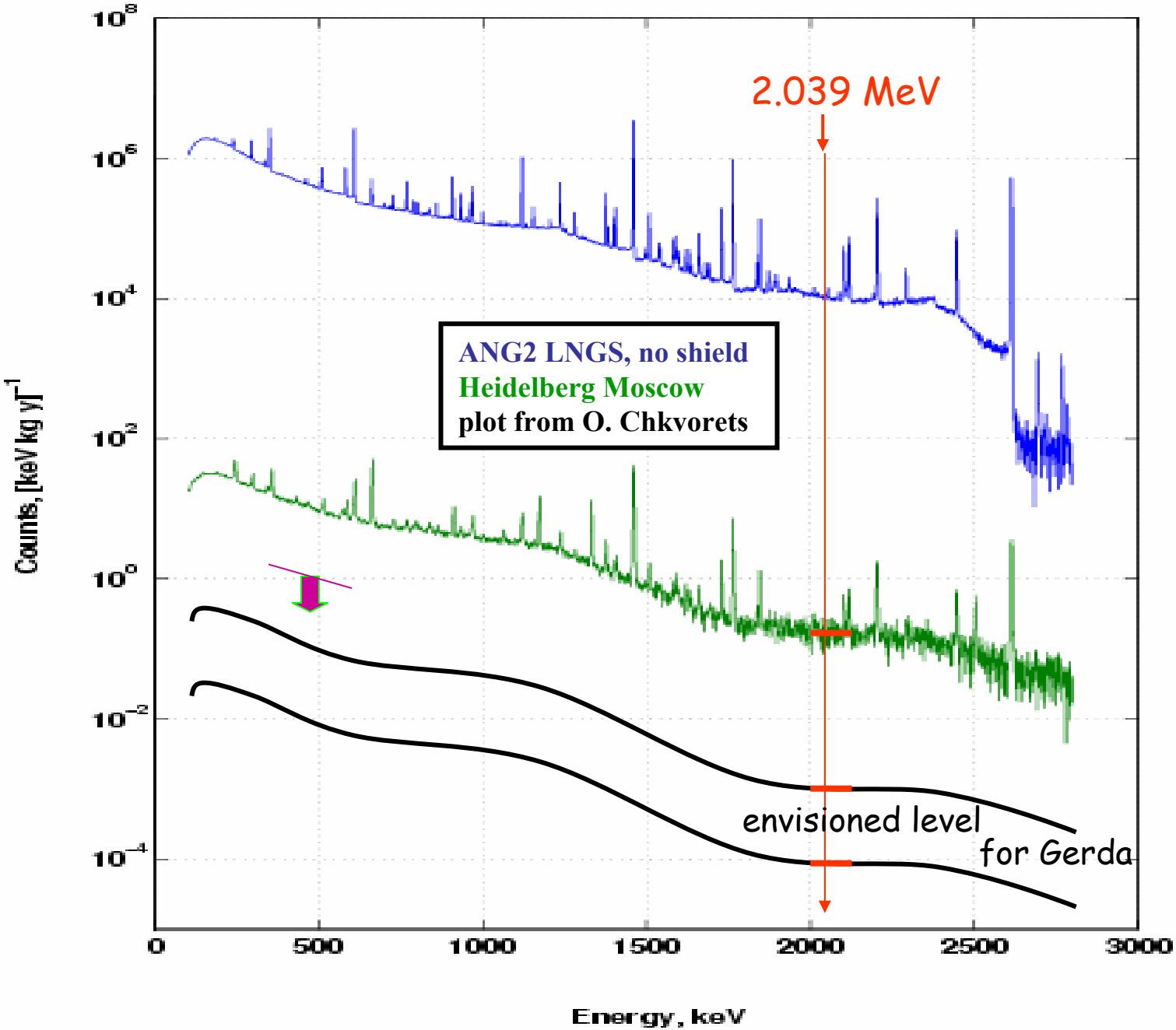
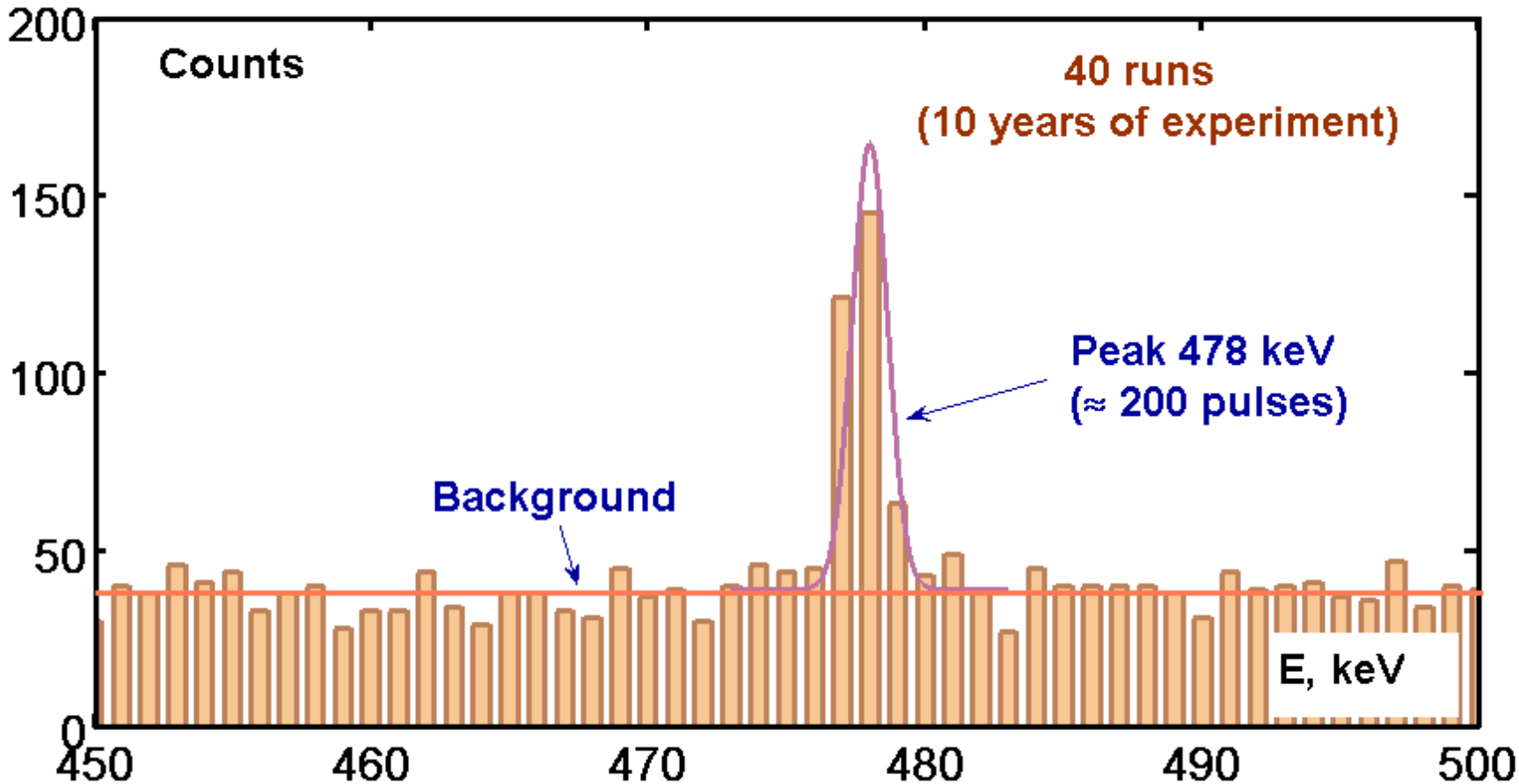


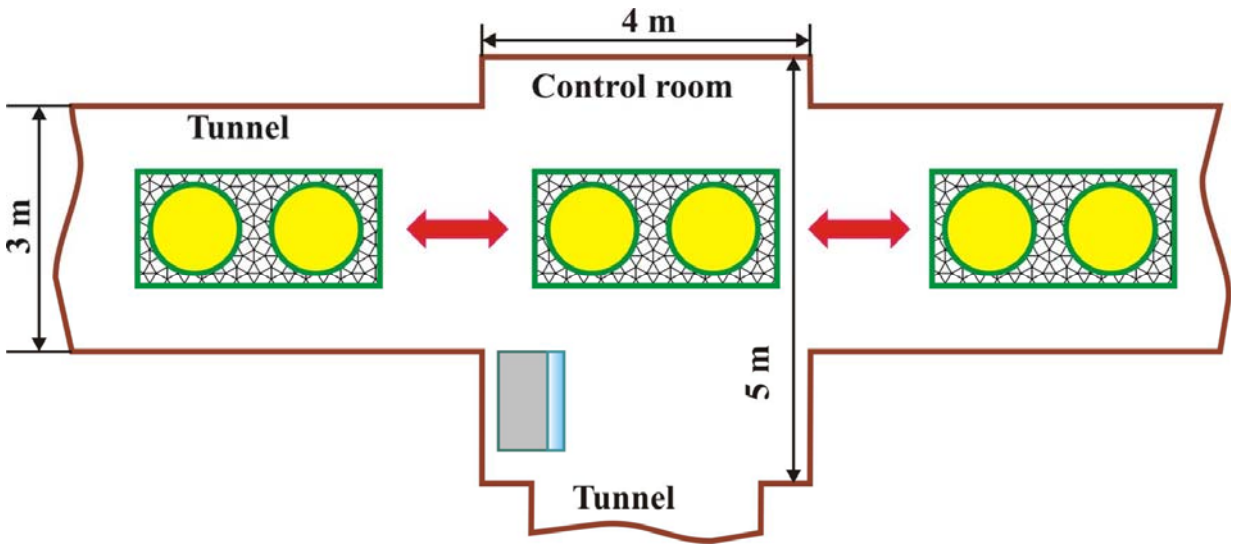
Fig. 6. Current data from twin detectors normalized to 124 days live time and previous detector volume.


2.039 MeV
ANG2 LNGS, no shield
Heidelberg Moscow
plot from O. Chkvorets
envisioned level
for Gerda
Counts, [keV kg y]$^{-1}$
Energy, keV
10^8
10^6
10^4
10^2
10^0
10^{-2}
10^{-4}
0
500
1000
1500
2000
2500
3000

The simulation of the result after 40 runs of experiment using HPGe counting system in 4π geometry



A technical feasibility of the project



Variant with a small control room (method with an assembly line).

- Lithium modules are placed in a tunnel at depth of about 3500 m.w.e. and are transported by turns to a special hall (control room), where beryllium are extracted from lithium.
- A control room with an isolated entrance is placed at the joining of tunnels (~ 4m x 5m in plane with a hight 3.5 m) and is instrumented with an adequate equipment for the technology (electric equipment, ventilation with an air dehumidifier, a vacuum line, an argon line etc.)

Specific Infrastructure Requirements Underground
Basic Requirements

Item	Comments/Details
Depth	At 3300 m.w.e. the background from muons ~ 0.33 SNU
Hall A for the apparatus	4m x 5 m h=3.5 m
Low background hall B for counting of ^{7}Be	3m x 5 m h=3.5 m
Electric power(~ 12 days each 3 months)	~30 kW
Cooling of hall A	~5 kW of a thermal release during a run time

Specific Infrastructure Requirements Underground
Background Tolerances

Item	Comments/Details
Muons	Depth 3300 m.w.e. is OK
Gamma Rays	Not important
Neutrons (< 10 MeV) Neutron flux $=10^{-6}$ n/cm^{2}sec Surface of 20 lithium containers = 100 m^2 Time - 1day (8.64E4 sec) Yield of ^{7}Be per fast neutron : $7\cdot10^{-4}$x$5\cdot10^{-4}=3.5\cdot10^{-7}$ **Background from neutrons:** **0.03 atoms of ^{7}Be/day (< 2% of CR)**	< 10^{-6} n/cm^{2}sec (As a mean energy of fast neutrons it was taken here 6.0 MeV, then a proton with energy 3.3 MeV is generated in (np) reaction on ^{6}LI; the yield of ^{7}Be in a metallic lithium per one proton of 3.3 MeV is $5\cdot10^{-4}$) **Capture Rate @ 25 SNU:** **10^7 x 0.93/7 x $6\cdot10^{23}$ x $25\cdot10^{-36}$x $8.64\cdot10^4$ = 1.7 atoms of ^{7}Be/day**
Neutrons (> 10 MeV)	Depth 3300 m.w.e. is OK
Radon	Not important
Shielding Requirements	If the flux of fast neutrons in Hall A > 10^{-6} n/cm^{2}sec some neutron shield will be required

Conclusions:

- The development of a lithium technology for the detection of solar neutrinos has been principally solved on the laboratory installation.
- The optimal conditions are found and the coefficient of extraction of beryllium 96% is obtained.
- It has been shown that losses of lithium during the extraction procedure are less than 1%.
- The upper limit on the concentration of 238U/232Th 10-9 g/g (in the condition of equilibrium with daughters) was obtained by means of a low background spectrometer using detectors NaI(Tl). By this limit the background from an internal 238U/232Th contamination will be less than 1% of the effect from solar neutrinos.
- The results obtained demonstrate the feasibility of the realization of the full scale lithium experiment on solar neutrinos on 10 tons of lithium using 20 lithium modules each 500 kg lithium. The installation can be placed in the junction of two tunnels at the depth of about 3300 m.w.e. and do not need the excavation of the special chamber, what makes the project far less expensive.
- Next phase – the construction of a pilot installation on 500 kg of lithium (one lithium module).