MOON (Mo Observatory Of Neutrino)

Spectroscopy of Inverse-β Decays & $\beta\beta$ Decays from ^{100}Mo For Solar ν & ν Masses

1. Unique features of MOON
2. Sensitivities and Background
3. Possible MOON Detector
4. Present Status

nucl-ex/9911008, Phys. Rev. Lett. 85(2000)2917

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Unique Points for Double-Beta Decay of ^{100}Mo

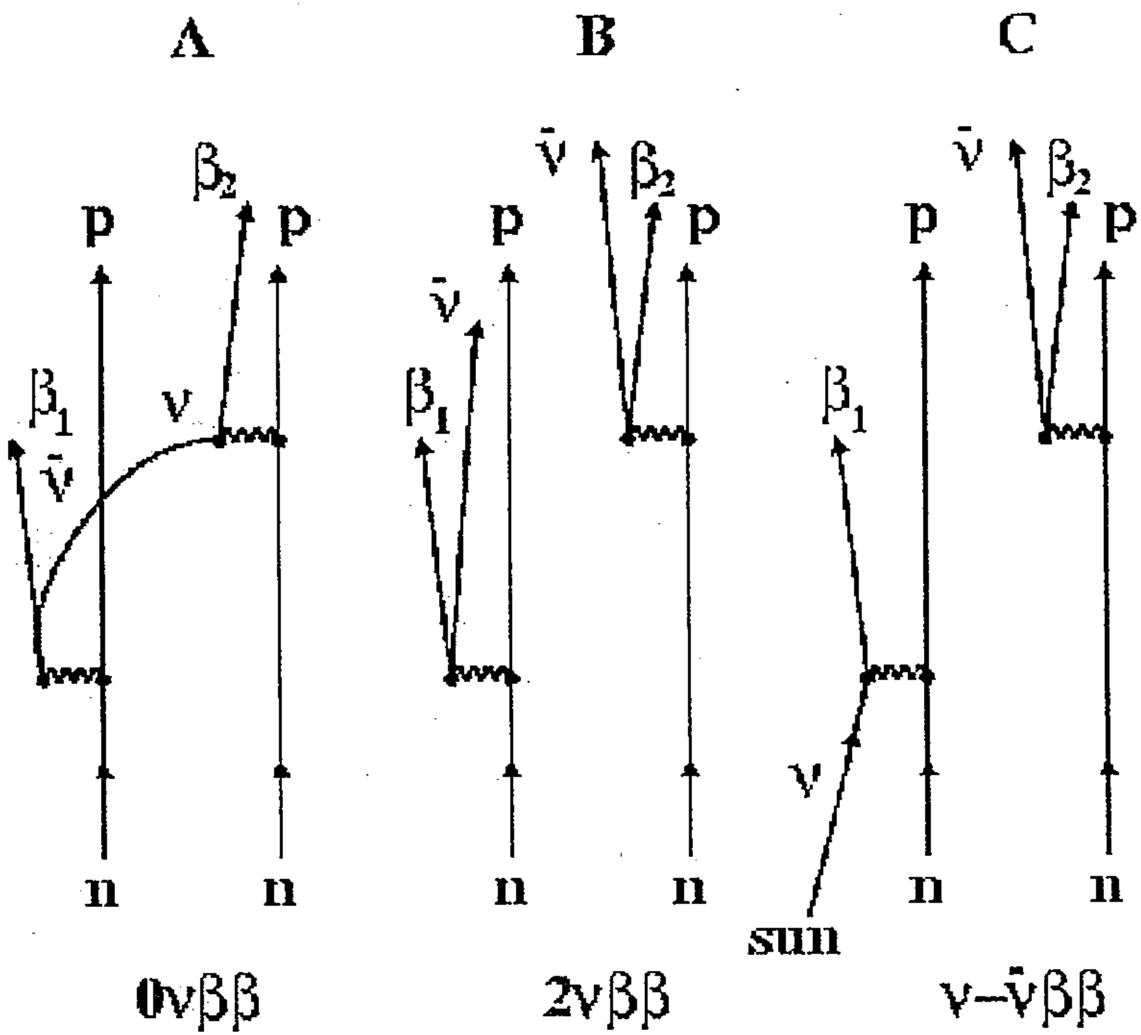
1. Potential of Majorana-ν mass ~ 0.03 eV

2. Large Q-Value of 3 MeV to Enhance $0\nu\beta\beta$ & put the Signal Far Above BG

3. Spectroscopic Studies of Two Beta-Rays to identify the ν-mass Process

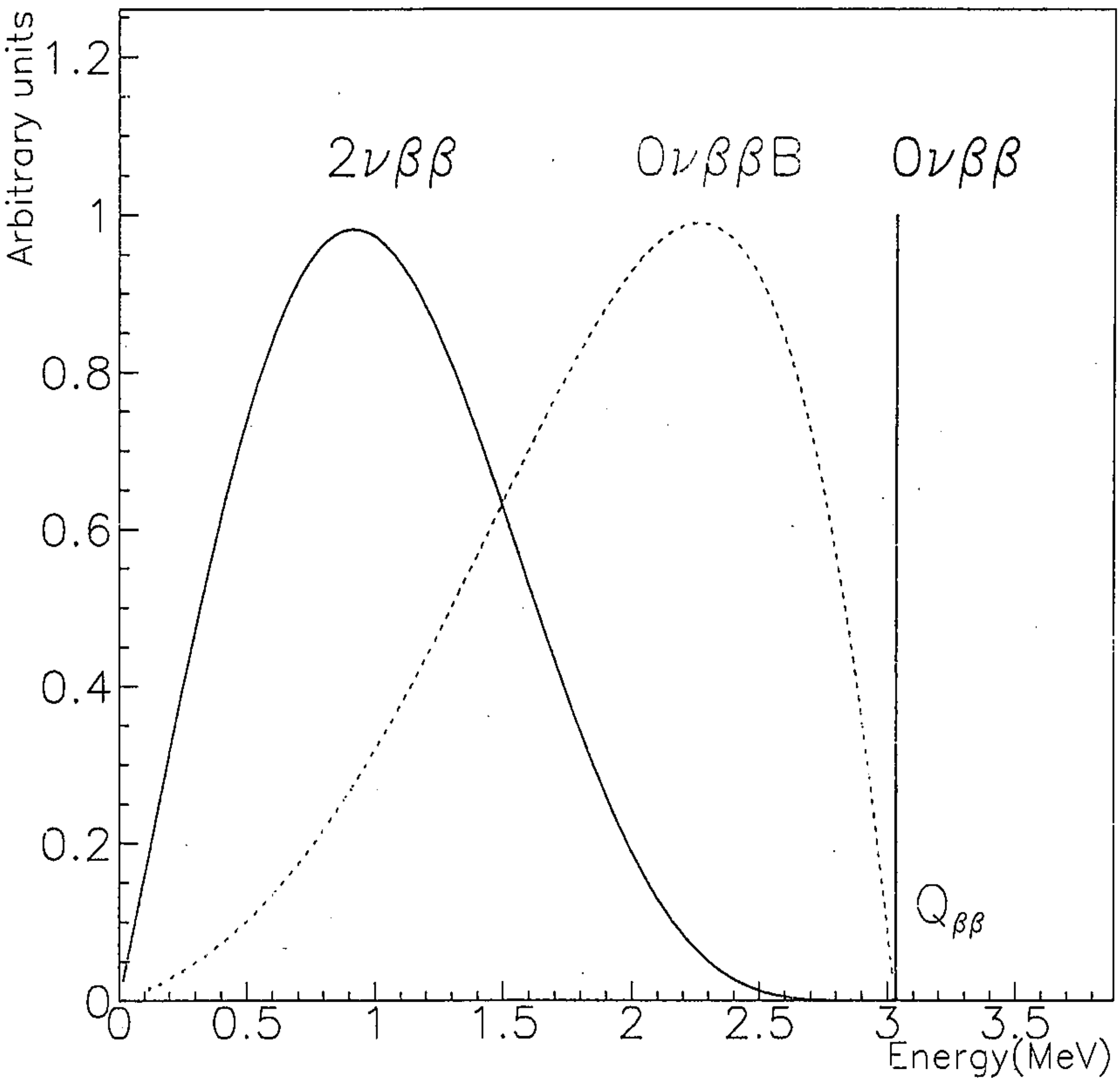
4. Large Known Nuclear Responses by $2\nu\beta\beta$ & Nuclear Reactions

5. Based on Studies With ELEGANT Detectors at RCNP, Osaka

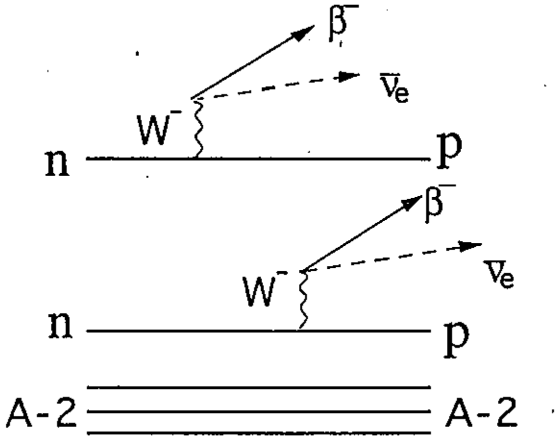


$E_1 + E_2$ Spectra

(calculated for $\beta\beta$ of ^{100}Mo)



Within Standard Model

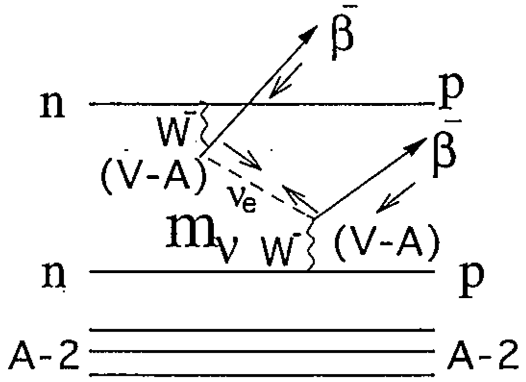


2νββ

So far ELEGANT V

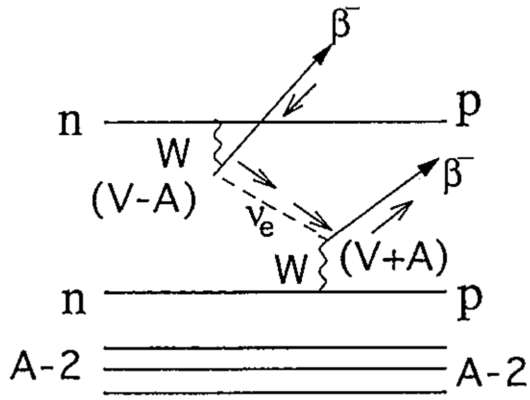
	$T_{1/2}$
^{100}Mo	$1.15^{+0.3}_{-0.2} \times 10^{19}$ y
^{116}Cd	$2.6^{+0.9}_{-0.5} \times 10^{19}$ y

Beyond Standard Model



0νββ (mass term)

$\longrightarrow m_\nu$



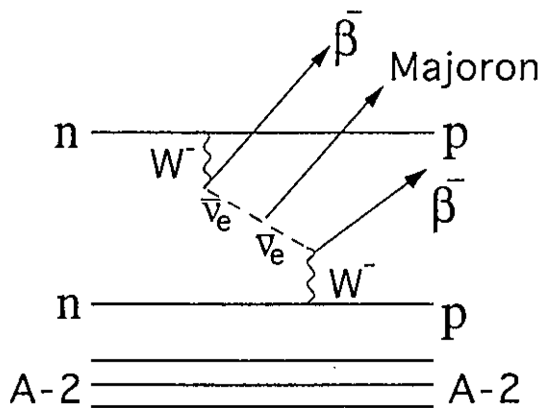
0νββ (V+A term)

$$\longrightarrow \lambda \sim \left(\frac{M_L}{M_R}\right)^2$$

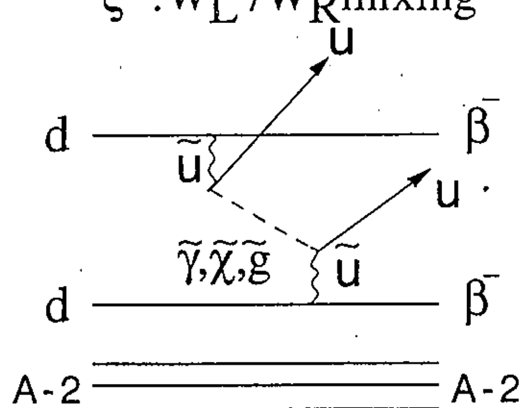
$$\eta \sim -\tan\zeta$$

M_L, M_R :boson mass

ζ :W_L/W_R mixing



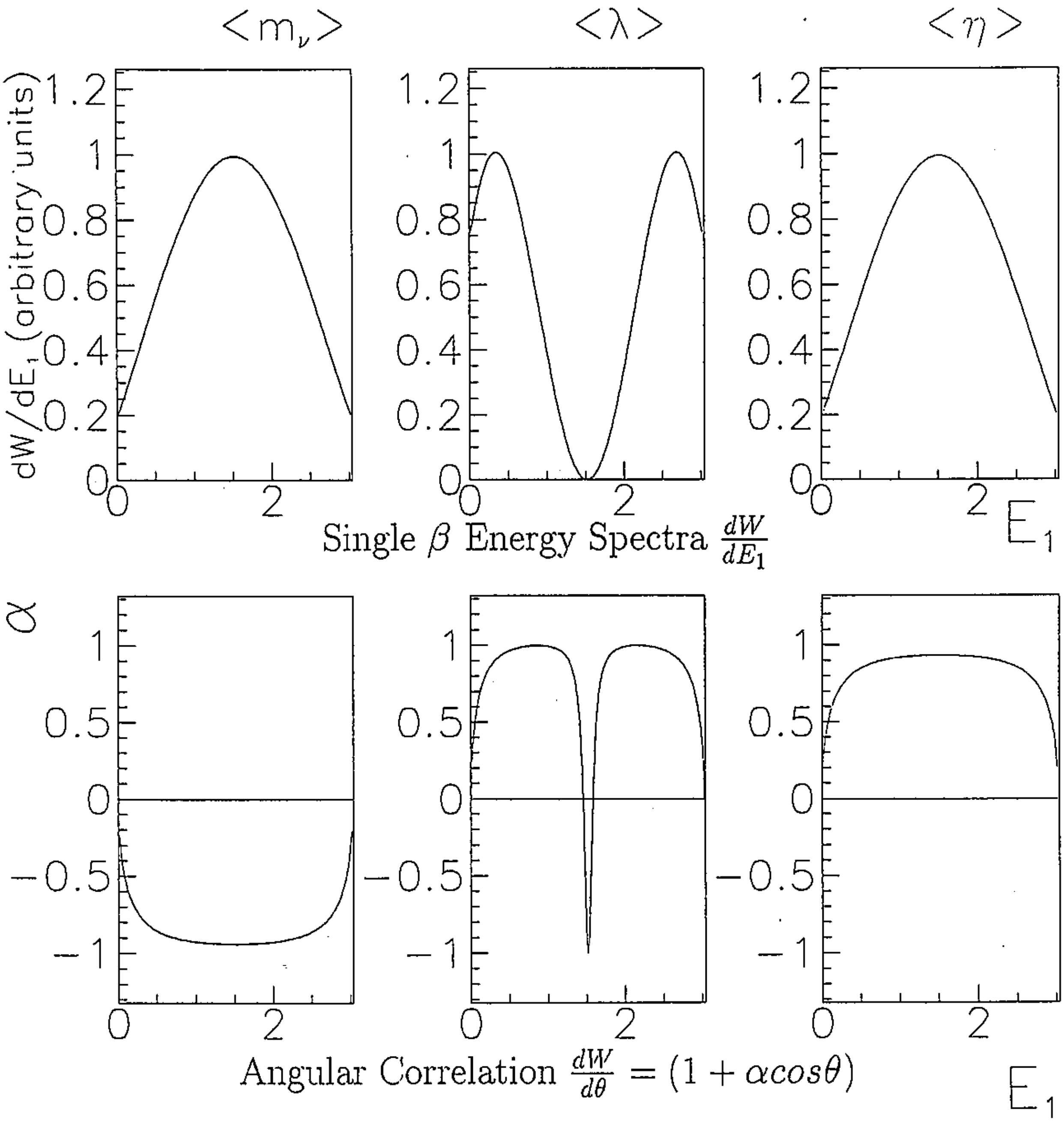
0νββ B (Majoron) emission



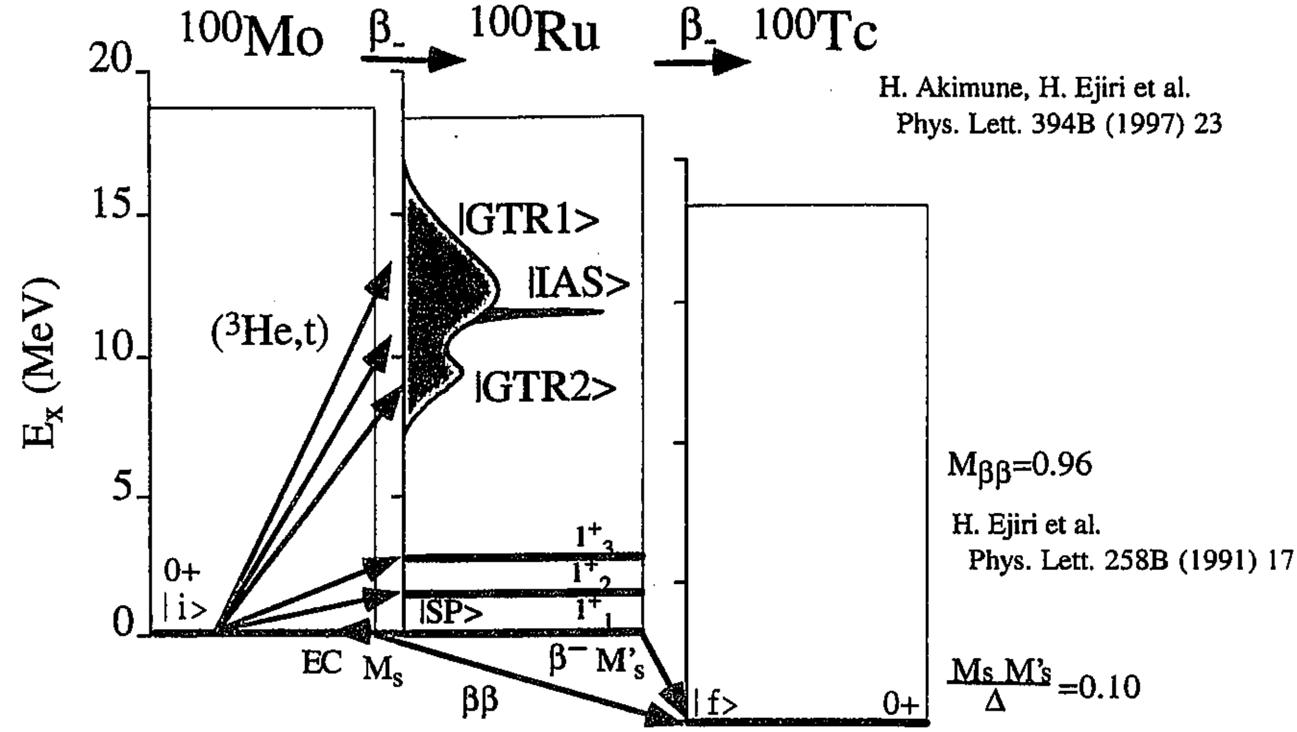
SUSY

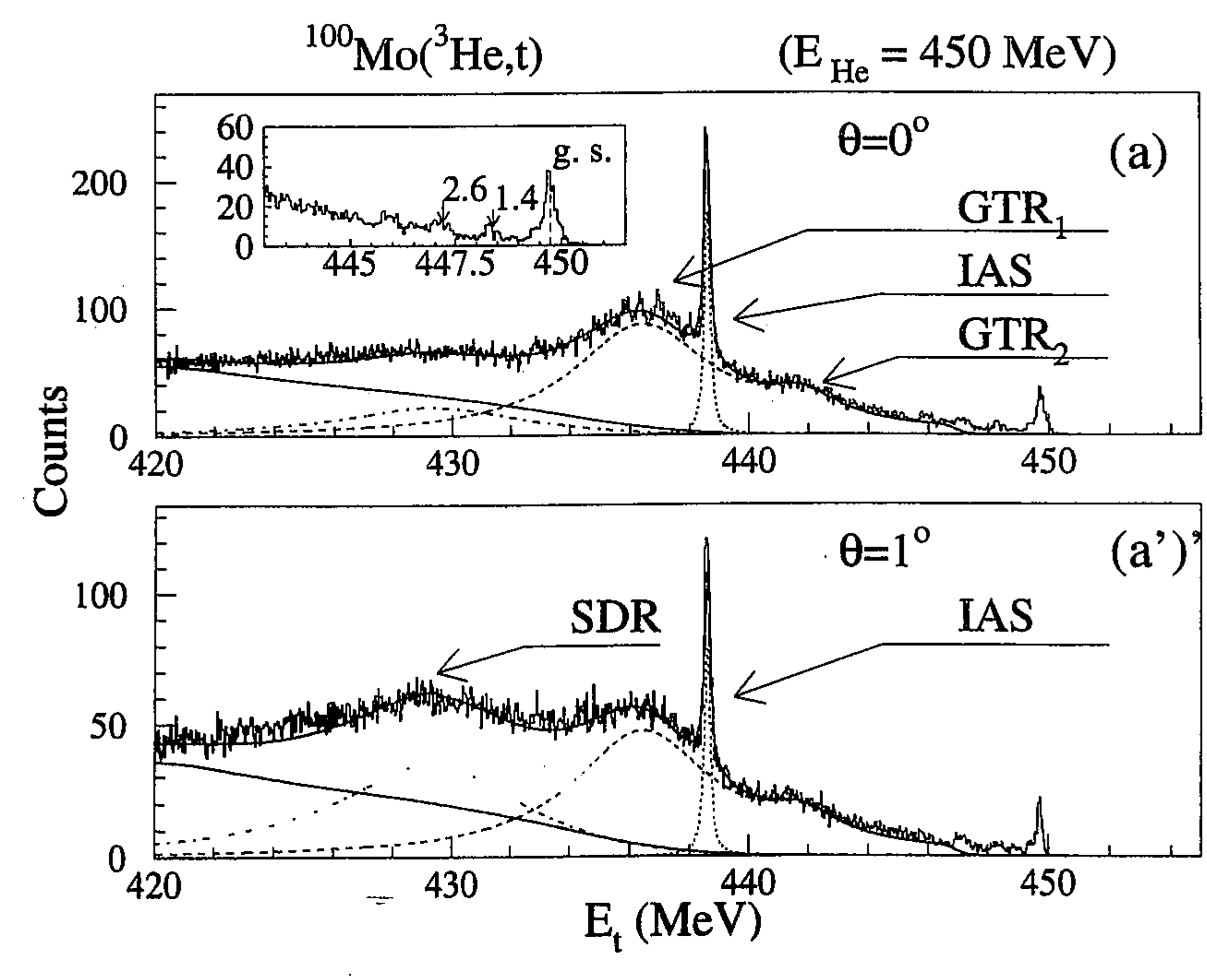
$0\nu\beta\beta$ Decay

(calculated)



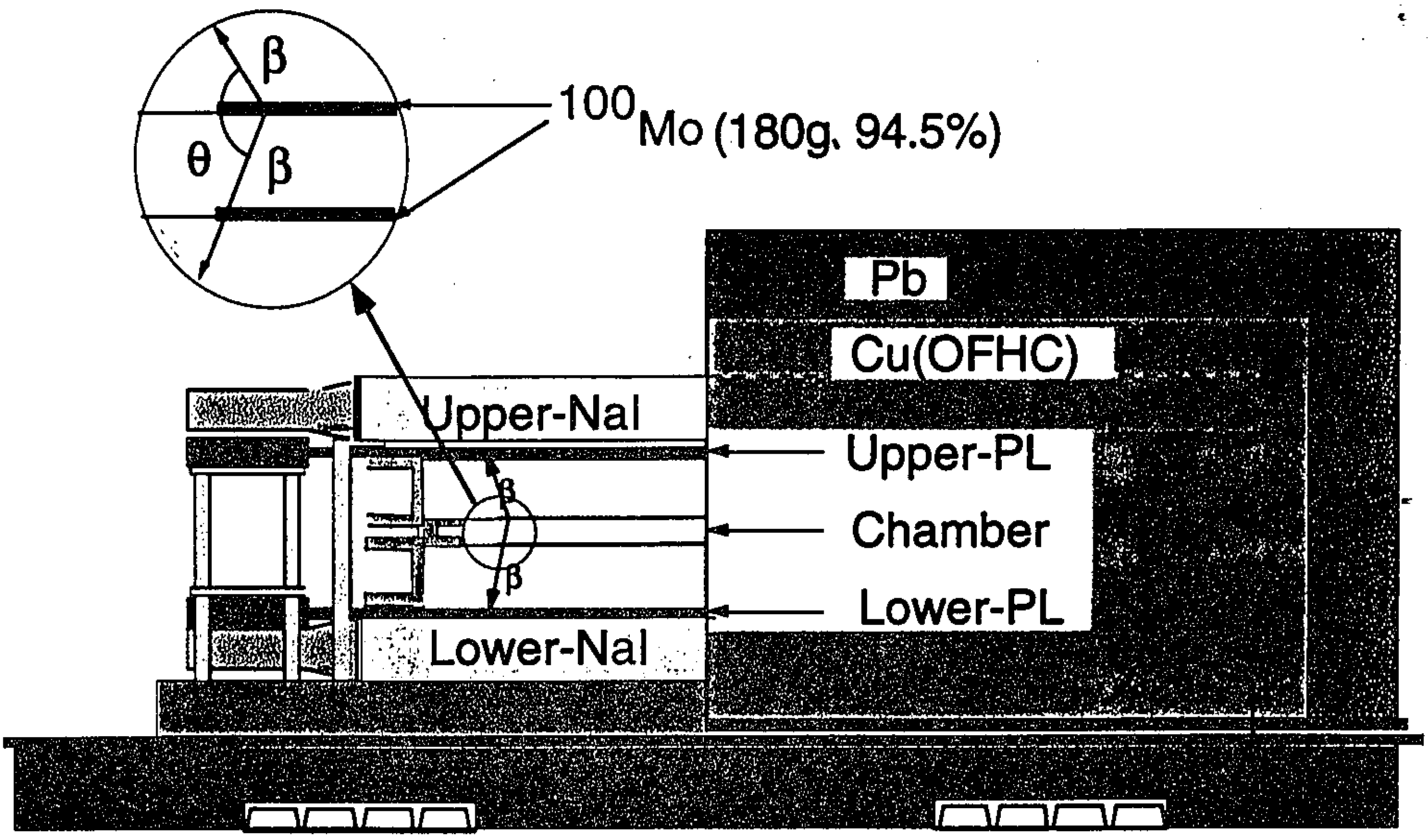
Spin Isospin Responces for ββ–ν





ELEGANT V

NIM A302(1991)304



Energy and Angular Correlations of β_1 & β_2

Source : ^{100}Mo 180g, 94.5% enriched(20mg/cm^2)

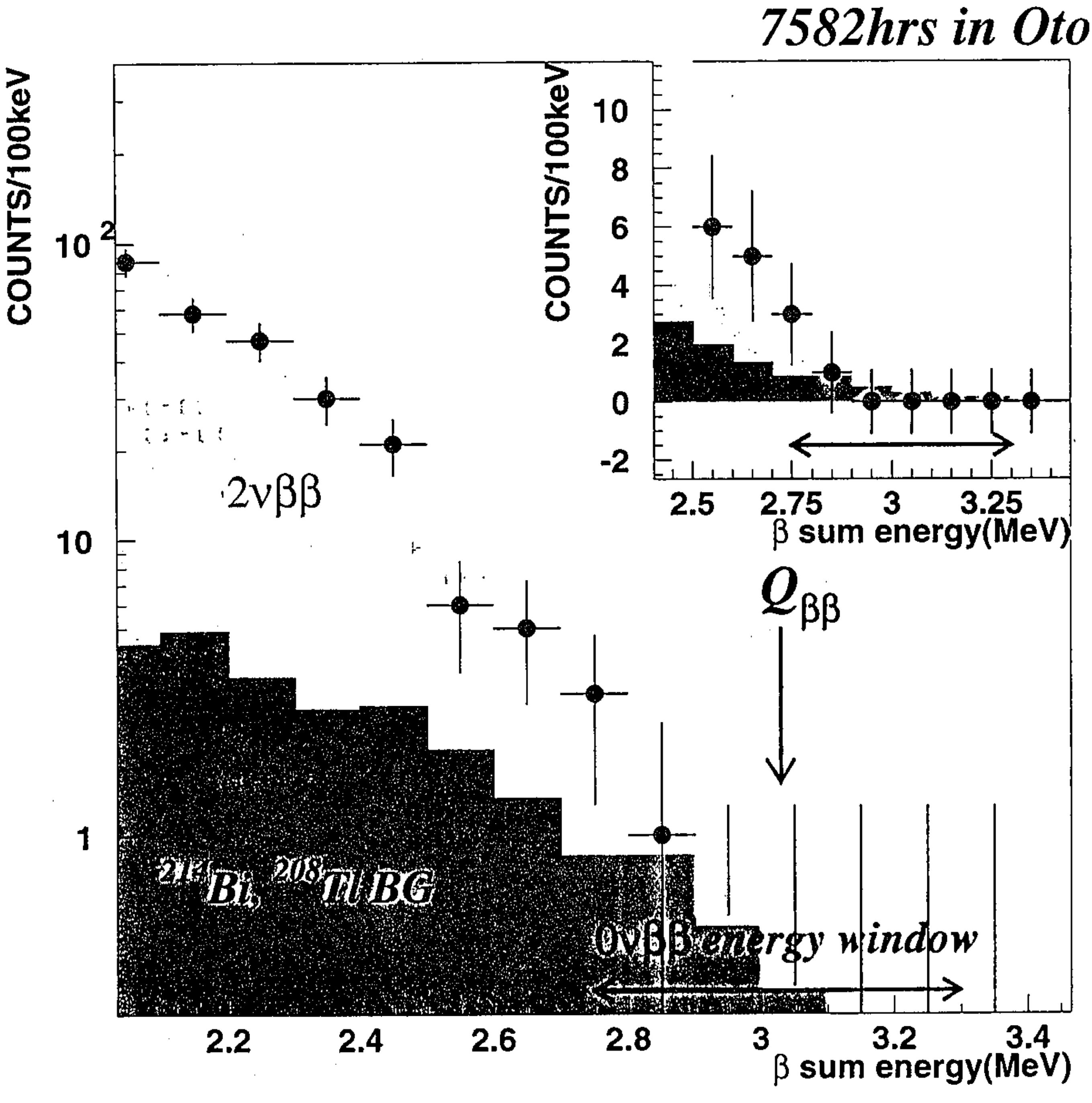
Tracking : β–trajectory, 15 layers ΔX, ΔY=1cm on source plane

Plastic Scintllator : β Enery and Timing, ΔE/E=13%@1MeV

NaI Scintillator : γ, X-rays to reject BG, ΔE/E=7.5%@1MeV

$E_1, E_2, \theta_1, \theta_2$ → **Exclusive Measurement**
γ

- $2\nu\beta\beta$
- $0\nu\beta\beta$ $\langle m_\nu \rangle \langle \lambda \rangle \langle \eta \rangle$
- SUSY
- Excited state



$\chi^2/n\text{-}2 = 11.3/(10-2)$

$0\nu\beta\beta$ and $2\nu\beta\beta$

	$Q_{\beta\beta}$(MeV)	$T_{1/2}(2\nu\beta\beta)$	$T_{1/2}(0\nu\beta\beta)$ $\langle m_\nu \rangle = 0.1$eV	$\frac{T_{1/2}(0\nu\beta\beta)}{T_{1/2}(2\nu\beta\beta)}$
		$*10^{19}$yr	$*10^{25}$yr	$*10^5$
^{76}Ge	2.04	84-140	24	2
^{82}Se	3.00	9.7-12	6.0	6
^{100}Mo	3.03	0.95-1.2	2.5	20
^{116}Cd	2.80	2.6-2.7	4.9	20
^{150}Nd	3.37	1.0-1.7	0.45	3
	$G_{0\nu}$ BG natural activity	BG for $0\nu\beta\beta$		↑ $\sim \frac{G_{2\nu}}{G_{0\nu}} \sim \frac{Q^{11}}{Q^5} \sim x \left(\frac{M_{2\nu}}{M_{0\nu}}\right)^2$

$$\langle m \rangle^2 = (G_{0\nu} M^2 \; T_{1/2})^{-1}$$

$G_{0\nu} \sim Q_{\beta\beta}^5$

$G_{2\nu} \sim Q_{\beta\beta}^{11}$

Results (Preliminary)

Limits on Halflife of $0\nu\beta\beta$ of ^{100}Mo (10^{23}y) (90%CL)

Mode	selection	Kamioka (7333hrs)	Oto (7582hrs)	Combine
$<m_\nu>$ term	T	0.28	0.36	0.55
	m			0.31
$<\lambda>$ term	T	0.17	0.21	0.34
	λ			0.42
$<\eta>$ term	T	0.27	0.29	0.49
	η			0.20
Majron Emission	T	0.031	0.015	0.046

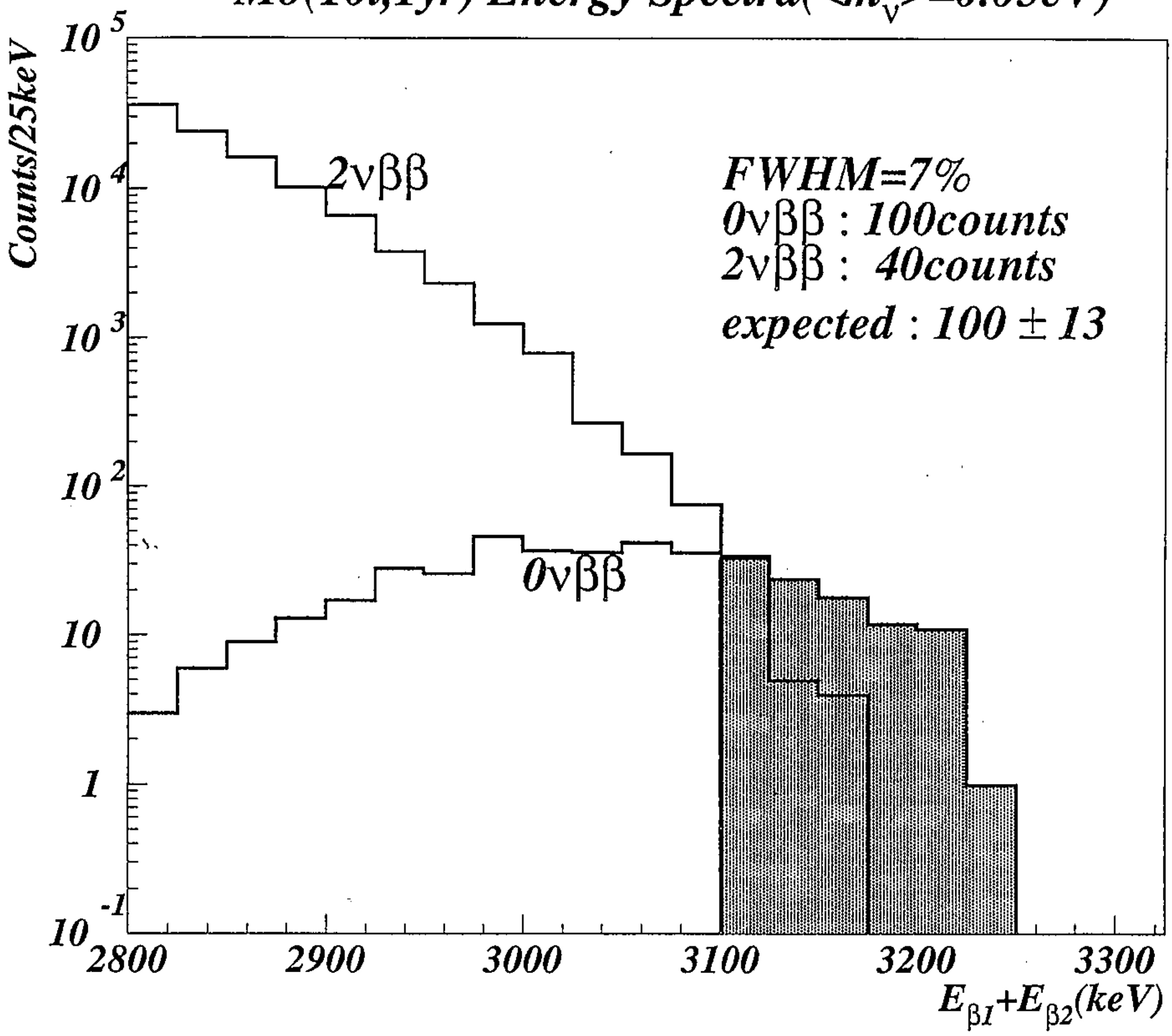
T : True $\beta\beta$ selection
$m\ \lambda\ \eta$: selection for each term

Limits on Particle Physics Parameters

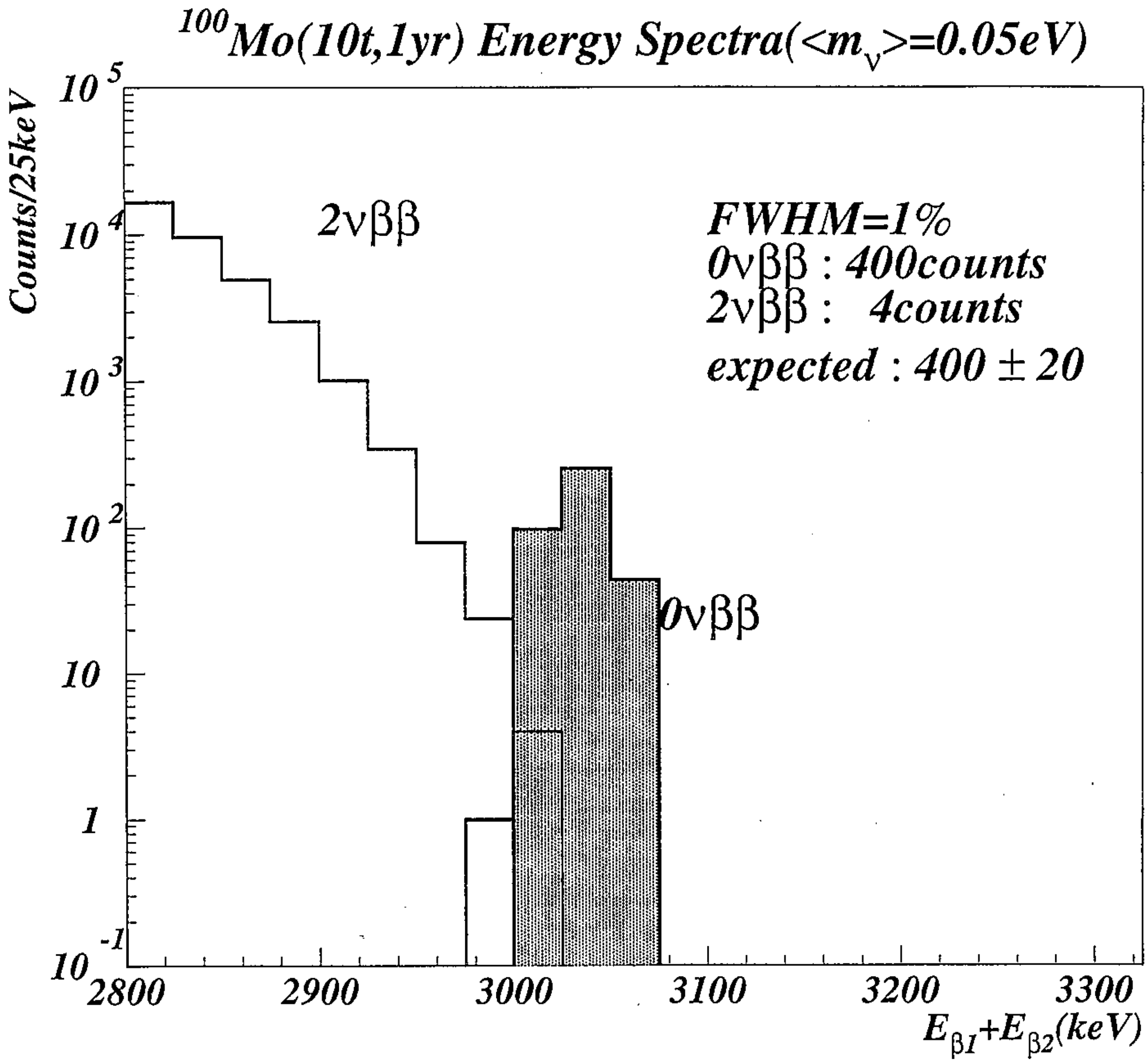
			^{76}Ge(H.M., IGEX)
$<m_\nu>$ (eV)	2.0	2.0--4.5	0.36--1.3 eV
$<\lambda>$(10^{-6})	3.1		
$<\eta>$ (10^{-8})	2.1		
$<g_B>$(10^{-5})	7.9		18

Matrix Element in Ref T.Tomoda,
Rep. Prog. Part. Phys. 54,53(1991)

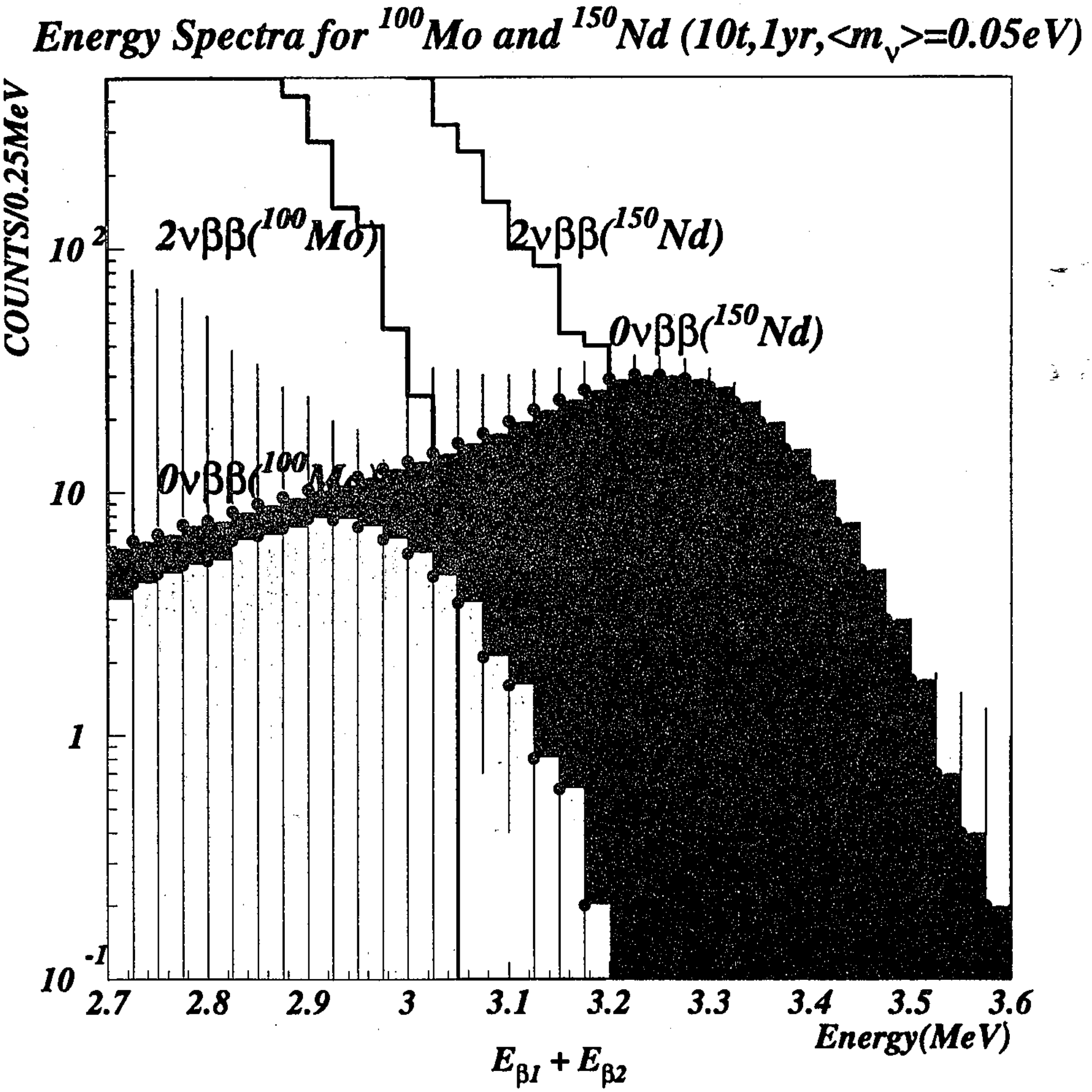
^{100}Mo(10t,1yr) Energy Spectra(<m$_\nu$>=0.05eV)



evaluated by N. kudomi



evaluated by N. kudomi

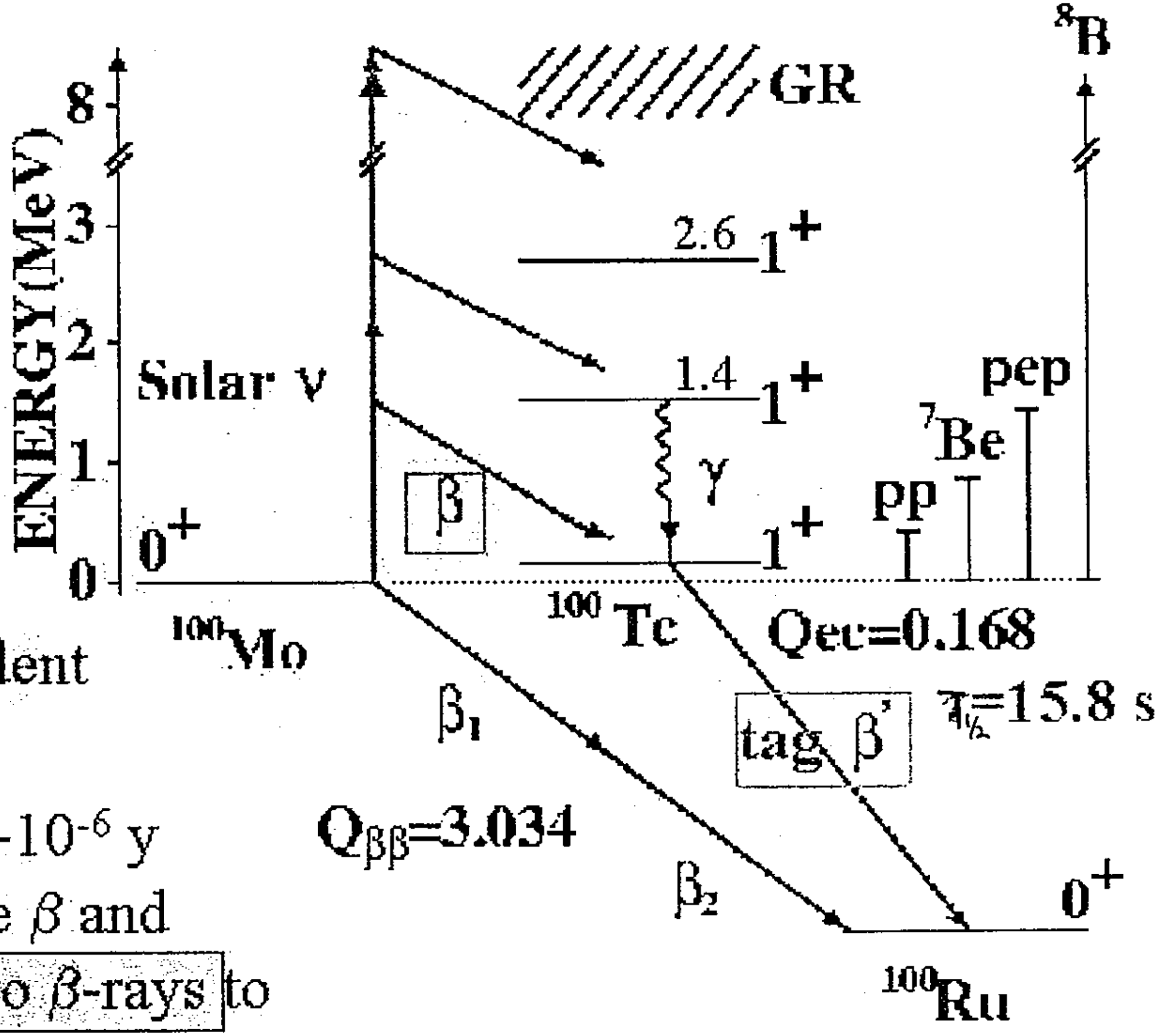

Energy Spectra for ^{100}Mo and ^{150}Nd (10t,1yr,<m$_\nu$>=0.05eV)
COUNTS/0.25MeV
10^2
10
1
10^{-1}
2νββ(^{100}Mo)
2νββ(^{150}Nd)
0νββ(^{150}Nd)
0νββ(^{100}Mo)
2.7
2.8
2.9
3
3.1
3.2
3.3
3.4
3.5
3.6
Energy(MeV)
$E_{\beta 1} + E_{\beta 2}$

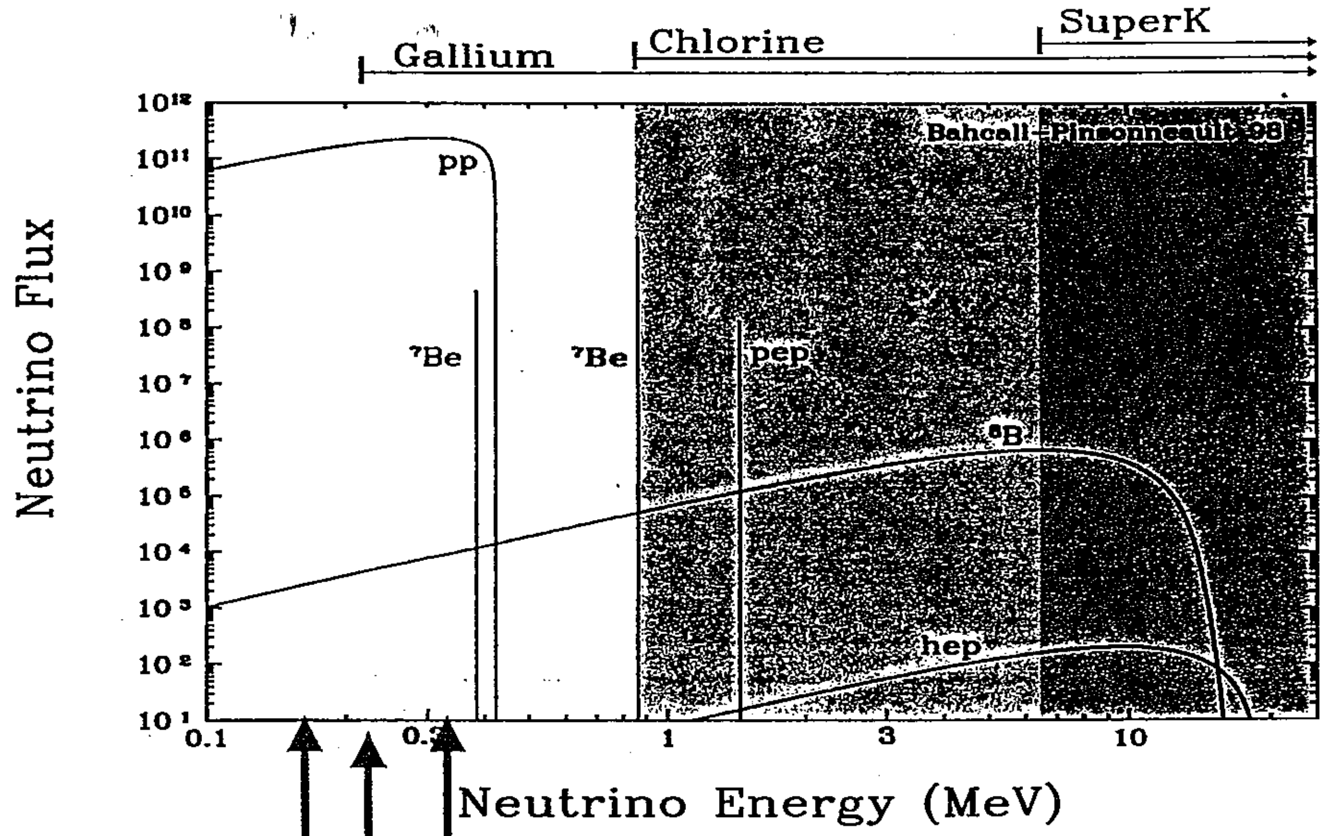
Unique Points of ^{100}Mo Solar-ν Studies

1. Low Threshold Energy
   & 0.17MeV
   Large Sensitivities for
   Low-E ν; Large SNU

2. Real Time Spectroscopy of ν_e Individual
   Sources in the Sun.
   &
   Ratio(^{7}Be/pp) is independent
   of the B(GT) value

3. Ideal Time Window 10^{-7}-10^{-6} y
   for Inverse β & Succesive β and
   Space Resolution with two β-rays to
   Reject Correlated & Accidental BG
   Multiplicity (γ veto) rejection





Solar neutrino energy spectrum

Inverse β decays

^{71}Ga	$E_\nu > 0.23$ MeV	pp, ^{7}Be, ^{8}B
^{37}Cl	> 0.81	^{7}Be, ^{8}B
^{127}I	> 0.66	^{7}Be, ^{8}B
^{13}C	> 2.2	^{8}B
^{176}Yb	$> 0.31, > 0.45$	pp, ^{7}Be, ^{8}B
^{100}Mo	$>$ **0.17**	pp, ^{7}Be, ^{8}B

Isotopes used for ν-mass by ββ decays & solar-ν by inverse-β decays

Isotope	$Q_{\beta\beta}$(MeV)	Q_{β}(MeV)	Intermediate state	halflife	trigger	ν-source
^{76}Ge	2.039	-0.923	2^-(gs), 1^+(-,-) 0.046?	26.32 h	γ	^{8}B
^{82}Se	2.992	-0.098	5^-(gs), 1^+(-,-)	35.3 h	γ	^{8}B ?
^{96}Zr	3.351	0.164	6^+(gs), 1^+(-,-)	23.35 h	γ	^{8}B ?
^{100}Mo	**3.034**	**-0.168**	**1^+(gs), 1^+(1.4,2.6)**	**15.8 s**	**β**	**^{8}B, ^{7}Be, pp**
^{116}Cd	2.804	-0.470	1^+(gs), 1^+(1.0,2.2)	14.1 s	β–γ	^{8}B, ^{7}Be
^{130}Te	2.529	-0.420	5^+(gs), 1^+(-,-)	12.36 h	γ	^{8}B, ?
^{136}Xe	2.467	-0.081	5^+(gs), 1^+(-,-)	13.16 d	γ	^{8}B, -
^{150}Nd	3.368	-0.086	1^-(gs),1^+(-,-)	2.68 h	γ	8B, ?

Solar-ν capture rates in units of SNU

Nucleus	-Q(MeV)	pp	^{7}Be	^{13}N	pep	^{15}O	^{8}B	Total
^{2}H[a]	1.442	0	0	0	0	-	6	6
^{37}Cl[a]	0.814	0	1.1	0.1	0.2	0.3	6.1	7.9
^{40}Ar[b]	>1.505	0	0	0	0	0	7.2	7.2
^{71}Ga[c]	0.236	70.8	35	3.7	2.9	5.8	12.9	132
^{100}Mo[d]	**0.168**	**639**	**206**	**22**	**13**	**32**	**27**	**965**
^{115}In[a] (β active)	0.120	468	116	13.6	8.1	18.5	14.4	639
^{127}I[e]	0.789	0	9.4	-	-	-	13	24.6

GT Strength & Capture rate

	I_i	Spin factor $1/(2I_i+1)$	*B(GT)* g.s.	1st	Sum
^{71}Ga	(3/2)+	0.25	0.089	0.005 (0.175MeV)	3.8
^{100}Mo	0+	1	0.33	0.13 (1.4MeV)	3.3

a; Bahcall 88 b; Bhattacharya 98 c; Ejiri 98 d; Ejiri 99 e; Engel 91

Solar-ν absorption rates R_ν for ^{100}Mo

Source	$E_\nu^{(max)}$ (MeV)	$E_\beta^{(max)}$ (MeV)	R_ν/SNU
pp	0.42	**0.25**	**639 ± 85**
pep	1.44	1.27	13 ± 2
^{7}Be	0.86	**0.69**	**206 ± 35**
^{8}B	~15	~14.2	27(23) *± 4
^{13}N	1.20	1.03	22 ± 3
^{15}O	1.74	1.57	32 ± 4

Measured by both (^3He,t) & EC

$E_\nu^{(max)}$, $E_\beta^{(max)}$ are the maximum ν & β energy.
SSM capture rates based on BP98 with errors from those of *B(GT)*.
*Rate for the state below the effective neutron threshold energy.

Sensitivity to solar-ν capture rate

The solar-ν signal rate per year

$$Y_S = 0.2 \cdot \underline{N_0} \cdot S \cdot \varepsilon_S$$

N_0: in tons of ^{100}Mo

S: the solar-ν capture rate in SNU, $S = 206$ (for ^7Be)

$\varepsilon_S \sim 0.35$ (for ^7Be)

The time window from $t_1 = 1$ sec to $t_2 = 31$ sec

long enough to reject correlated BG

2νββ, β-rays followed by conversion e, scatterings of single β

$^{214}Pb \rightarrow {}^{214}Bi(19.9m) \rightarrow {}^{214}Po$

$$Y_{DC} \sim 8 \times 10^9 \cdot N_0 \cdot b \cdot \Delta T$$

short enough to reduce accidental BG

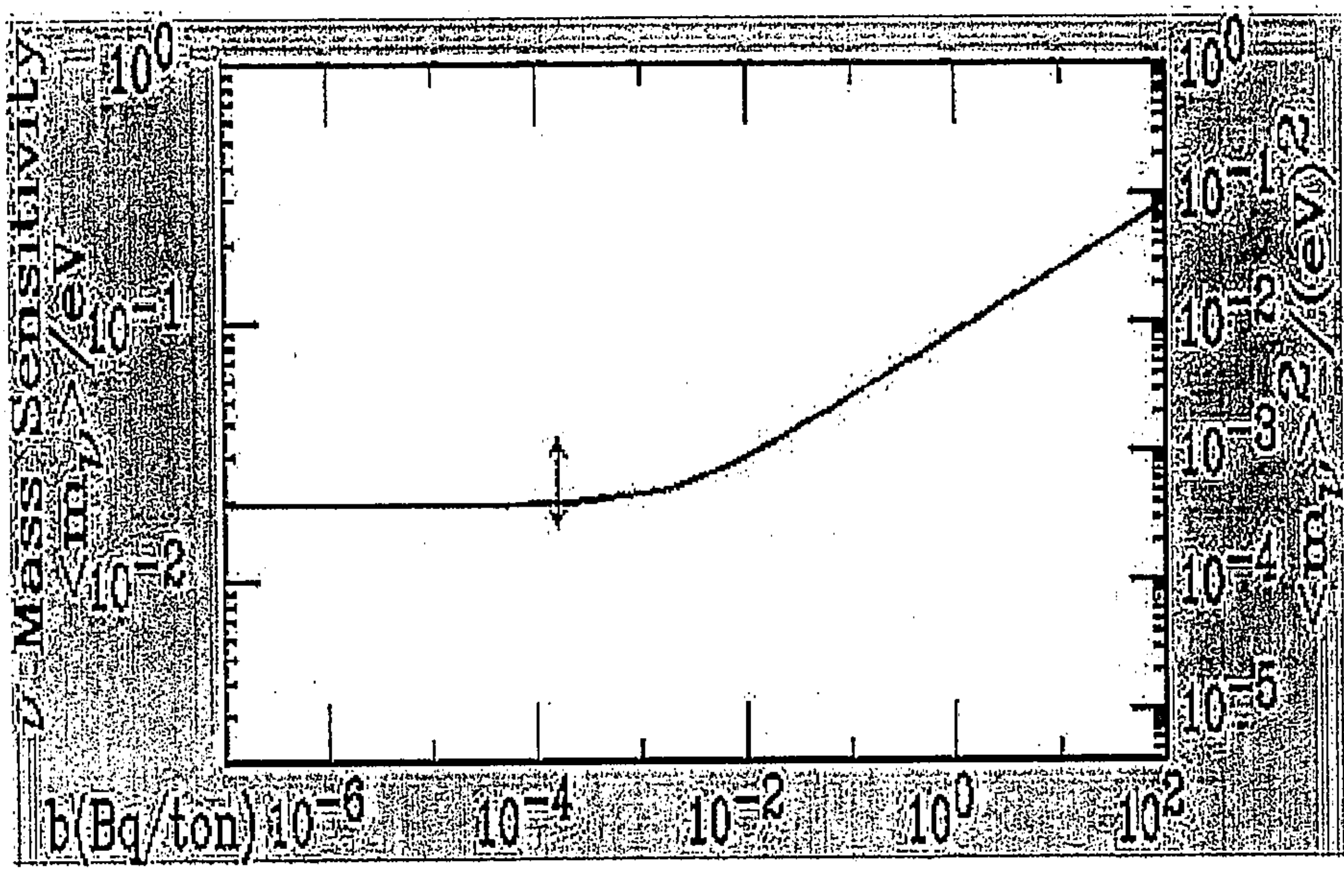
$$Y^{RI}{}_{AC} \sim N_0{}^2 \cdot b^2 \cdot 5 \times 10^{14} \cdot \Delta T/K$$

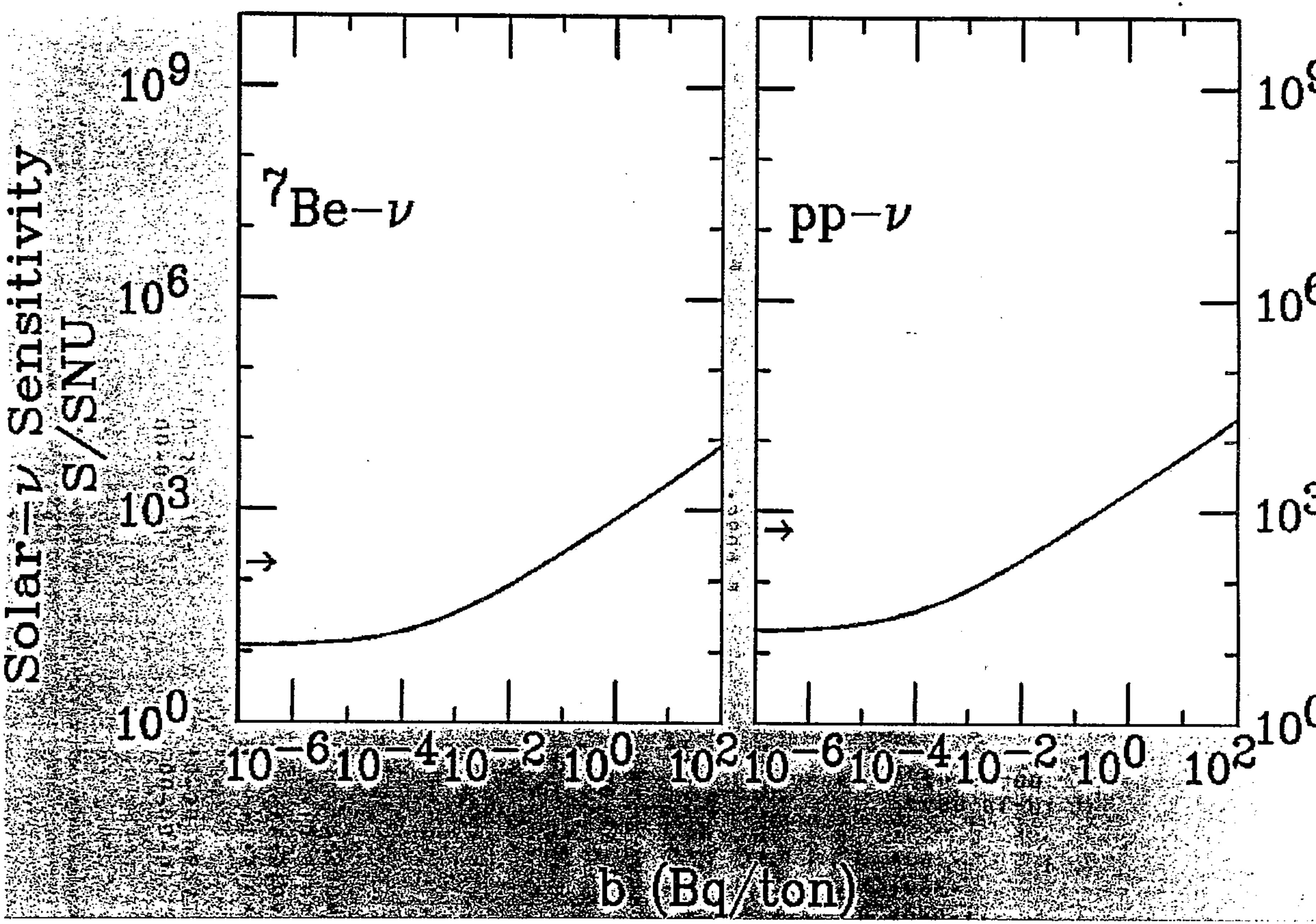
ΔT is 10^{-6} y

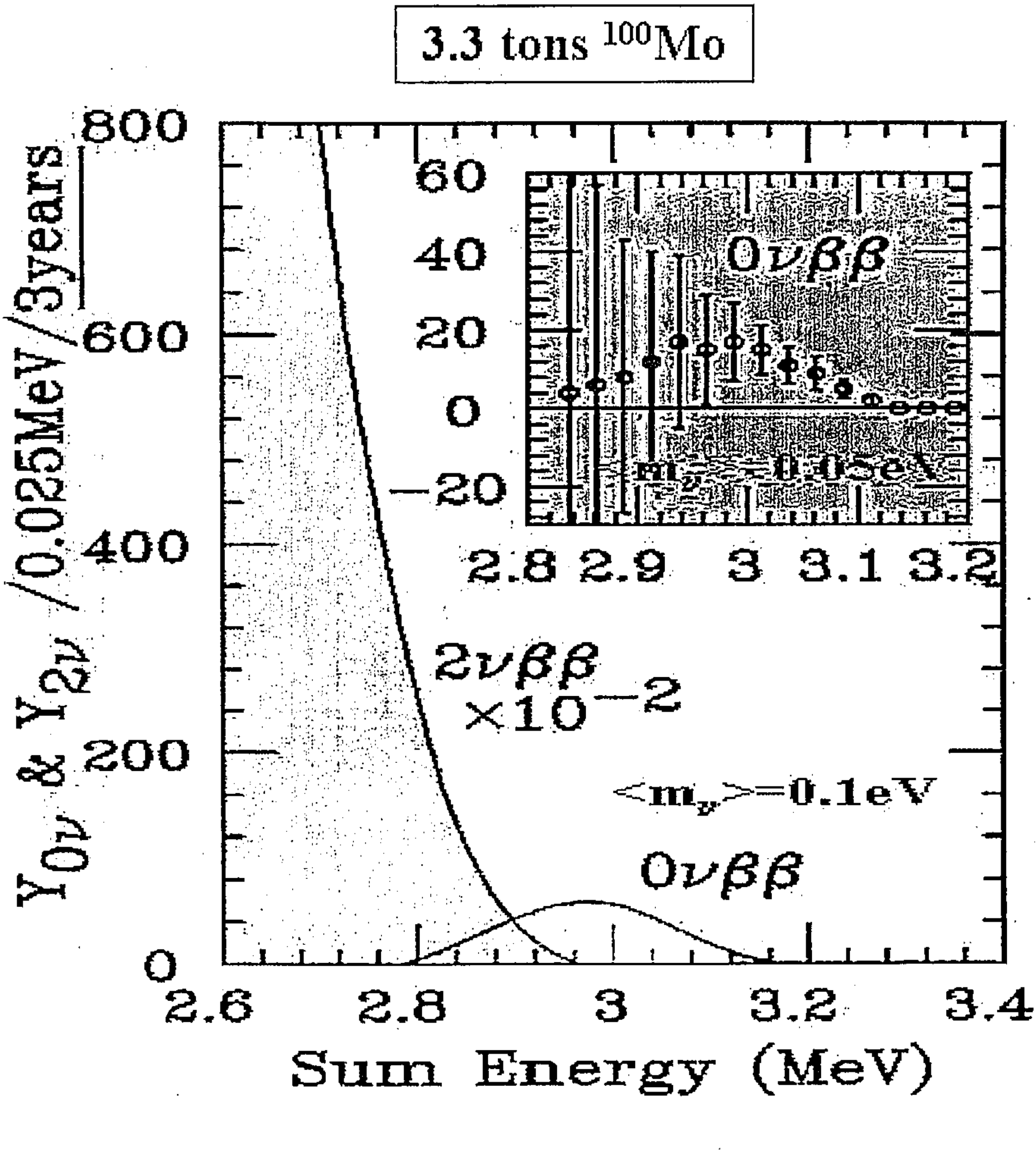
K is N_0 of unit cells localized in the detector

$$Y^{2\nu}{}_{AC} \sim N_0^2 \cdot 16 \times 10^{14} \cdot \Delta T/K$$

$$Y_S = \sqrt{Y_{DC} + Y^{RI}{}_{AC} + Y^{2\nu}{}_{AC}}$$


ν Mass Sensitivity
<mν>/eV
10^0
10^-1
10^-2
<mν>^2/(eV)^2
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
b(Bq/ton) 10^-6
10^-4
10^-2
10^0
10^2


Solar−ν Sensitivity
S/SNU
^{7}Be−ν
pp−ν
10^9
10^6
10^3
10^0
10^{-6} 10^{-4} 10^{-2} 10^0 10^2
b (Bq/ton)


3.3 tons ¹⁰⁰Mo
Y_0ν & Y_2ν /0.025MeV/3years
800
600
400
200
0
2.6
2.8
3
3.2
3.4
Sum Energy (MeV)
60
40
20
0
−20
2.8 2.9 3 3.1 3.2
0νββ
<m_ν>=0.05eV
2νββ ×10^−2
<m_ν>=0.1eV
0νββ

Detector R&D

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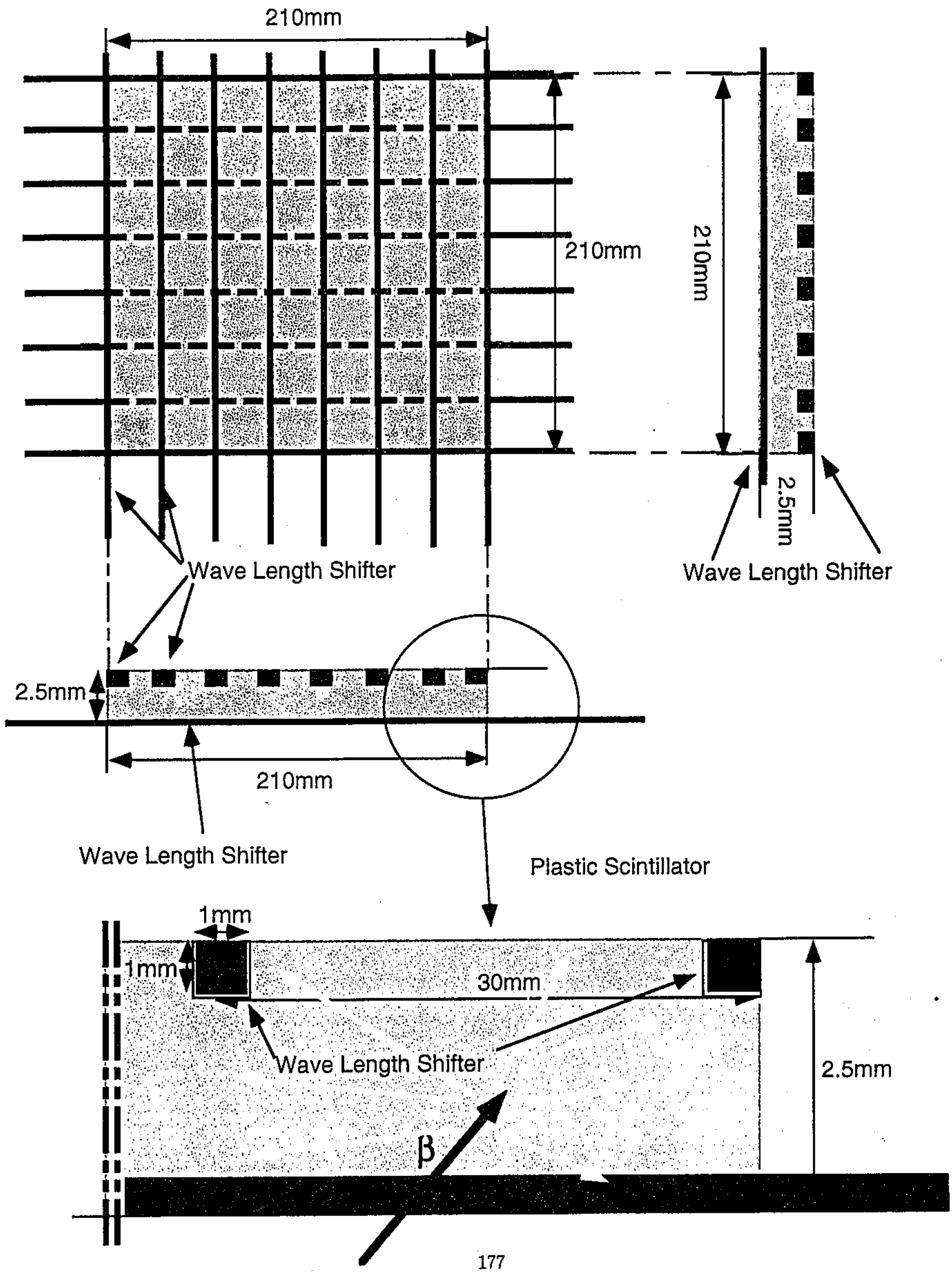
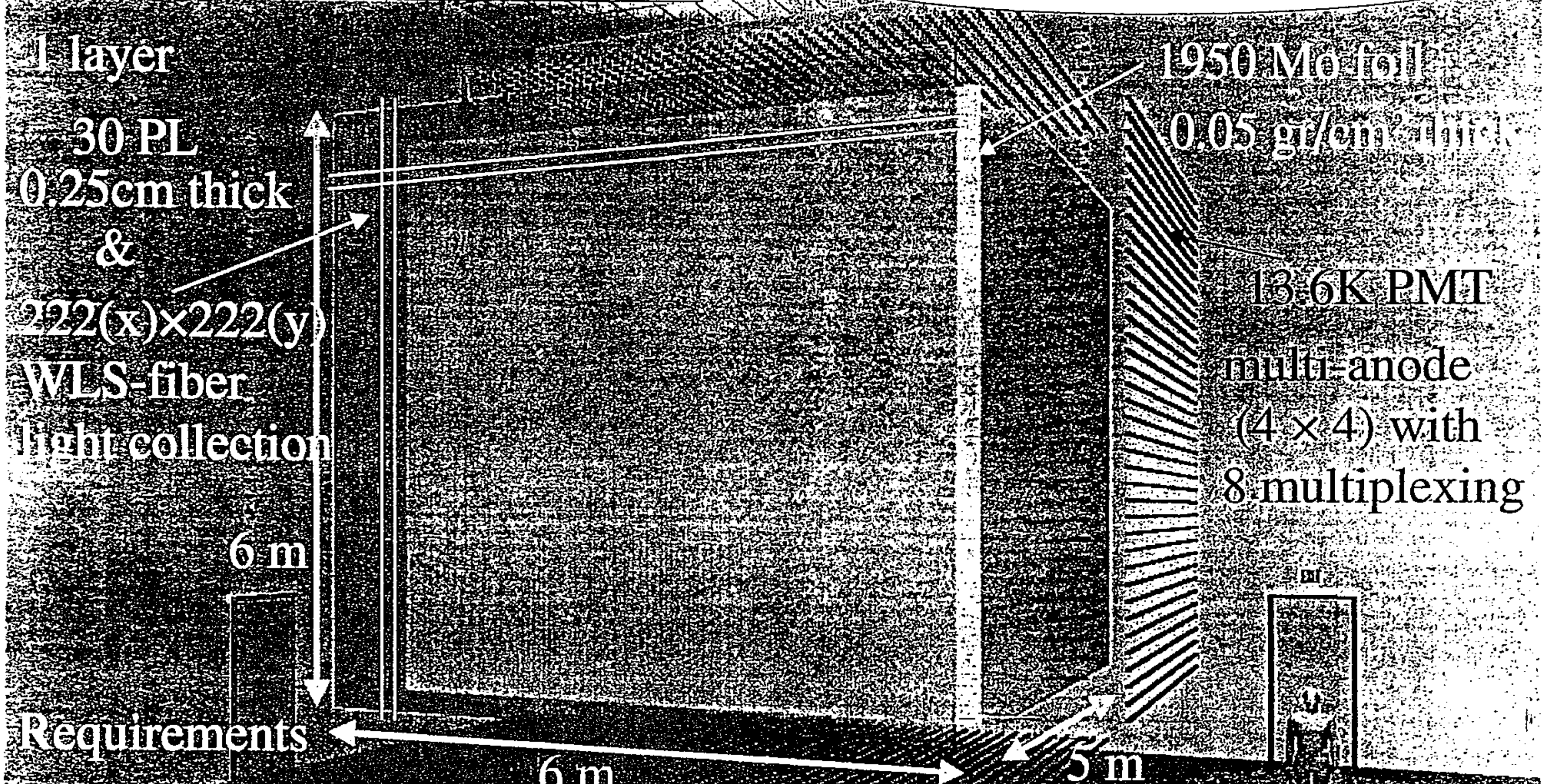
Good Energy and Position Resolution



Possible MOON Detector



Requirements

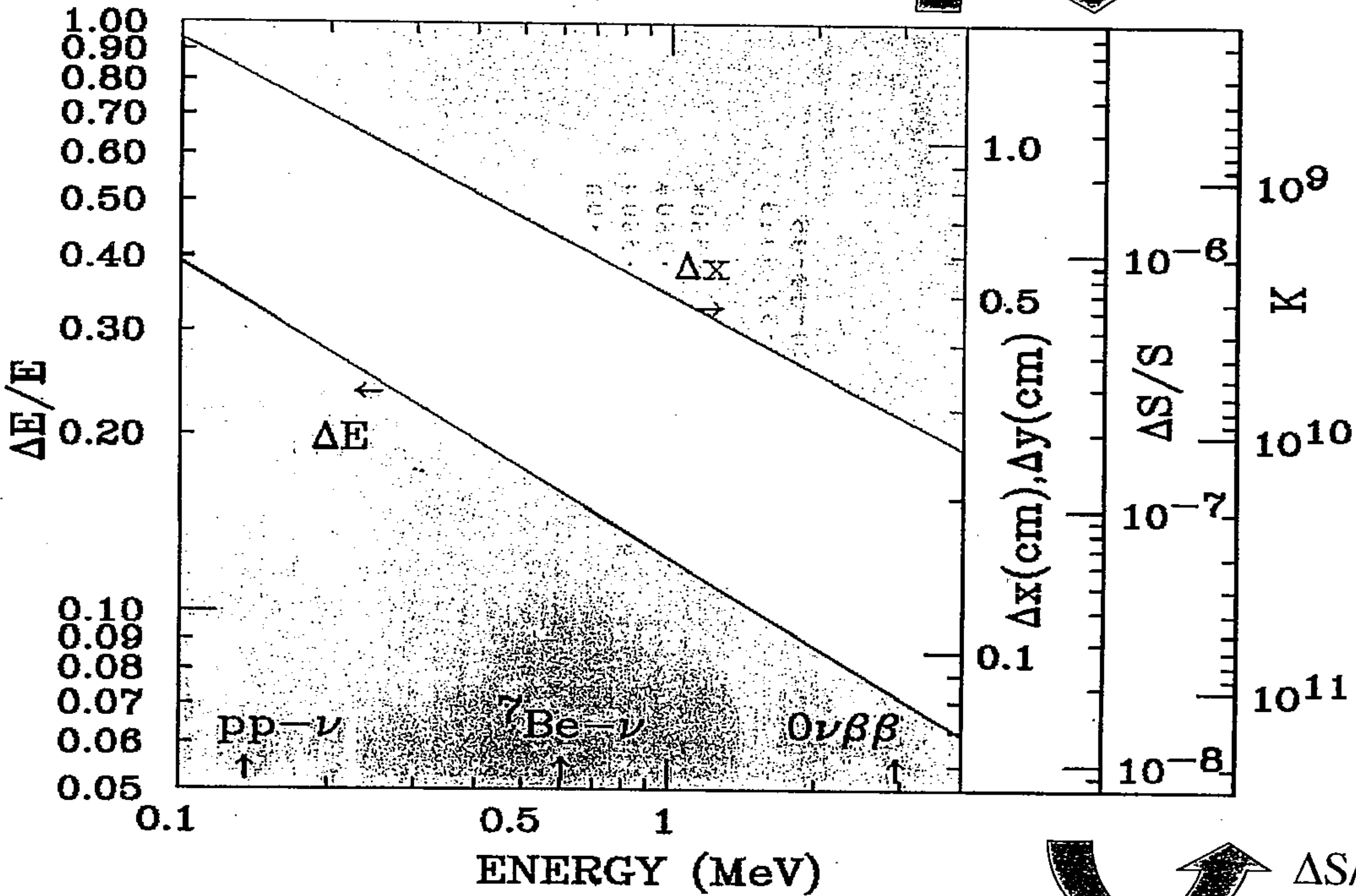
- ^{100}Mo 3.3 tons ; ^{nat}Mo 34 tons(9.6% ^{100}Mo)
- Energy resolution ⇨ 15% for ^{7}Be-ν (7% for 0νββ)
- position resolution ⇨ 1/K~10^{-9}
- purity of Mo foil etc. ⇨ b < 10^{-2}Bq/ton(~ppt)

Energy & Spatial resolution

$\sigma = 1\sqrt{(npe{=}349\ E(MeV))}$
$= 5.34\%/\sqrt{(E)}$
$\Delta E/E(FWHM) = 2.3\sigma = \mathbf{12.4\%/\sqrt{(E)}}$

$\sigma = (2.7cm/2)/\sqrt{(n_{pe}^{1\text{-}fiber}{=}69)} = 0{:}16cm$
$(/\sqrt{2}$ by both ends$)$
$\mathbf{\Delta x = \pm 2\sigma = 0.5cm/\sqrt{E(MeV)}}$

$(\Delta x)^2/(6m\times 6m)$



$\Delta S/S/1950$

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Specifications of Detectors

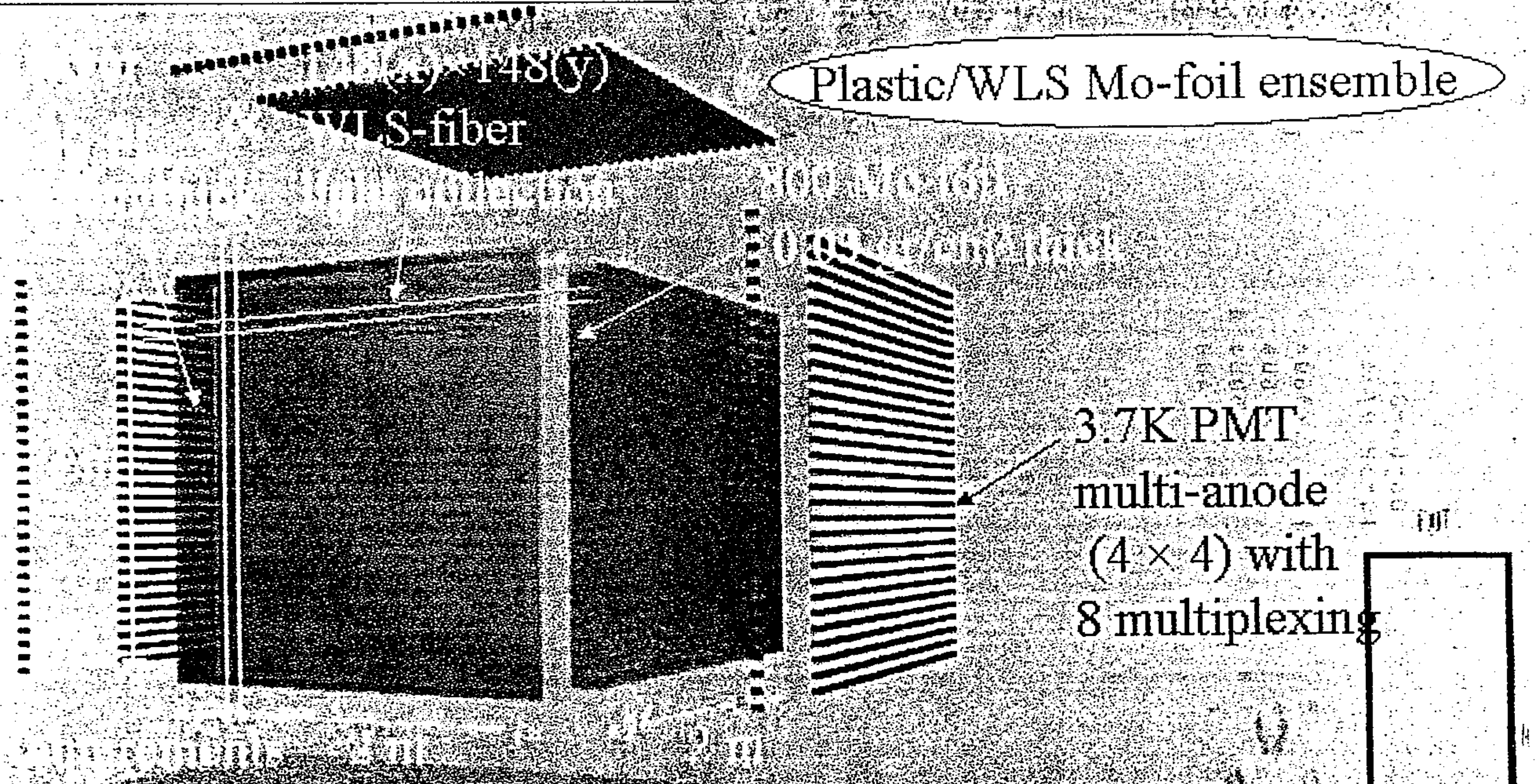
	Mo(9.6 % ^{100}Mo)	^{100}Mo (85%)	Ratio
PL volume	6m-6m-5m=180m^3	2m-2m-2m=8m^3	1/22.5
PL module	6m-6m-0.25cm	2m-2m-0.25cm	1/9
N(module)	2000	800	1/2.5
S(area)	7.2 10^8 cm^2	3.2 10^7 cm^2	1/23
t(source)	0.05 gr/cm^2	0.03 gr/cm^2	1/1.7
N_0(total)	34 ton	0.96 ton	1/36
N (istope)	3.3 ton	0.83 ton	1/4
N(WLS)	8.8 10^5	2.4 10^5	1/3.7
N(PM)	13.6K	3.7K	1/3.7
D(WLS)	2.7 cm	1.35 cm	1/2
ΔE 0ν/^{7}Be-ν/pp-ν	7/15/30 %	4/9/18/%	1/1.7
1/K (^{7}Be-ν)	0.7 10^{-9}	1.1 10^{-9}.	1.6
$Y_{0\nu}^{eff}$/0.05 eV/3y	43	30	1/1.6
$\sqrt{Y_{0\nu}^{BG}}$	13	2.7	1/4.8
Y^{eff}(Be-ν)/y	47	20	1/2.3
Y^{eff}(pp–ν)/y	85	40	1/2.1
$\sqrt{Y_C^{BG}}$ (Be-ν)	13	2.7	1/5
$\sqrt{Y_{AC}^{BG}}$ (Be-ν)	4	2	1/2

Detector with Enriched ^{100}Mo source

Abundance 9.6 %

1. Reduce volume of source & scintillator by one order
2. Increase efficiencies of light collection by increasing # of WLS/area
   → improves ΔE/E & K by 1.7 & 1.6, respectively
3. Thin ^{100}Mo foils with 0.03 gr/cm^2
   → keep whole size reasonable & better efficiencies by smaller dE
   keep signal rate reasonable
4. Increase S/N by increase of relative concentration of ^{100}Mo
5. Reduction of BG rates due to cosmogenic RI(mainly from lighter Mo)
6. Small accidental 2ν-BG for solar-ν by a factor 10

Possible MOON Detector



- ^{100}Mo 0.96 tons ; ^{nat}Mo 0.83 tons
- Energy resolution ⇒ 9% for ^{7}Be-ν (4% for 0νββ)
- position resolution ⇒
- purity of Mo foil, etc. ⇒ b < 10 Bq/ton(~ppt)

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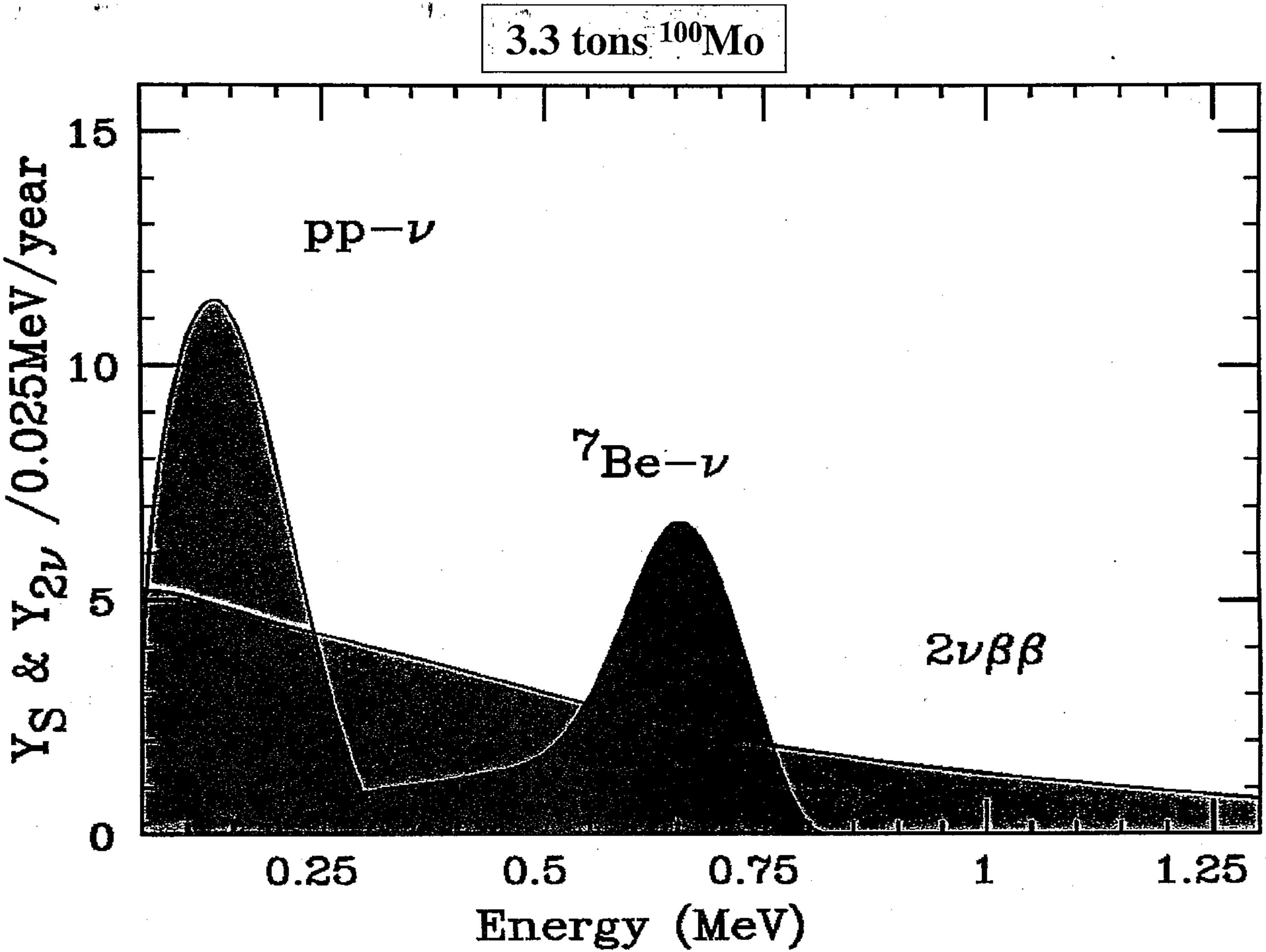
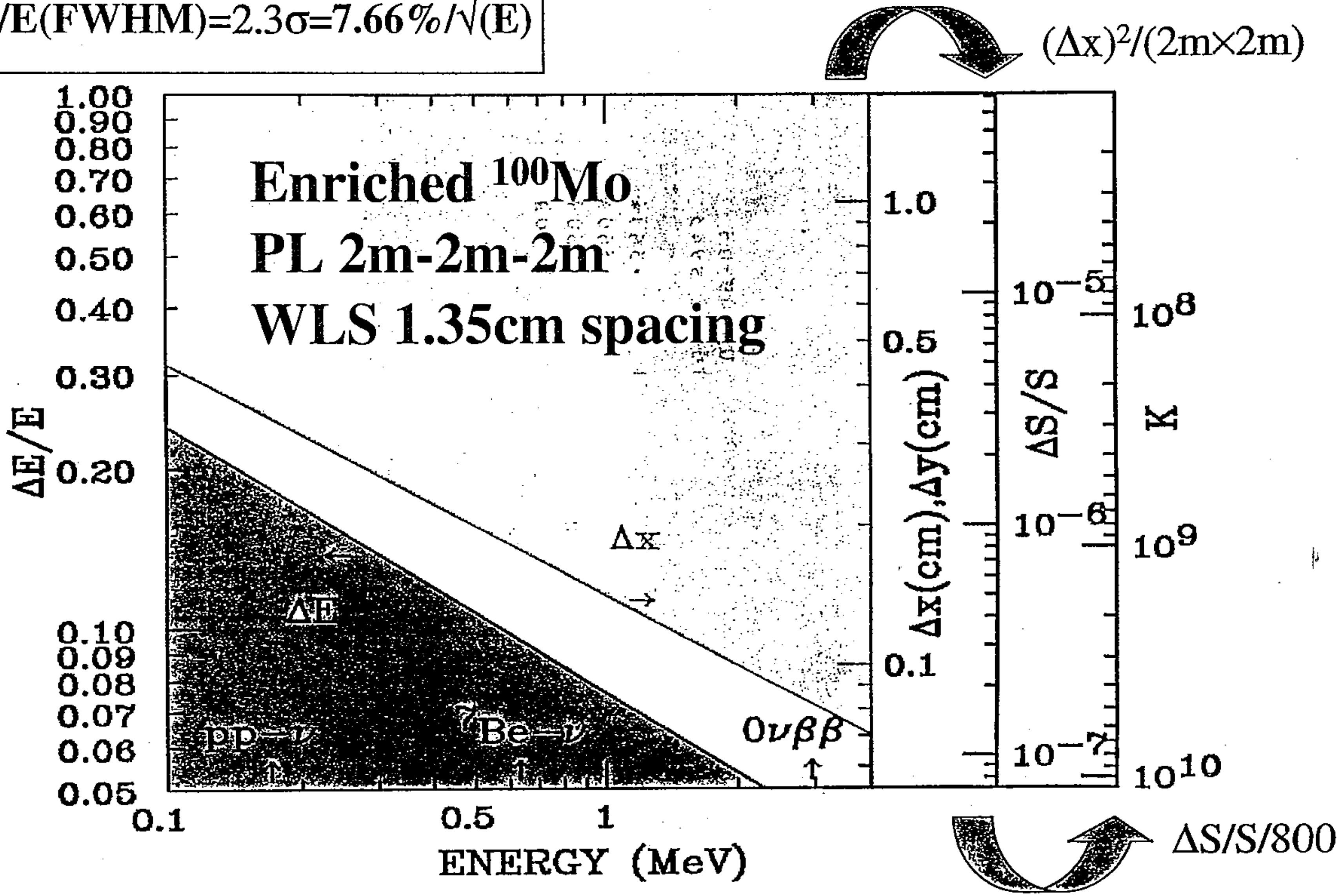

3.3 tons ^{100}Mo
pp−ν
^{7}Be−ν
2νββ
Y_S & $Y_{2\nu}$ /0.025MeV/year
Energy (MeV)
0
5
10
15
0.25
0.5
0.75
1
1.25

Energy & Spatial resolution

$\sigma = 1/\sqrt{(npe=903\ E(MeV))}$
$= 3.33\%/\sqrt{(E)}$
$\Delta E/E(FWHM)=2.3\sigma=7.66\%/\sqrt{(E)}$

$\sigma = (1.35cm/2)/\sqrt{(n_{pe}^{1\text{-}fiber}=181)} \doteq 0.050$ cm
($/\sqrt{2}$ by both ends)
$\Delta x=\pm 2\sigma=0.14cm/\sqrt{E(MeV)}$



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