

"Neutrino Telescopes"-1999.

ν - Mass Direct Measurements

V. M. Lobashev

Institute for Nuclear Research
of the Russian Academy of Sciences

Kinematic approach to rest mass. Balance of momentum and energy.

ν_e $m_{\nu_e} < 2.5 \text{ eV}$ <i>(recent result)</i>	$n \rightarrow p + e + \nu_e;$ $T_2 \rightarrow (THe^3)^+ + e + \nu;$ $N(E)_e; P_e;$ $E_0 = 18,573 \text{ eV}$
ν_μ $m_{\nu_\mu} < 0.17 \text{ MeV}$	$\pi^+ \rightarrow \mu^+ + \nu_\mu$ $m_\pi; m_\mu; P_\mu;$
ν_τ $m_{\nu_\tau} < 18 \text{ MeV}$	$\tau \rightarrow \underbrace{5\pi}_1 + \nu_\tau$ <i>all charged</i> $m_\tau; P_\pi;$

Advantage of T-decay:

1. Low E_0 .
 2. High specific activity ($T_{1/2} = 12.26 \text{ y}$).
 3. Low Z.
 4. Exact calculation of final state spectrum.
 5. Purity from other radioactive contamination.
- Next on E_0 Ni⁶³: $E_0 = 67.0 \text{ keV}$; $T_{1/2} = 92 \text{ y}$.

Search for kinematical neutrino mass –
main goal for study of tritium β -spectrum
near end point.

Around end point spectrum shape is dominated
by phase space of neutrino

$$\sim p_\nu^2 \text{ if } m_\nu = 0$$
$$\sim p_\nu E_\nu \text{ or } E_\nu (E_\nu^2 - m_\nu^2)^{1/2} \text{ if } m_\nu \neq 0.$$

Maximal sensitivity when $E_\nu \sim m_\nu$.

No lepton or flavor quantum number dependence is supposed.

$$m_{\nu_\tau}$$



ARGUS (1992)

$$\tau \rightarrow 5\pi^\pm \nu_\tau$$

$$m_{\nu_\tau} < 31 MeV/c^2 \quad 95\% \text{ C.L.}$$

CLEO II (1993)

$$\tau \rightarrow 5\pi^\pm \nu_\tau, \quad 3\pi^\pm \pi^0 \nu_\tau$$

$$m_{\nu_\tau} < 32 MeV/c^2$$

ALEPH (1998)

$$\tau^- \rightarrow 3\pi^\pm \nu_\tau; \quad 5\pi^\pm (\pi^0) \nu_\tau$$

Two-dimentional (Eh, Mh inv) fit

$$\frac{\Delta P_\perp}{P_\perp} = 6 \cdot 10^{-4} P_\perp \cdot GeV; \quad \Delta M \sim 10 \text{ MeV}$$

Combining 2 decay channels

$$m_{\nu_\tau} < 18.2 MeV/c^2$$

m_{ν_μ}

$\pi \rightarrow \mu + \nu_\mu$ decay at flight or at rest.

Most accurate at rest.

$$m_{\nu_\mu}^2 = m_\pi^2 + m_\mu^2 - 2m_\pi(m_\mu^2 + p_\mu^2)^{1/2}$$

$$\Delta(m_{\nu_\mu})^2 = [(60 \cdot \Delta m_\pi)^2 + (57 \Delta m_\mu)^2 + (75 \Delta P_\mu)^2]^{1/2} \text{ MeV}$$

Present accuracy	2.7 ppm	0.3 ppm	3.7 ppm
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A problem of negative $m_{\nu_\mu}^2$.

Origin – two solution of π -mass from
Mg 4d \rightarrow 3f cryst.-diff. experiment due to
uncertainty of screening factor.

(15 ppm – Jeckelmann, 94, 86)

From recent data:

$$m_{\nu_\mu}^2 (A) = (-0.143 \pm 0.024) \text{ MeV}^2$$

$$m_{\nu_\mu}^2 (B) = (-0.016 \pm 0.023) \text{ MeV}^2$$

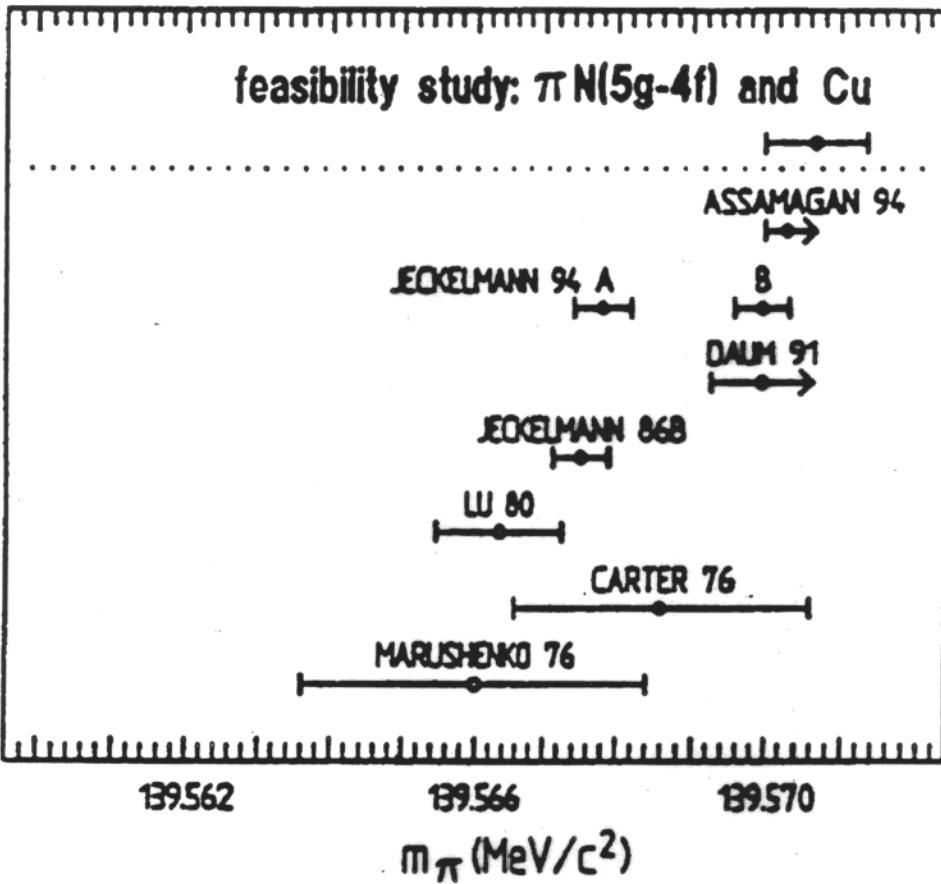
May be resolved by better resolution of CDSp
(Is under preparation at Moscow Meson Factory)

Alternative way π - X ray from lighter element.

Now first result from new experiment at PSI πN^- .

Ultimate goal – relative mass of π with respect to μ
from πN^{14} (5g – 4f) and μO_{5-4} (Not achieved yet)

Accuracy for $m_\pi \sim 1$ ppm.



Discard the solution A (Jeckelmann, 94)

Remain only:

$$m_{\nu_\mu}^2 = (-0.016 \pm 0.023) \text{ MeV}^2$$

$$m_{\nu_\mu} \left\{ \begin{array}{ll} < 0.17 \text{ MeV} & (90\% C.L.) \\ < 0.195 \text{ MeV} & (95\% C.L.) \end{array} \right.$$

(2)

Neutrino mass and β -decay.

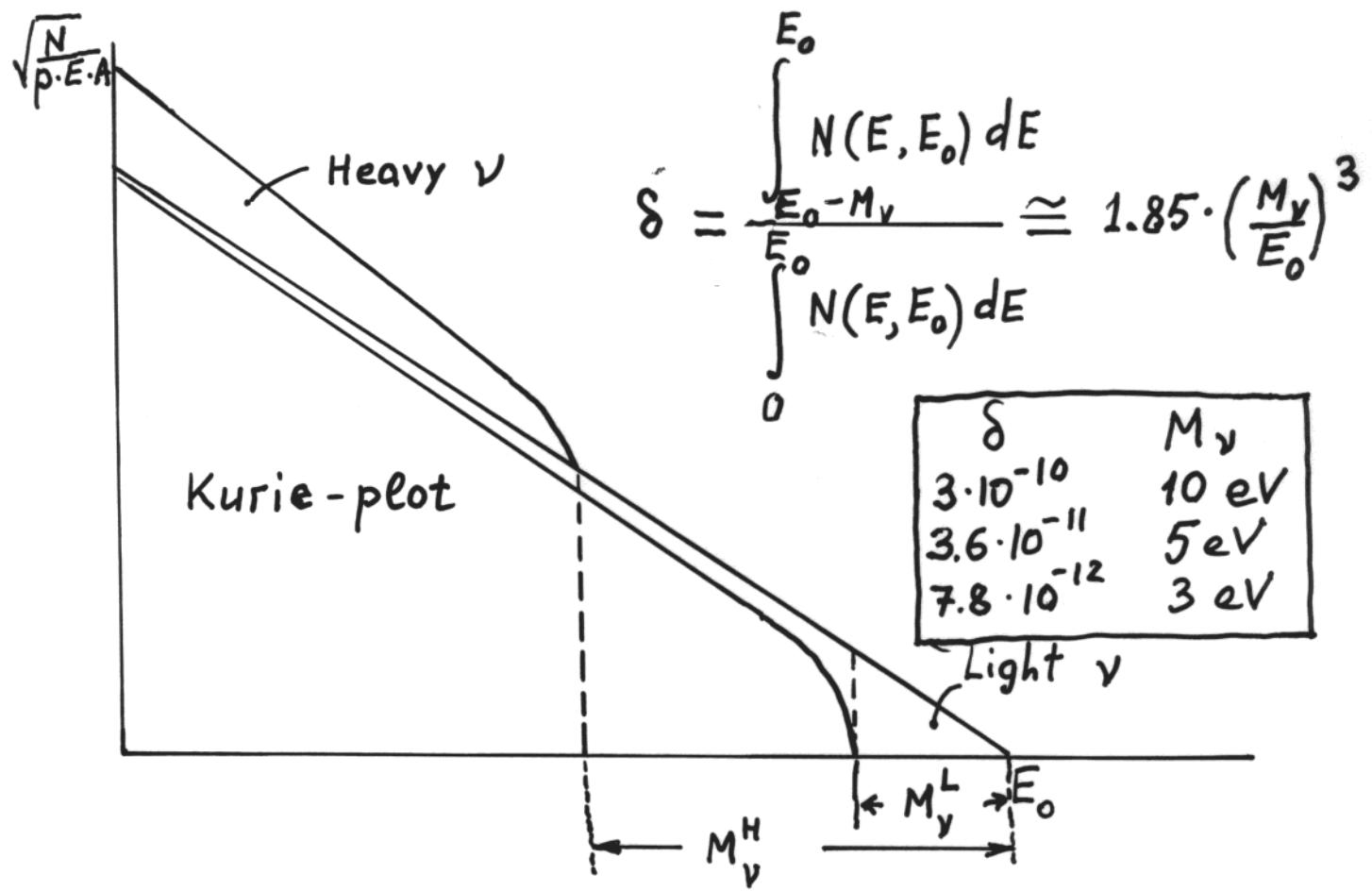
$$dN(E) = \underbrace{G_F^2 \cdot k F(z, E) |M|^2}_{a} \cdot P_e \cdot E_e \cdot (E_0 - E)^2 dE; m_\nu \equiv 0$$

$$dN(E) = a \cdot P_e \cdot E_e (E_0 - E) \left[(E_0 - E)^2 - M_\nu^2 c^4 \right]^{\frac{1}{2}} dE; \\ m \neq 0;$$

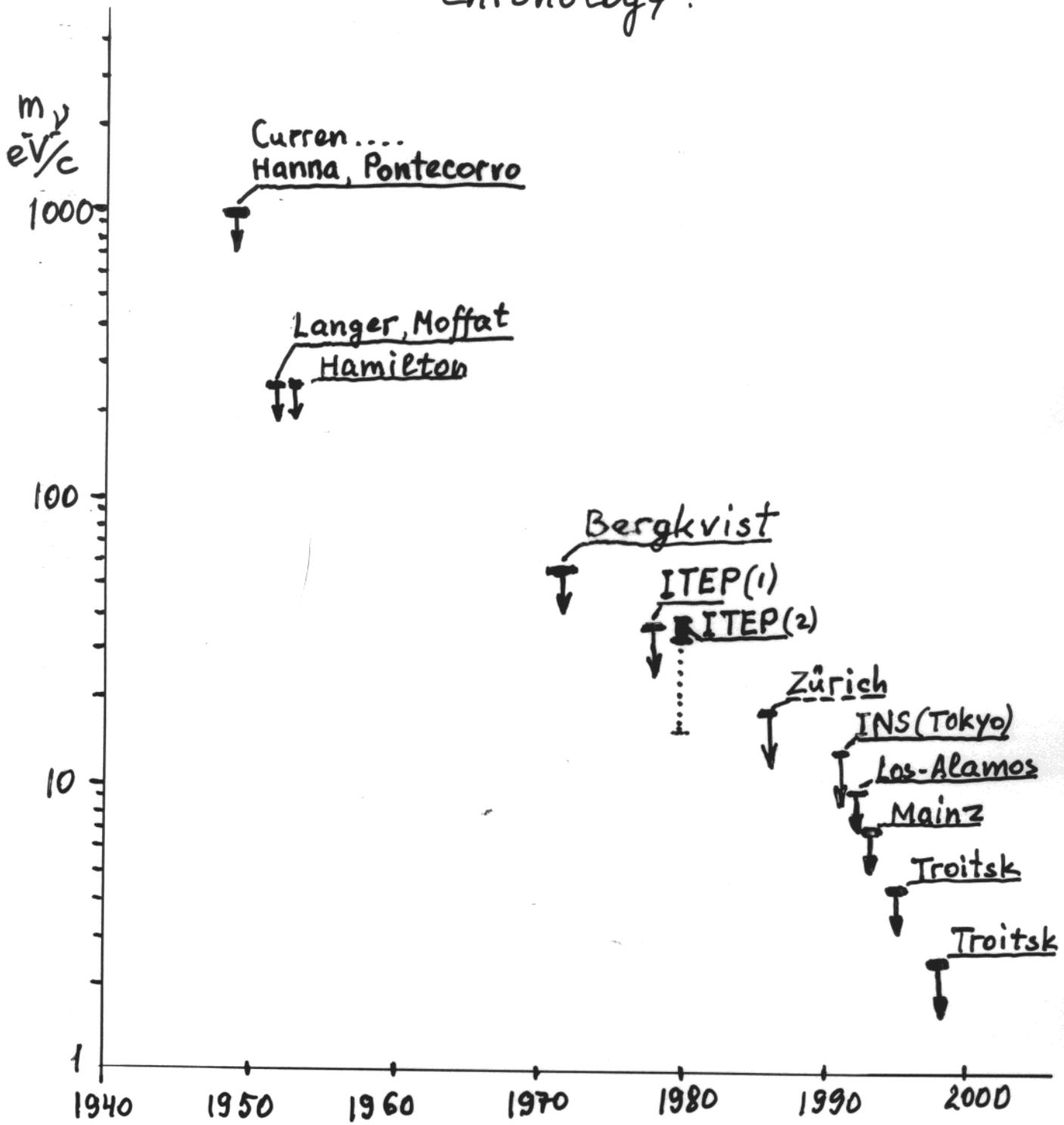
$E_0 - E = \varepsilon$; neutrino energy

$$dN(E) = a \cdot P_e E_e \sum_i w_i \cdot \varepsilon_i^2 \cdot \sqrt{1 - \frac{m_\nu^2 c^4}{\varepsilon_i^2}} \cdot d\varepsilon;$$

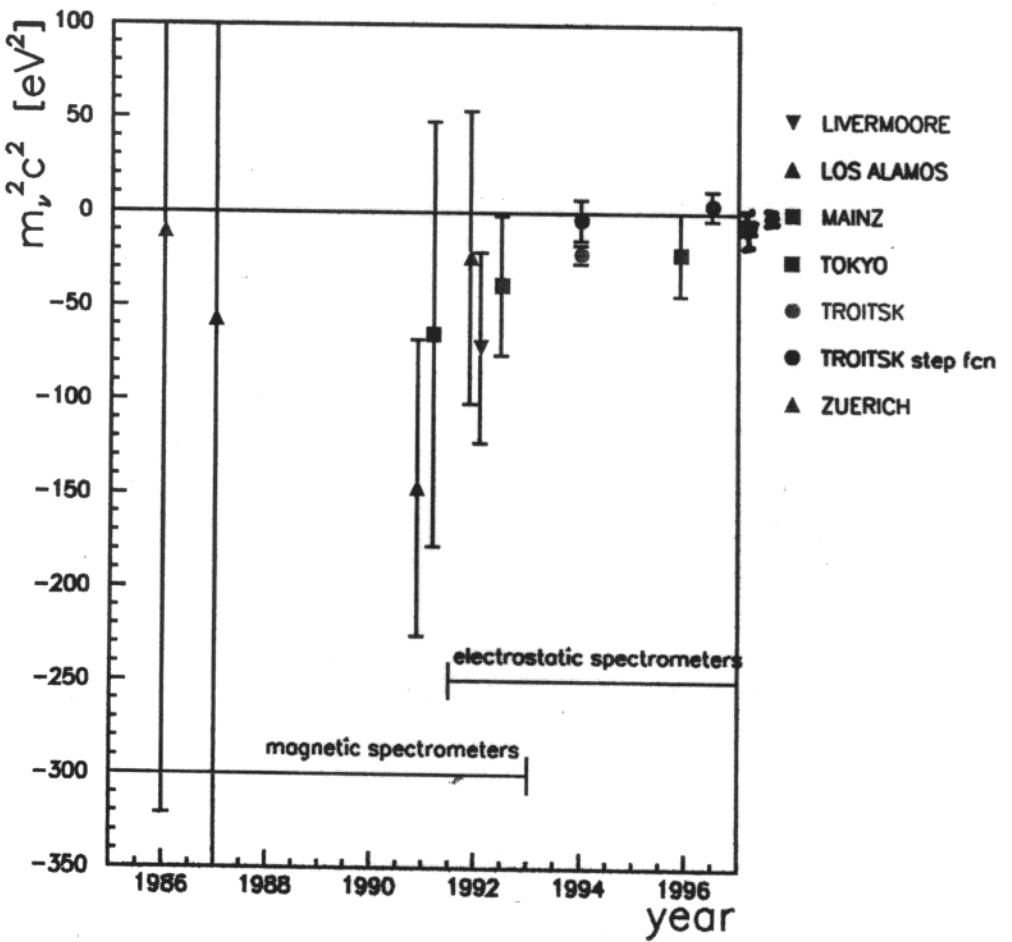
$\varepsilon_i = E_0 - E - V_i$; V_i - excitation energy of i -th final state.



The neutrino mass in ${}^3\text{T}$ decay. Chronology.



The last decade



- 2 running experiments (Mainz, Troitsk)
- Problem of $m_{\nu}^2 < 0$
→ 2 different Problems

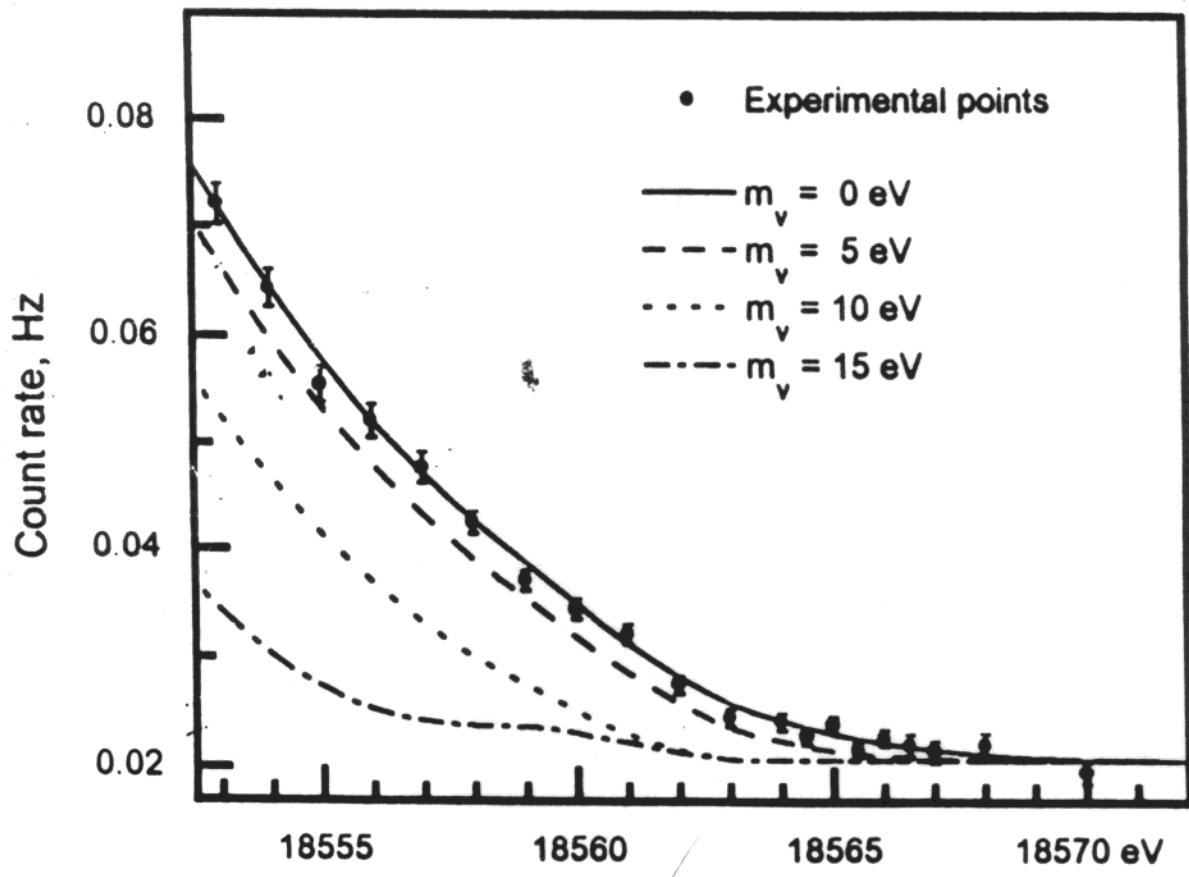


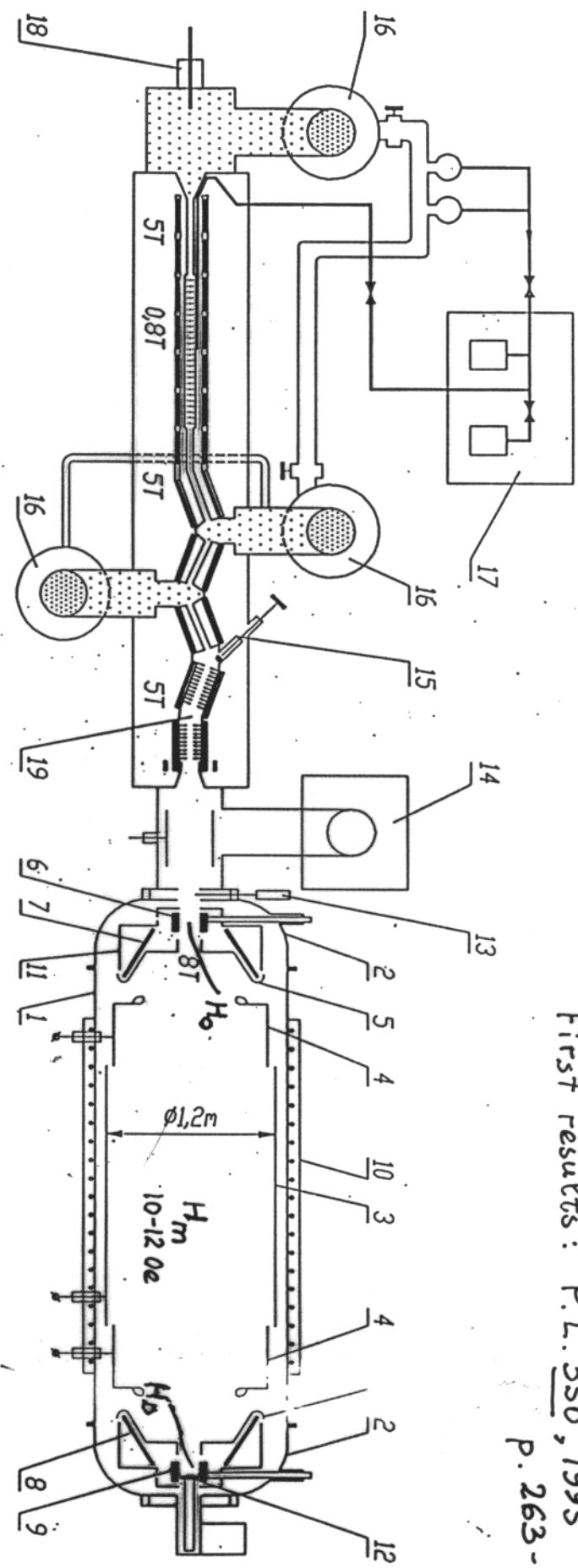
Figure 2: Part of the tritium spectrum near the end point. Solid and dotted curves present theoretical spectra (step included) with all the fitted parameters besides m_ν , that is fixed to shown figures.

NEUTRINO MASS AND ANOMALY IN THE TRITIUM BETA-SPECTRUM

Institute for Nuclear Research
of the Russian Academy of Sciences,
60th October Anniversary prospect, 7a, 117312 Moscow, Russia
"Troitsk ν -mass" experiment
V.M.Lobashev, A.I.Belesev, A.I.Berlev, E.V.Geraskin,
A.A.Golubev, N.A.Golubev, O.V.Kazachenko,
Yu.E.Kuznetsov, R.P.Ostroumov, L.A.Ryvkis,
B.E.Stern, N.A.Titov, S.V.Zadorozhny, Yu.I.Zakharov

Proposal 1982 ; A 4240, 305-310
1985

First results : P.L. 350, 1995
P. 263 - 271



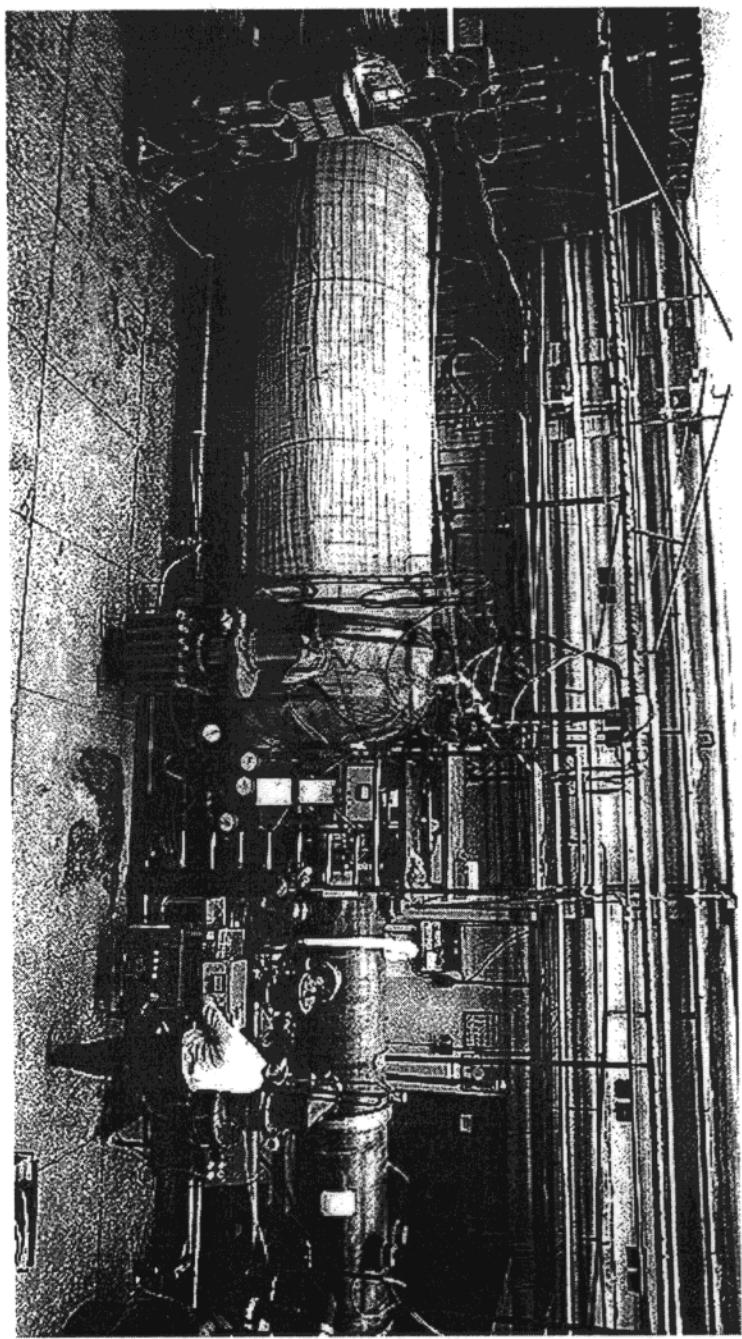
\square T_c -systen, 27K
 \blacksquare H_e -systen, 4,7K
(superconducting coil(s))

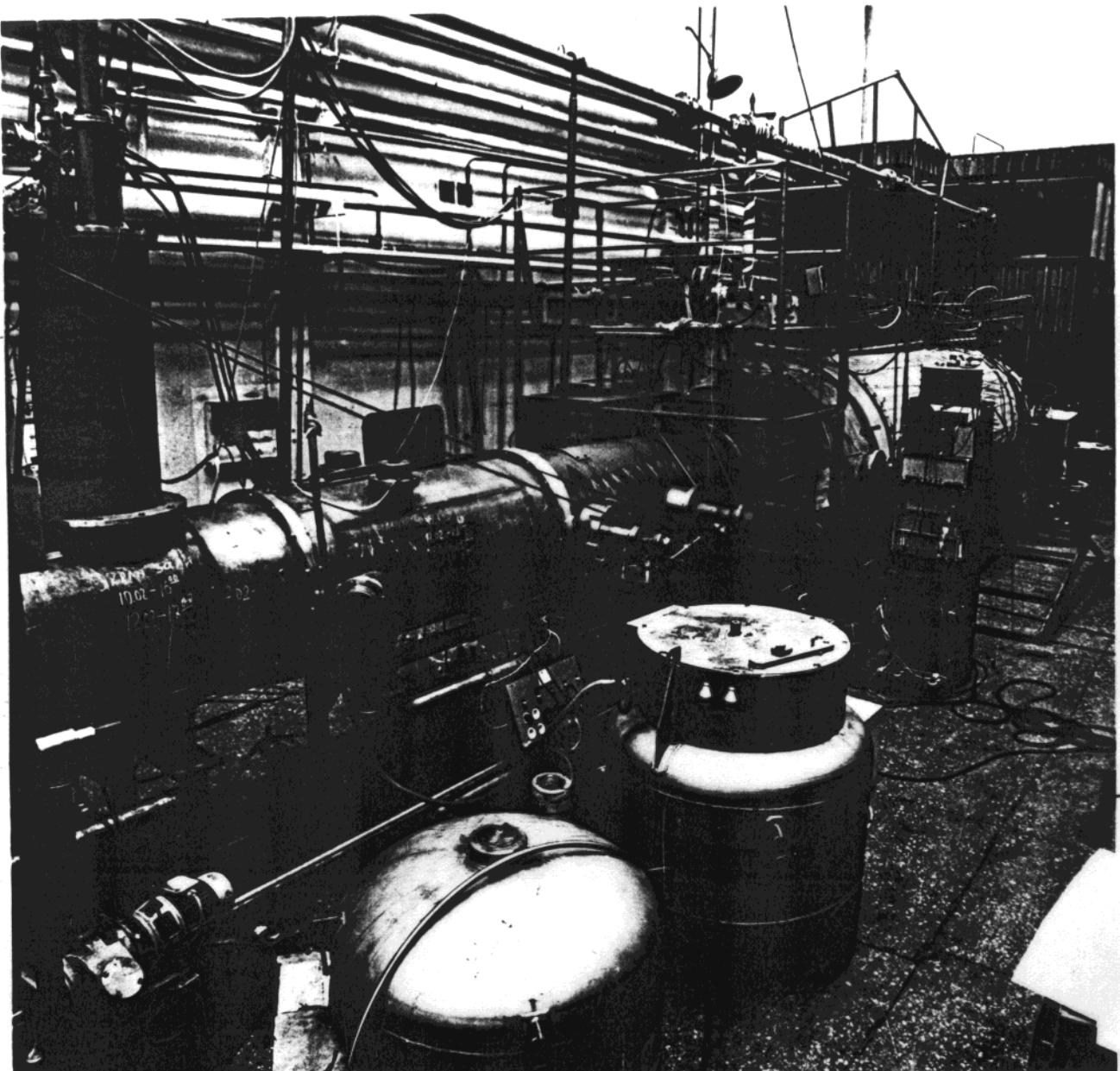
SPECTROMETER Response
for the monochromatice
electrons

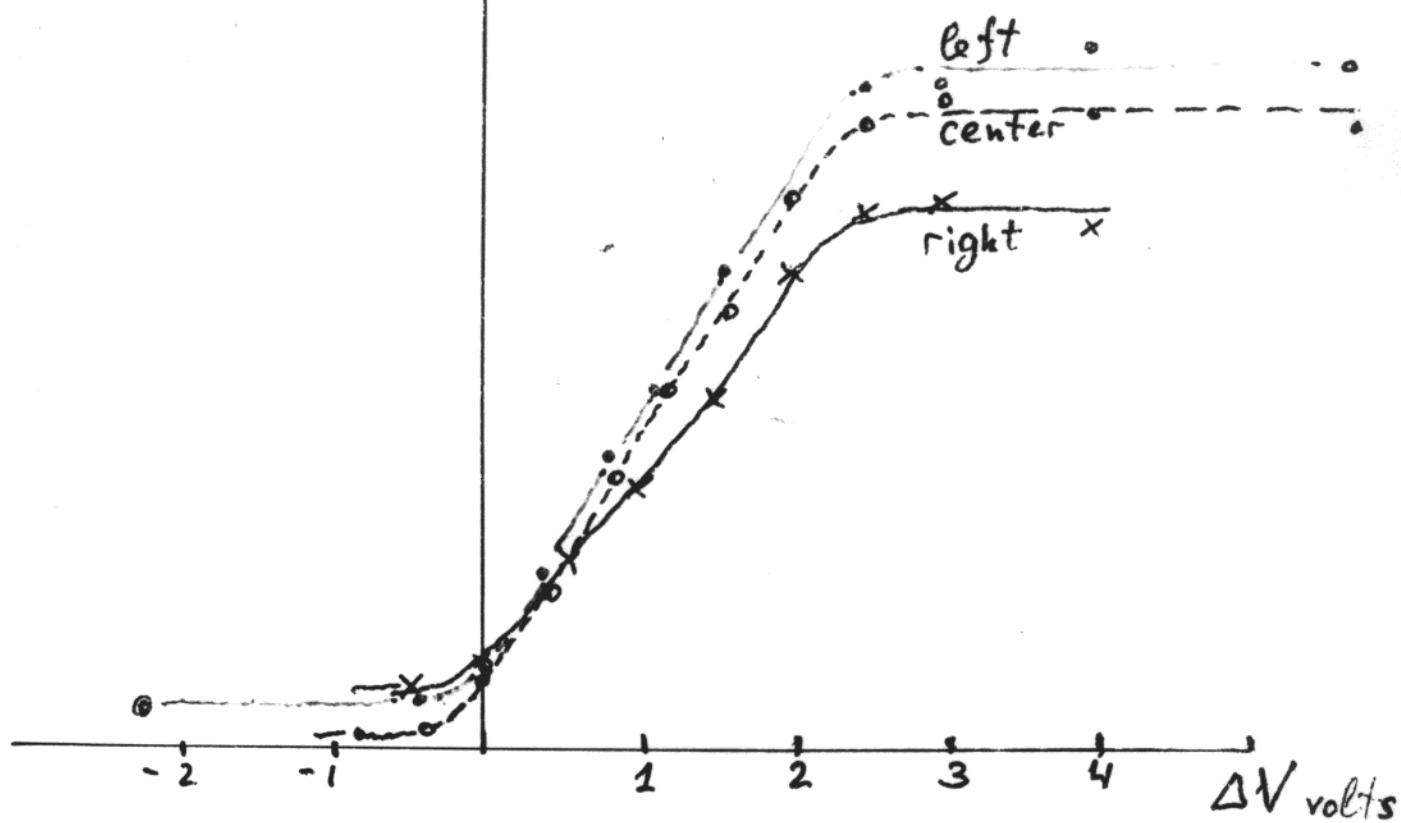
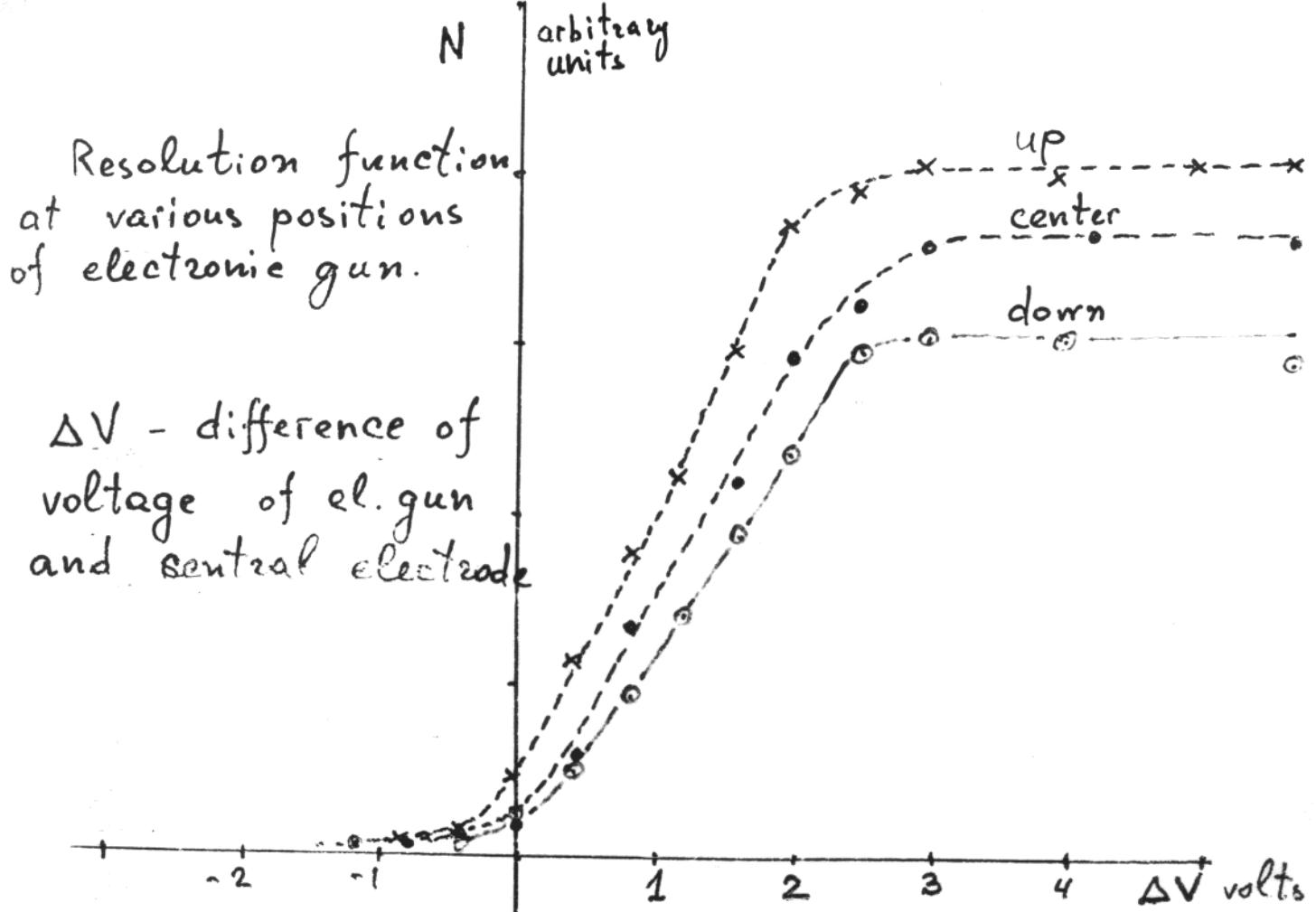
$$\Delta E = \frac{H_m}{H_0} \cdot E_0 \quad ; \quad L = S_p \cdot \frac{H_p}{H_0} \cdot \frac{1}{4}$$

$$E_0 = 18.6 \text{ keV} ; \Delta E = 3.5 - 4 \text{ eV (FW)}$$

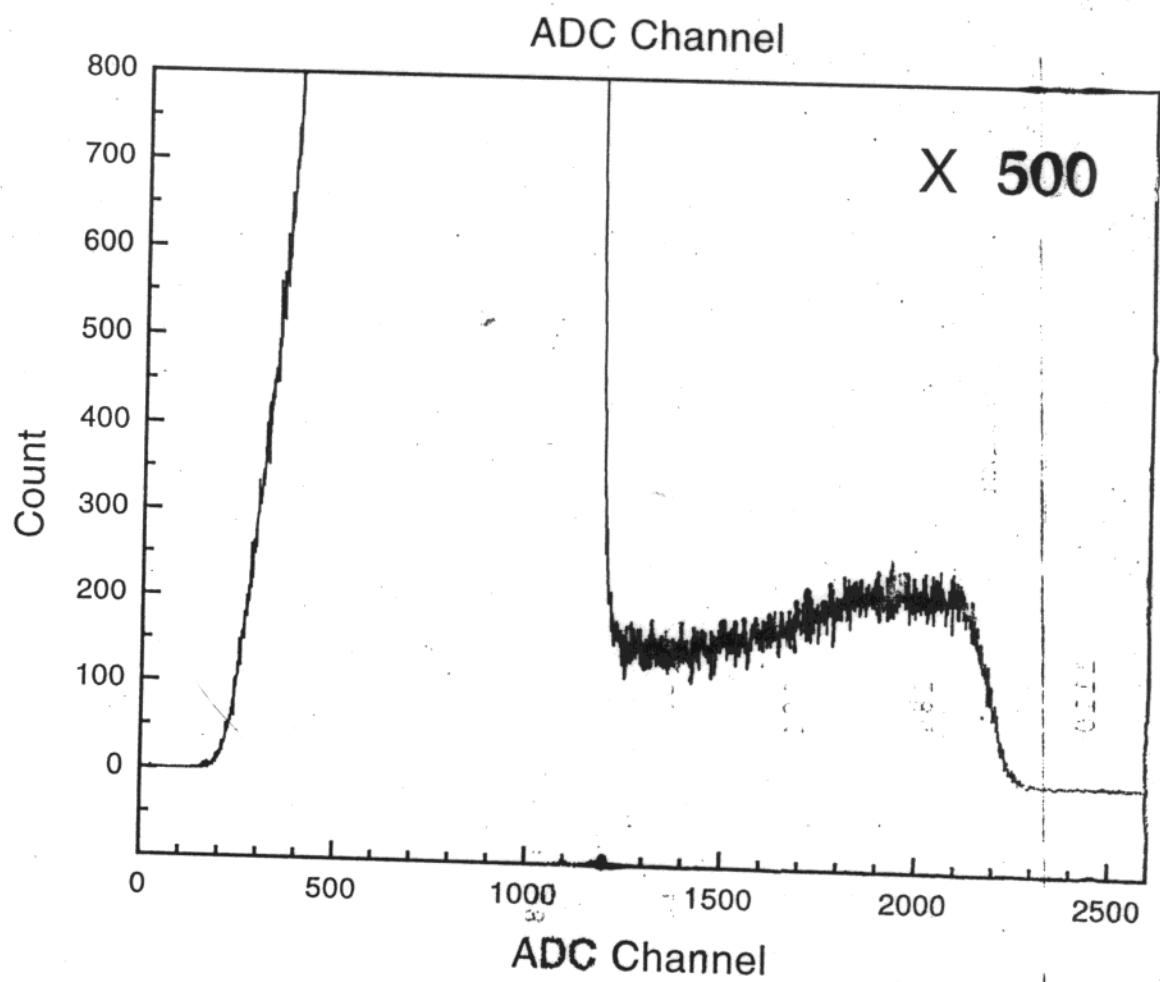
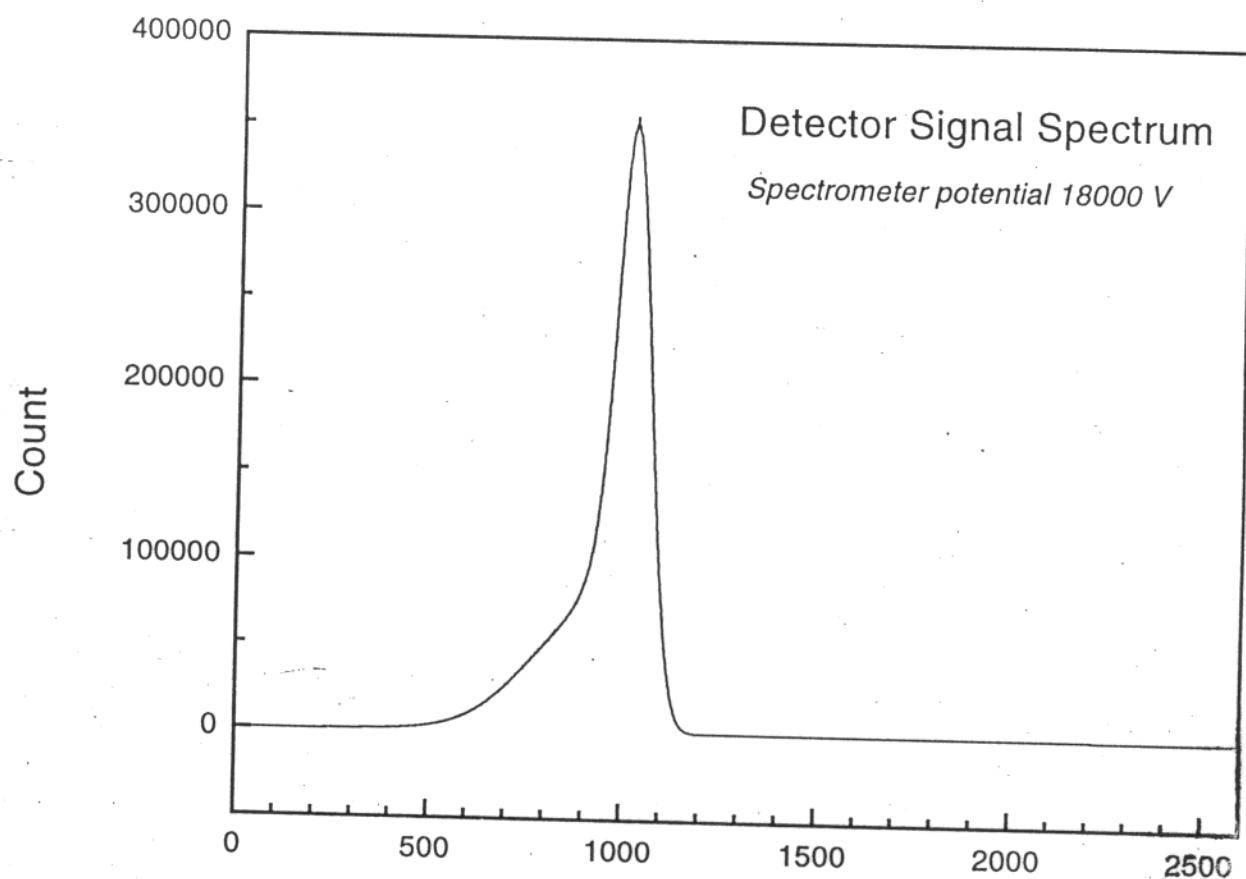
ΔE \sqrt{N}







calculated	FW	2.5 eV
measured	FW	2.6 - 2.8 eV



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Measurement procedure.

- Spectra were measured by scanning potential of spectrometer in steps 0.5÷50 V.
Stability of potential: ± 0.15 V short-term, ~ 2 V for 3 years.
- Voltage checked at each point by comparison with two independent attenuators.
- Measurement time per point 10÷200 sec.
- Direction of scanning was reversed after each cycle.
- After $\sim 10^3$ sec. H.V. was returned to reference point (18,000 or 18,175 V).
- Maximum count rate $\sim 6 \cdot 10^3$ sec $^{-1}$.
- Spectrum was measured for 1÷2 hours (cycle).
- Background $\sim 12 \div 30$ mHz independent of the spectrometer potential. Measured in the range 18,600÷19,600 V.
- Periods of running :

1994	January-February	3 X 12 days
	March	
	July	
1996	April - May	24 days
1997	February - March	40 days
	June	10 days
	December	20 days
1998	February	15 days
	June	15 days

Altogether ~ 180 days / 4 years.

+ 10 more days

Experimental spectrum corrections.

1. Search and elimination of tritium decay
in spectrometer volume.
 $5\div20$ sec bunch of pulses ($1\div3$ hour $^{-1}$). Cut-off level $\sim 3\cdot10^{-4}$.
2. Reference counting rate (T_2 source drift).
3. Dead time and pile-up of pulses.
4. Detection efficiency (~ 0.002).
5. Amplitude window corrections.

Data for fitting.

1. Resolution function (spectrometer response) was measured or calculated from magnetic field strength.
2. Energy loss spectrum and surface density of the source.
⇒ Measured by transmission through the source of electron from the gun with ultraviolet photoexcitation, injected from rear side.
No-hit factor and parameters of spectrum in the approximation obtained in these measurements were then used by accounting on the monitor counting rate and tritium percentage (from mass-spectrum).
3. Final state spectrum used from Jonsell, Monkhorst.
4. Correction for trapping-effect.

Results of the measurement were fitted to calculated spectrum
with 3 basic variable parameters:

A – normalization factor

b - background (constant over spectrum)

E_0 – end-point energy.

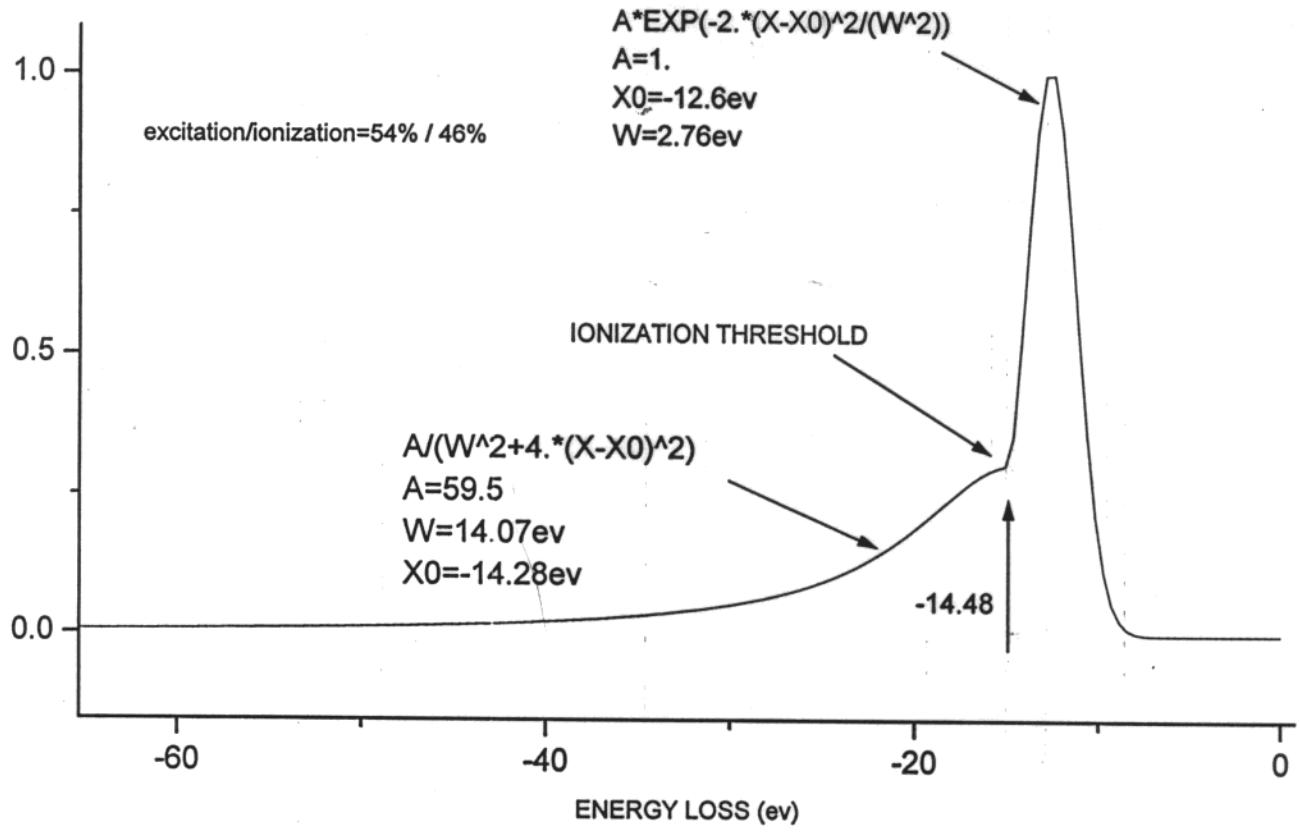
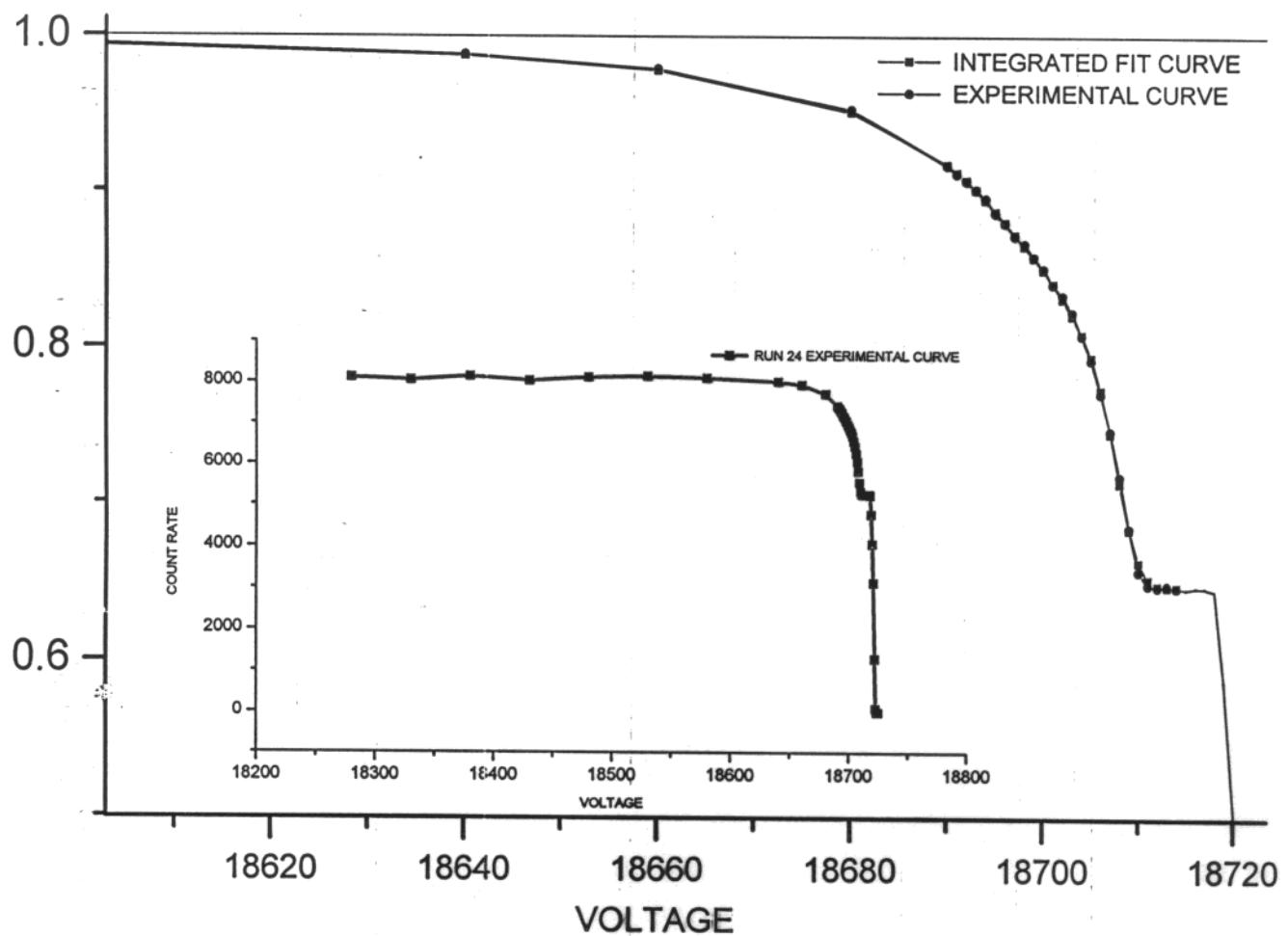
Next parameters were varied in different combination:

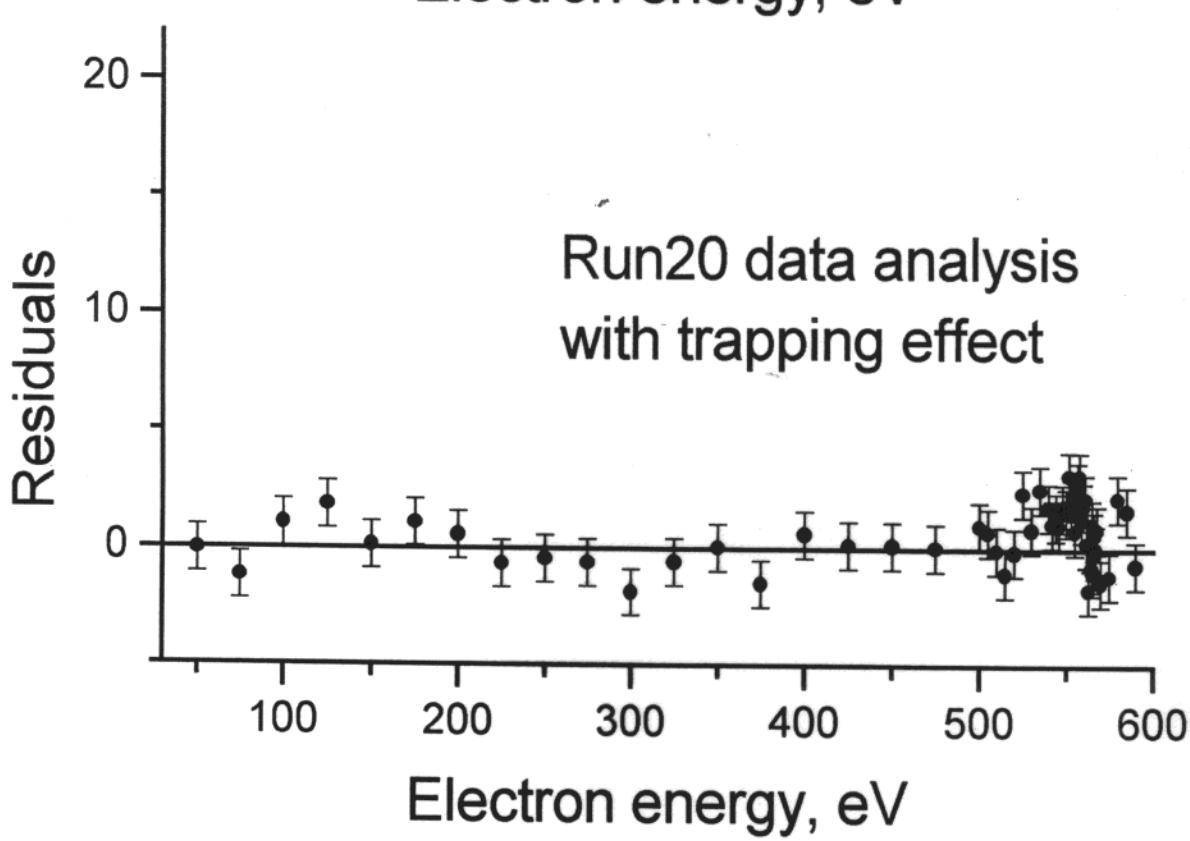
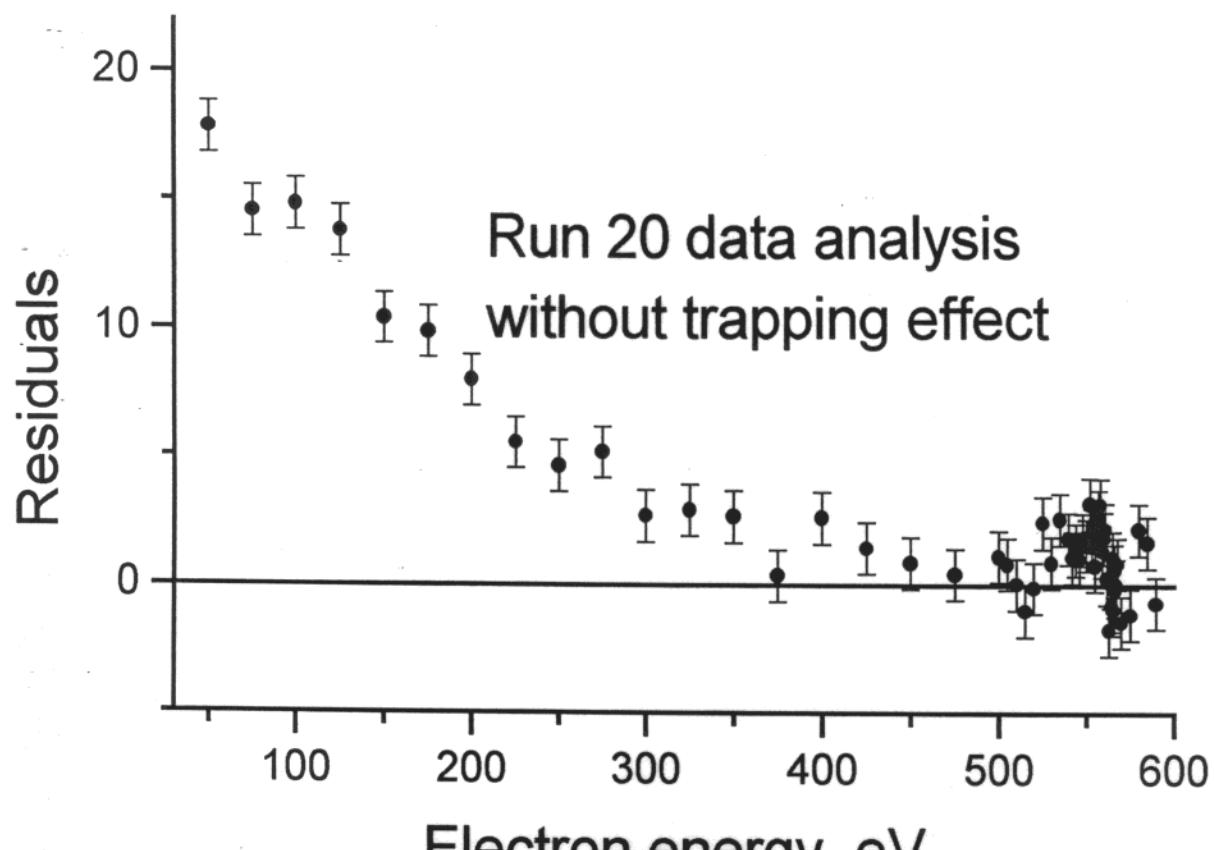
m_v^2 + basic
 E_{step} }
 N_{step} } Step function + basic

All of them variable.

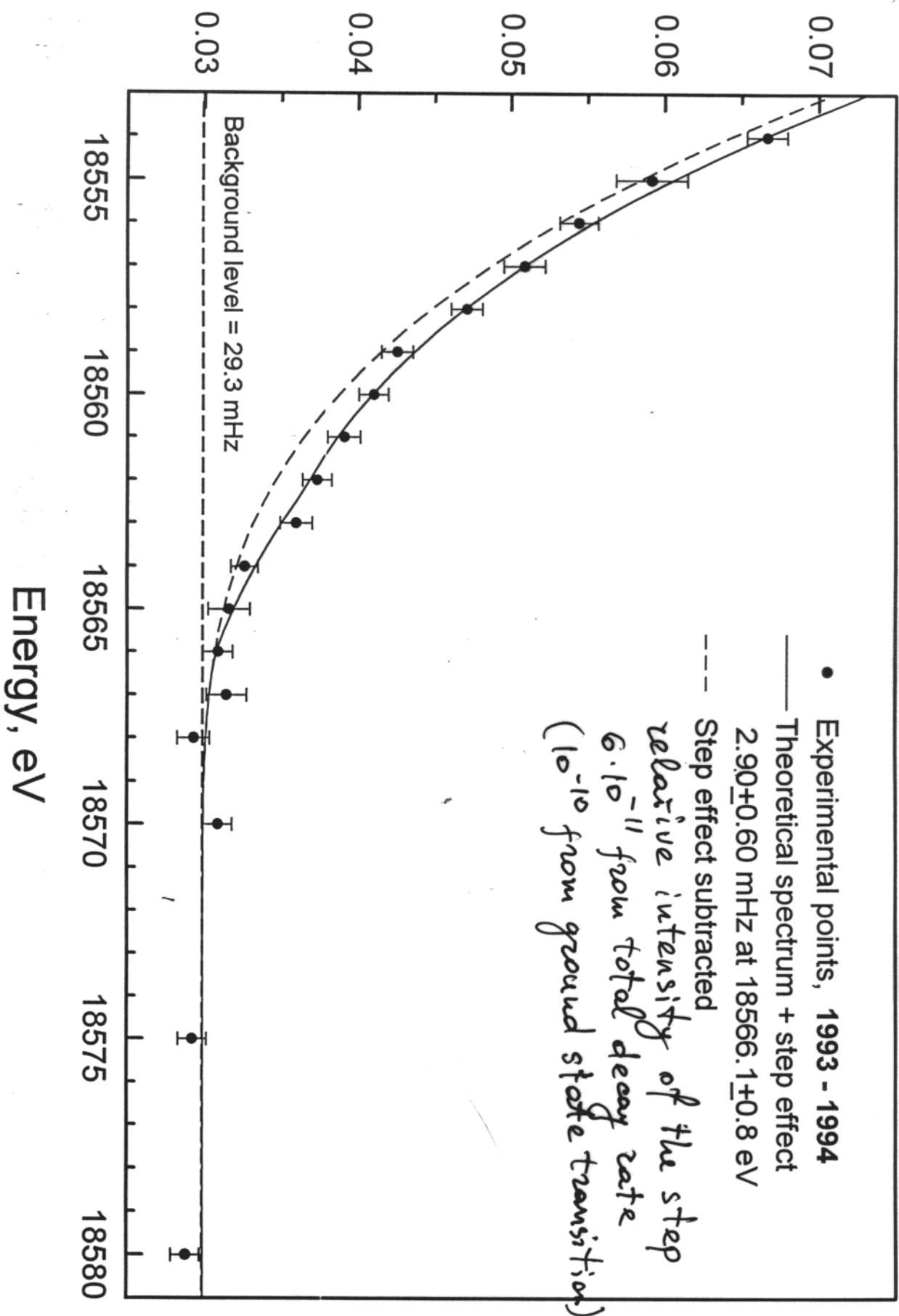
Some correction factors + basic + m_v^2 for regression coefficient determination.

Fit by MINUIT package.

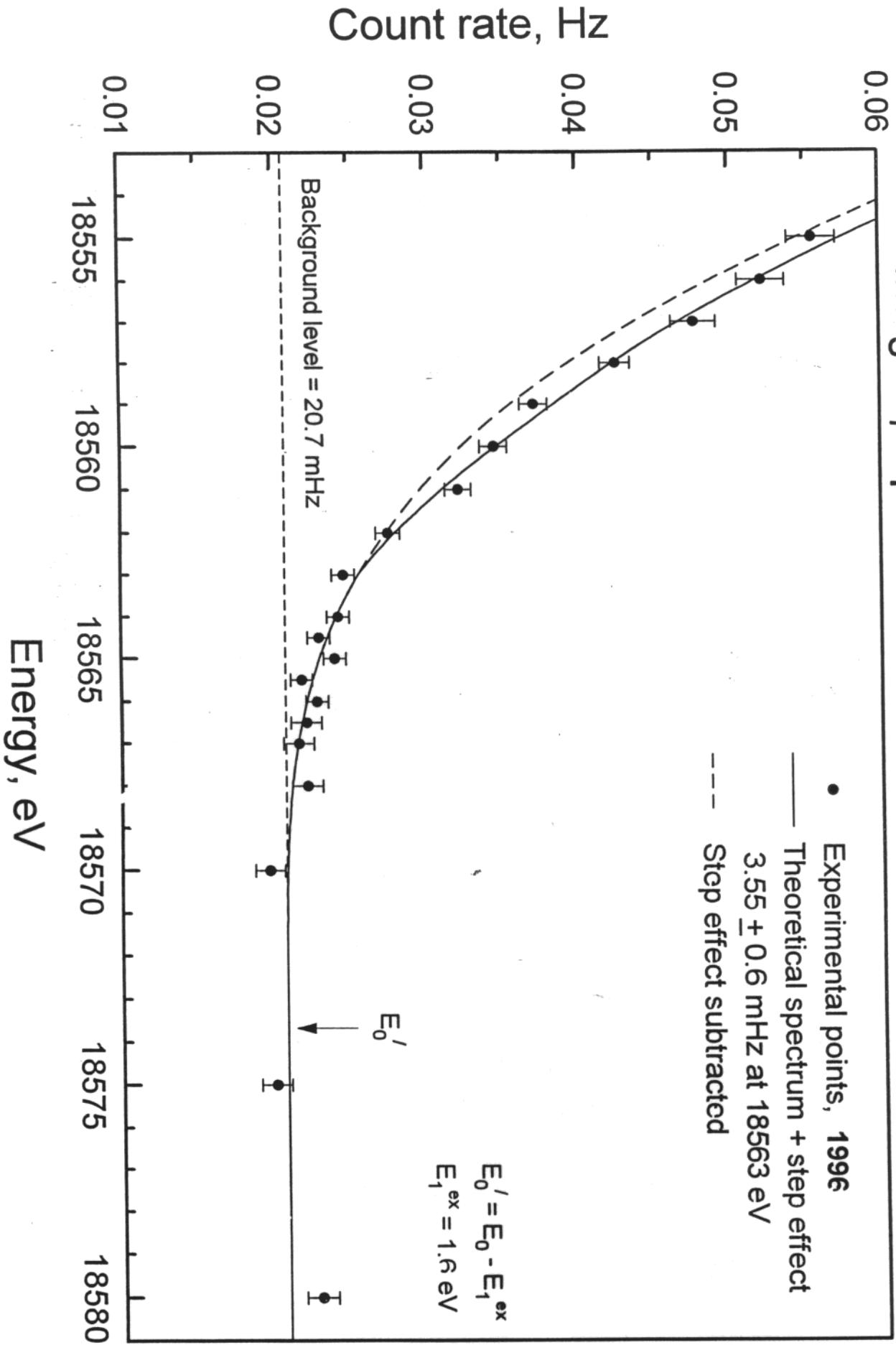




Integral β -spectrum of Tritium decay near end-point



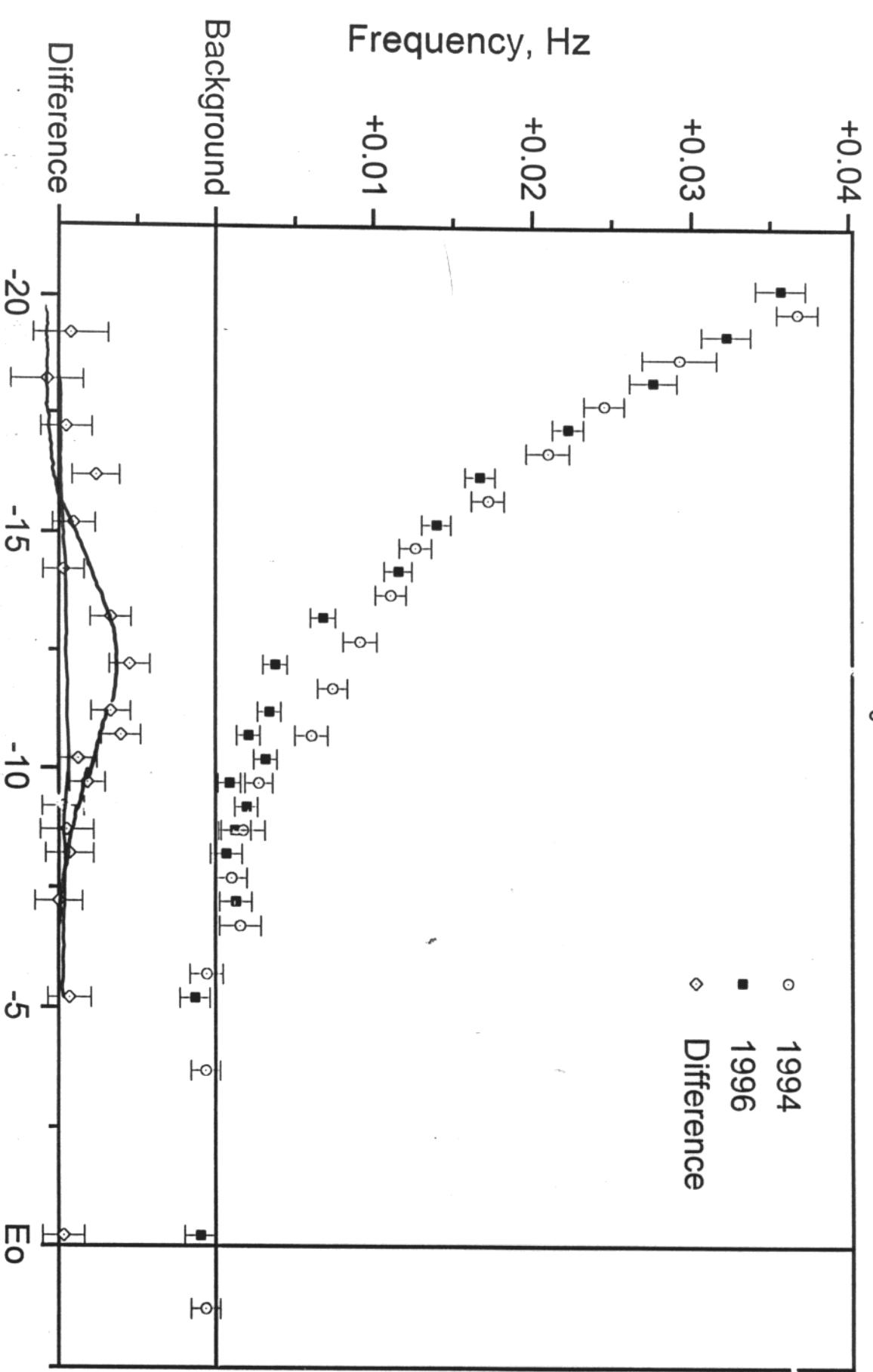
Integral β -spectrum of Tritium decay near end-point

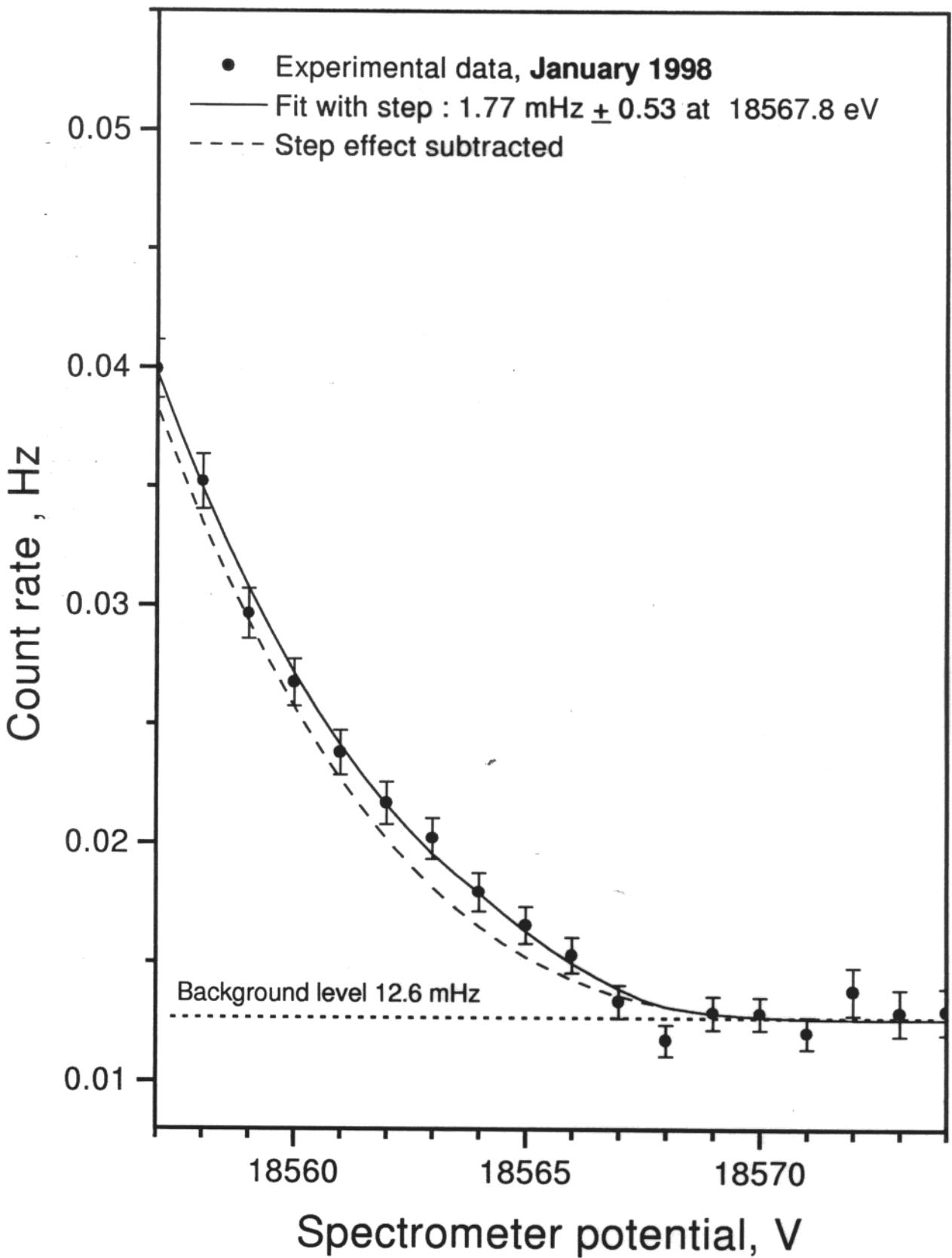


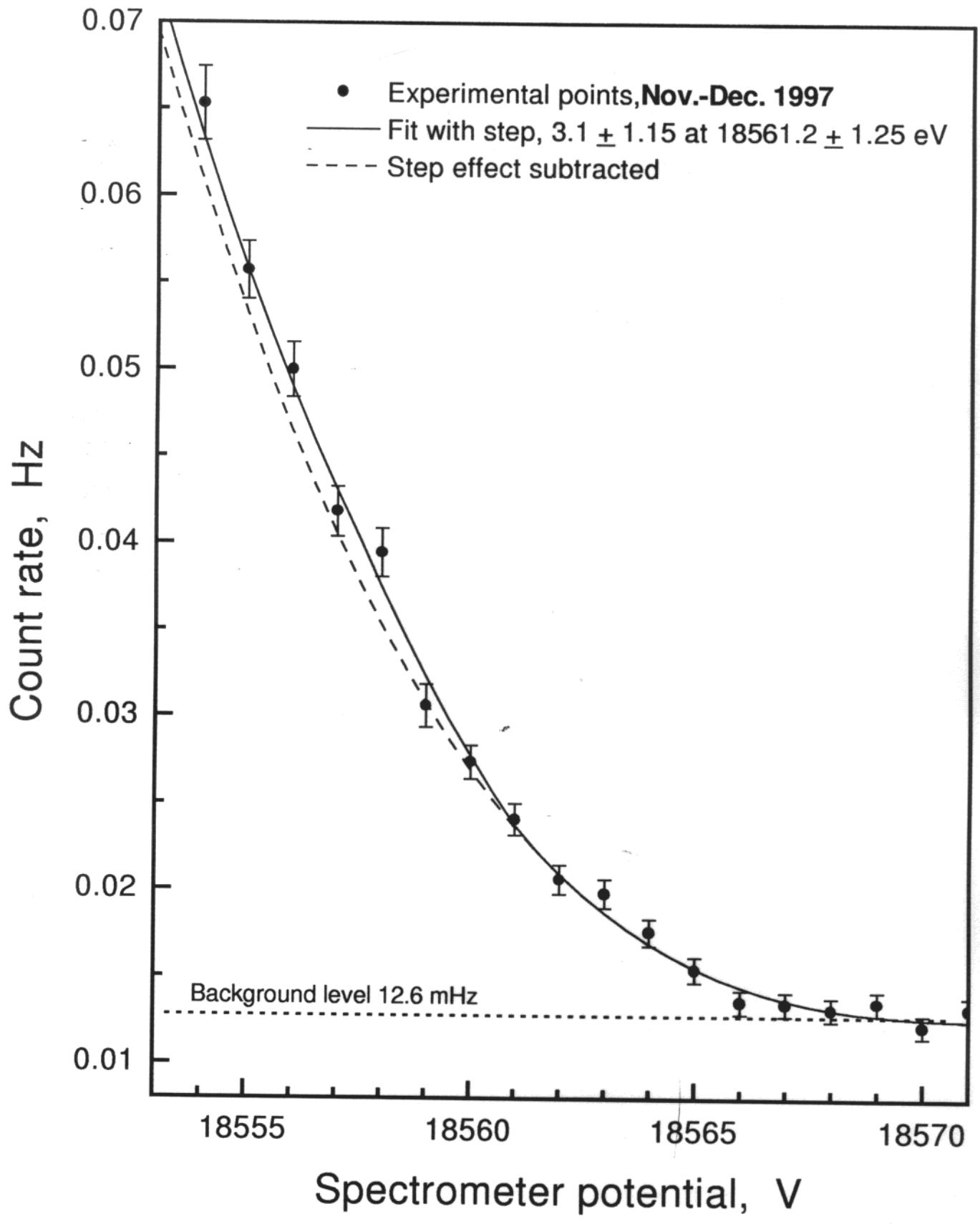
78

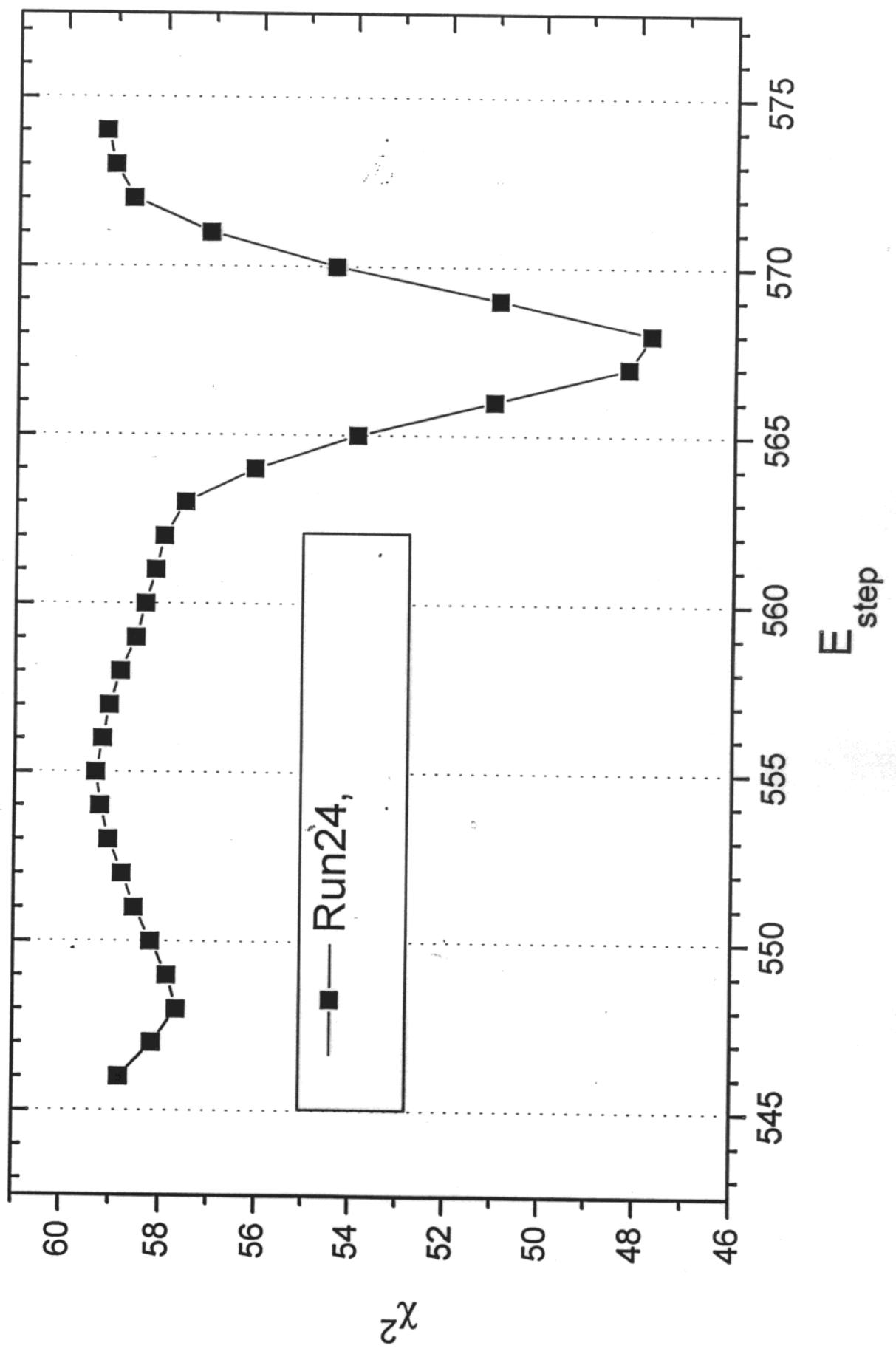
Comparison of measurements 1994 and 1996

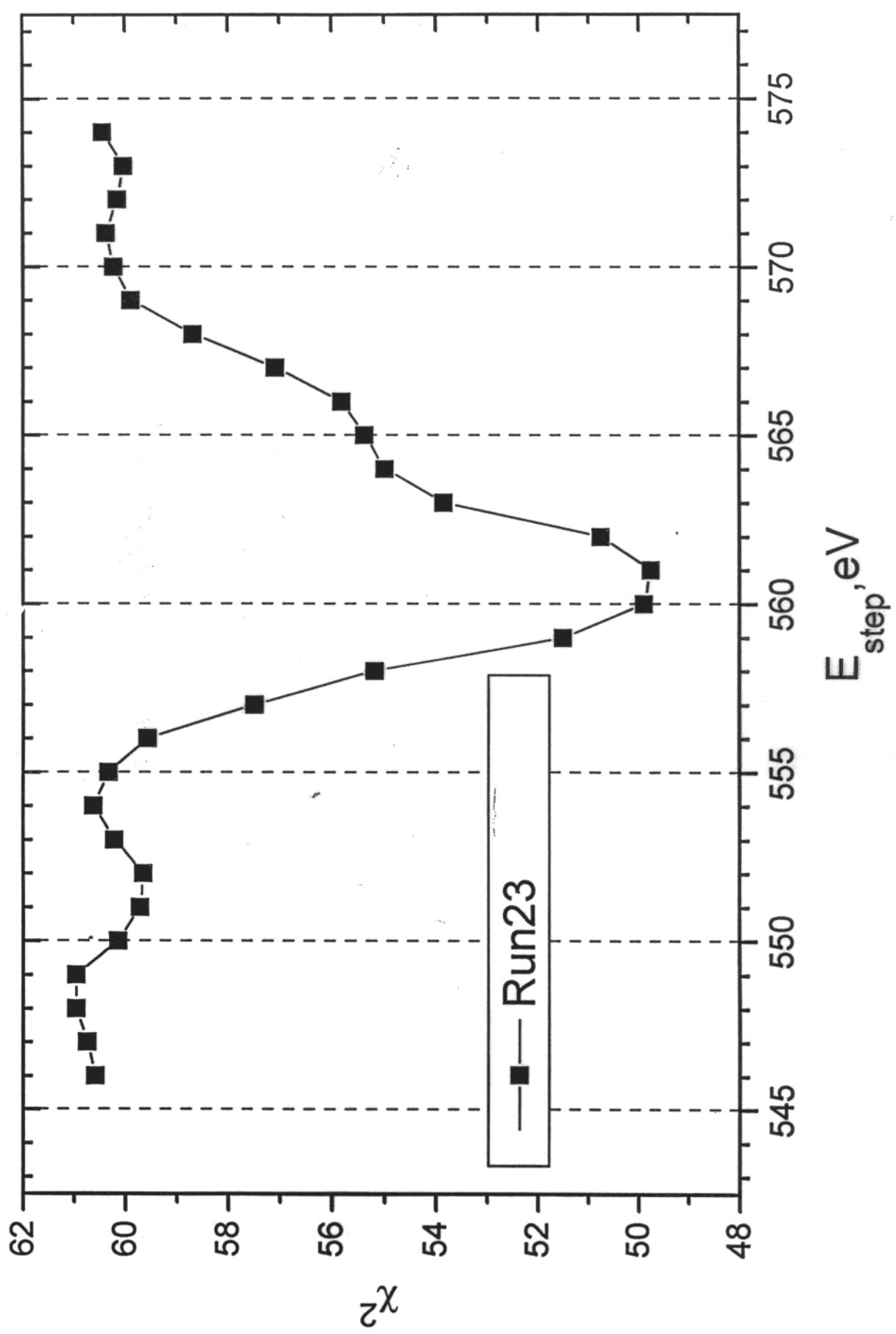
Spectra are matched in E_0 point and on integral intensity



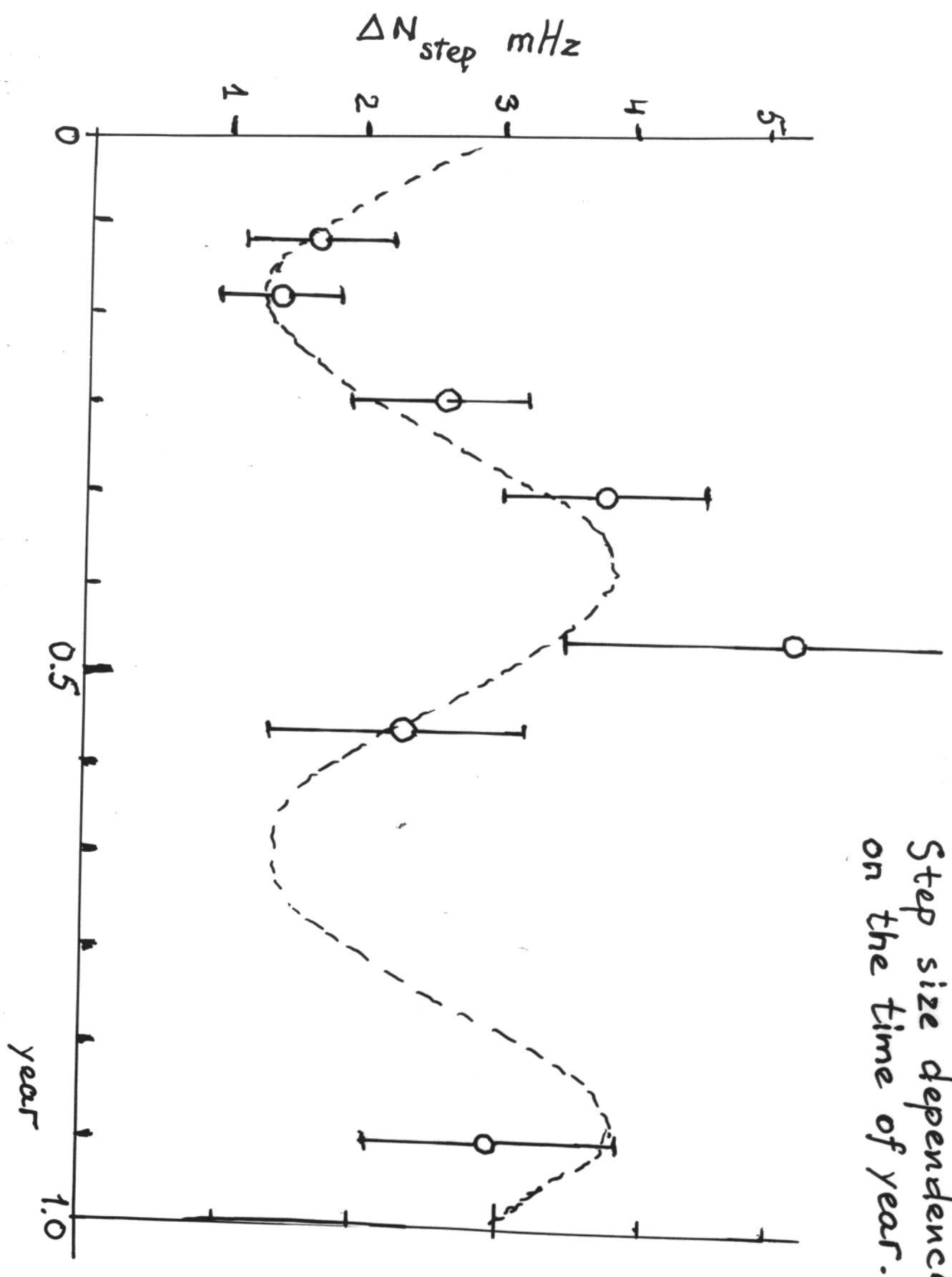


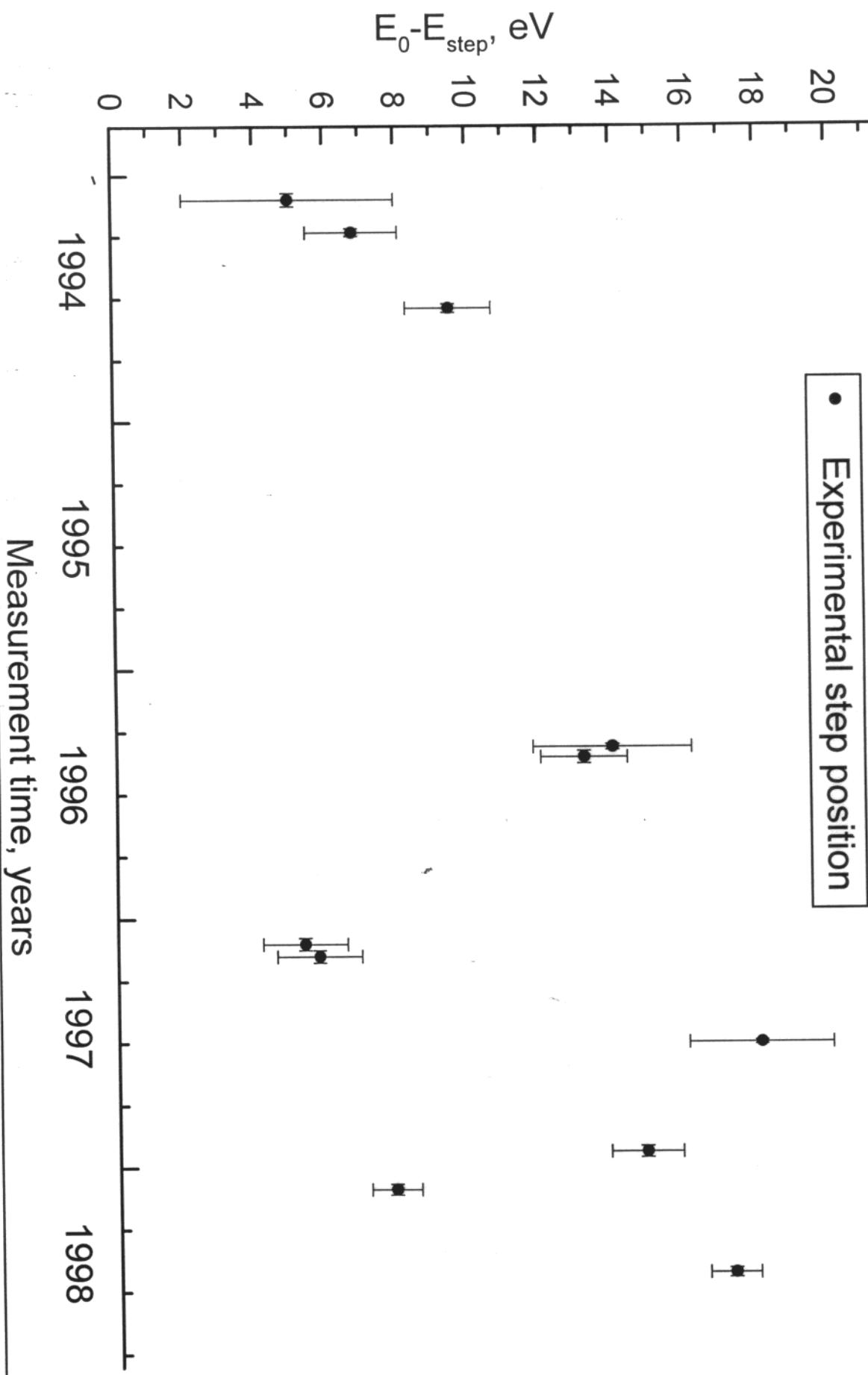


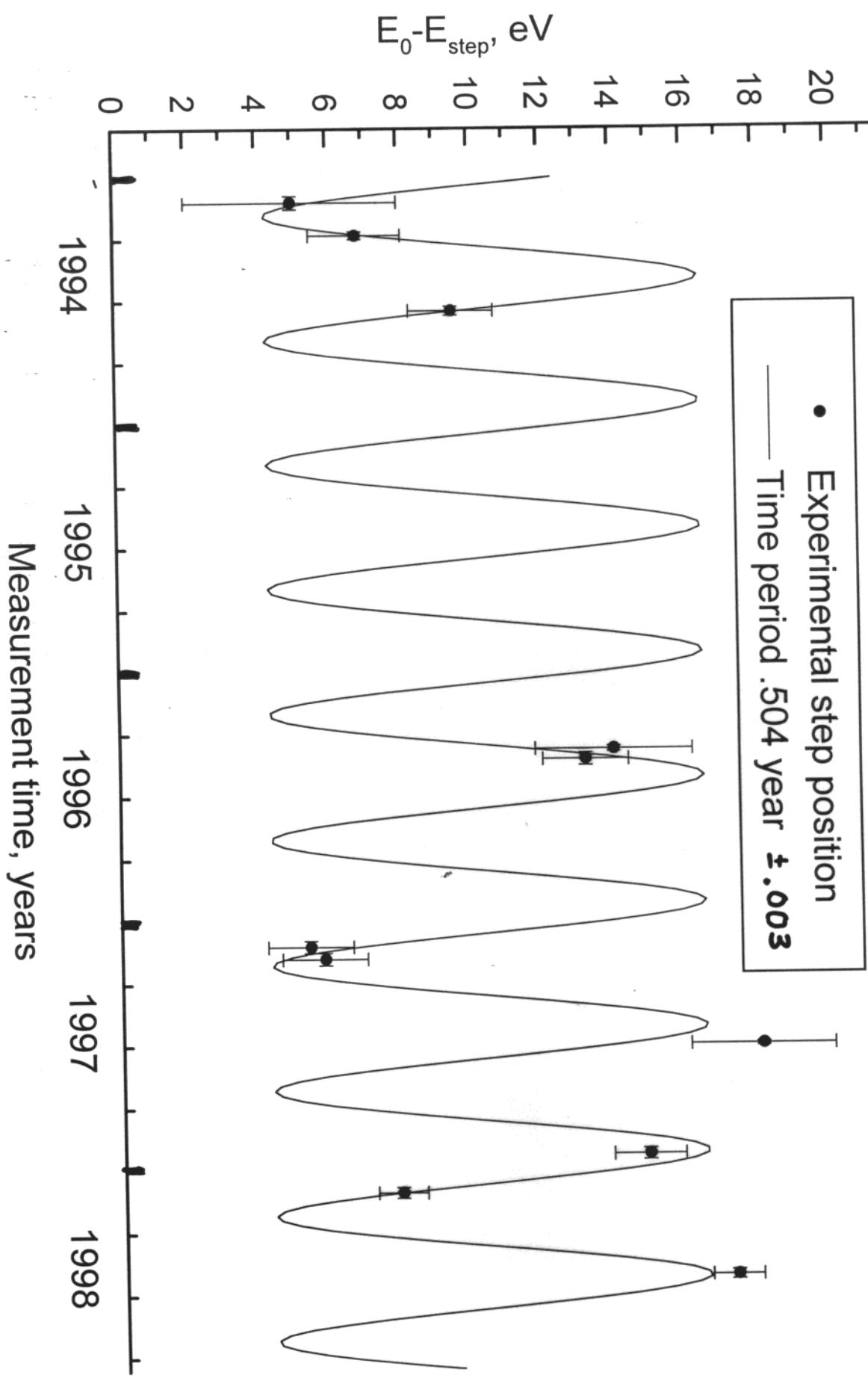


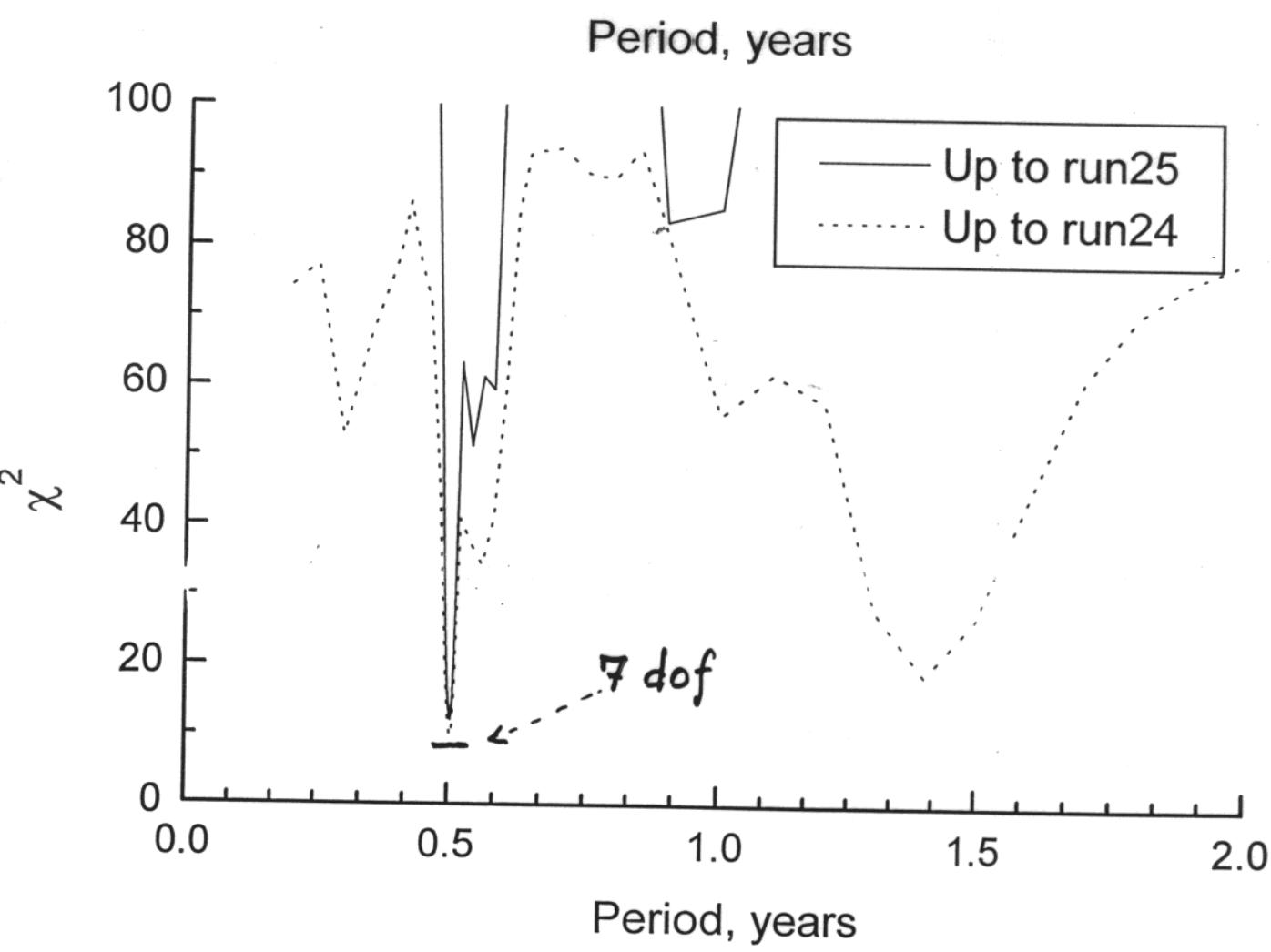
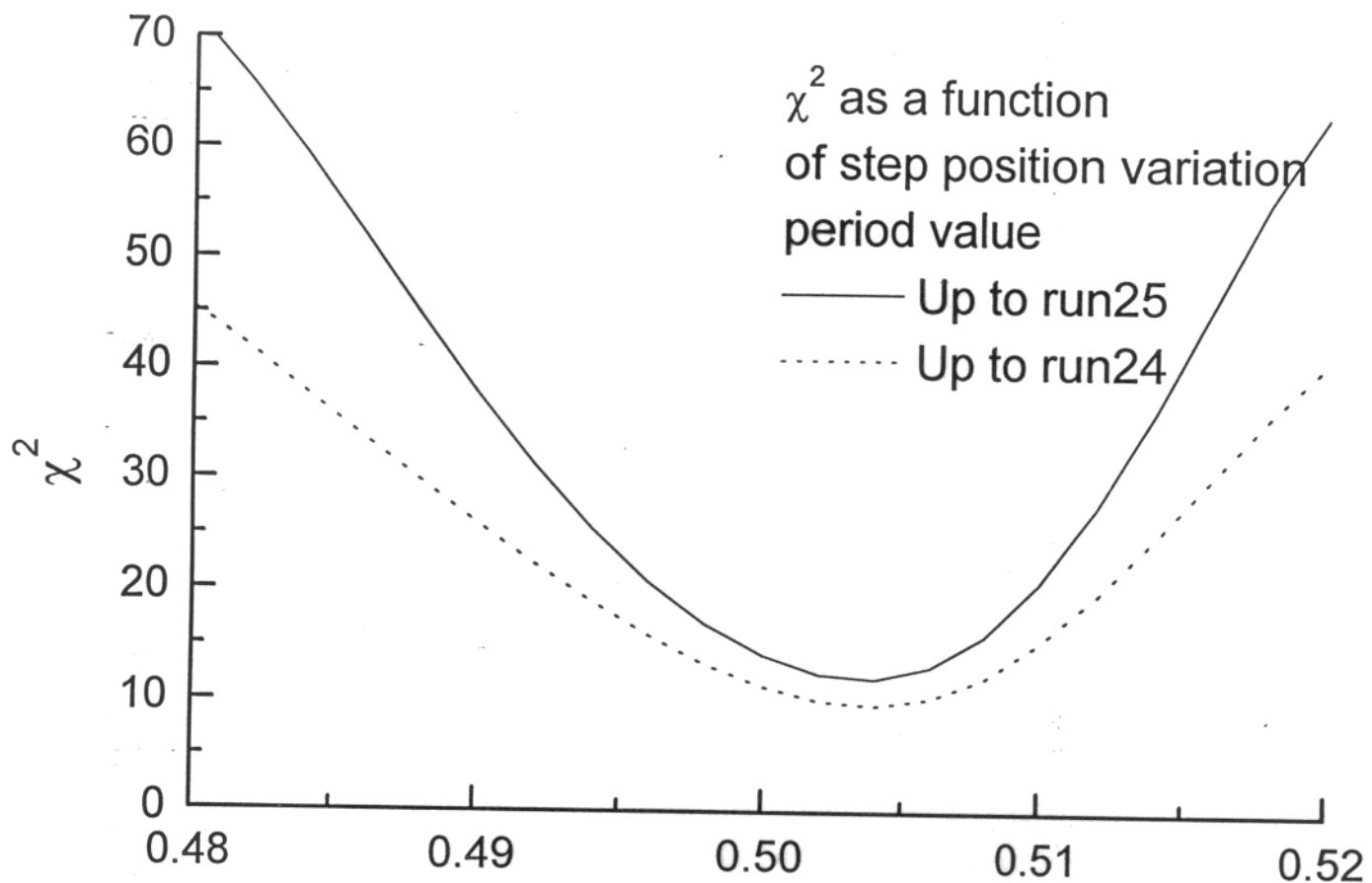


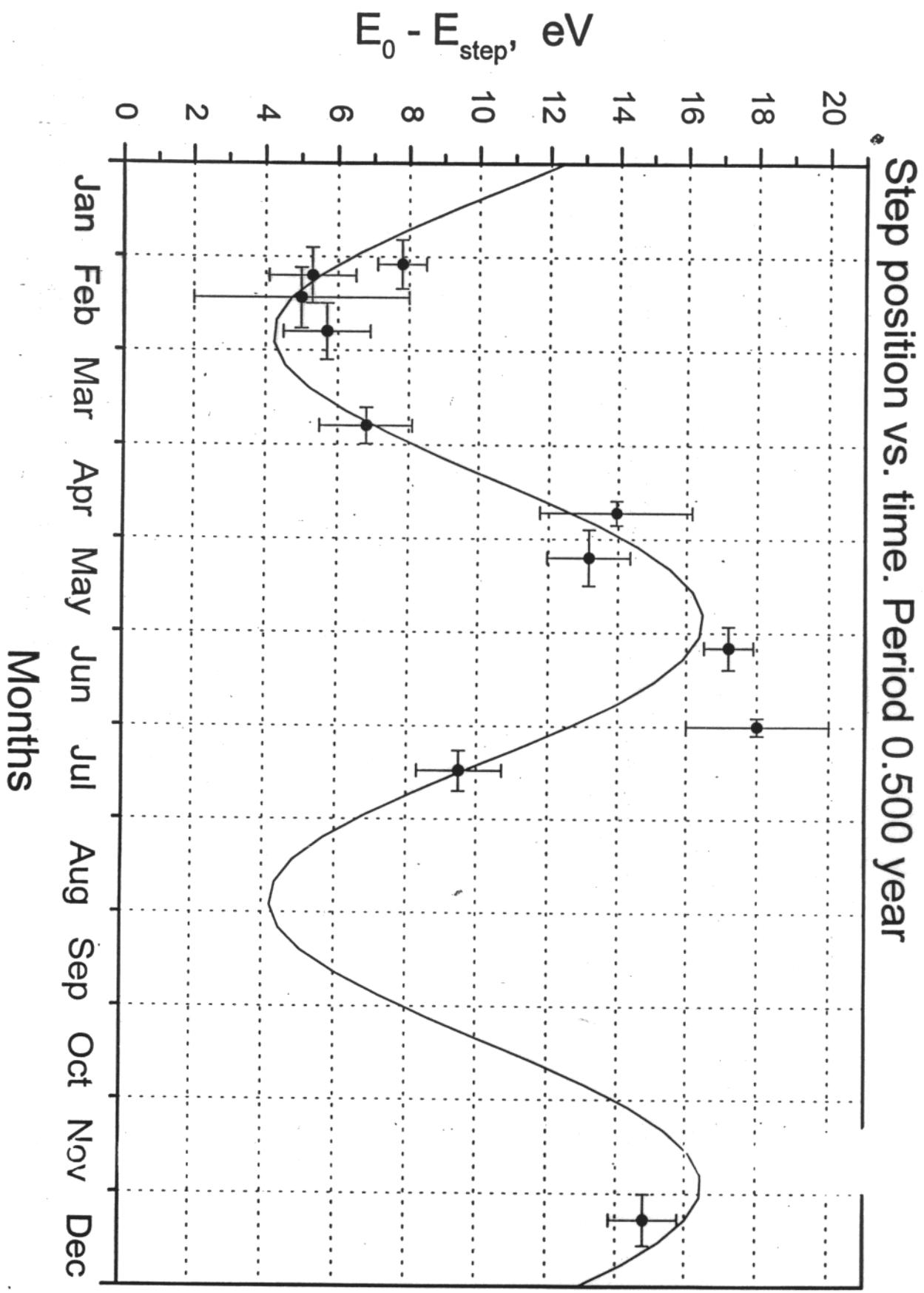
Step size dependence
on the time of year.











Features of the bump (step) effect.

1. Width ≤ 7 eV. (From comparison of Runs 94-96).
2. Integral intensity $\sim 1.0 \cdot 10^{-10}$ of ground state transition intensity.
3. Energy position $E_{\text{step}} = 5 \div 15$ eV below end point, periodically varying with calendar time.
4. Period of variation 0.504 ± 0.003 years.

Intensity correlates with the energy position. (*partially*)

5. Phase of variation corresponding to max E_{step} at 1-10 June and 1-10 December.
6. No dependence on the magnetic field setting in the spectrometer and source.
7. Bias of the source voltage (+15V) shifts the bump together with spectrum.
8. No radioactive admixture in the source.

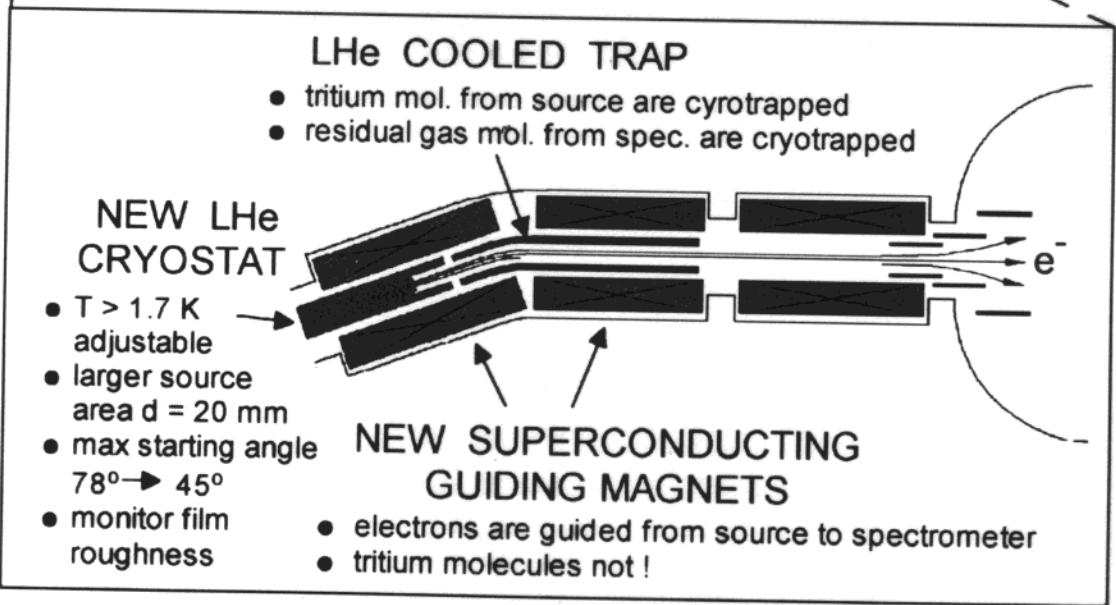
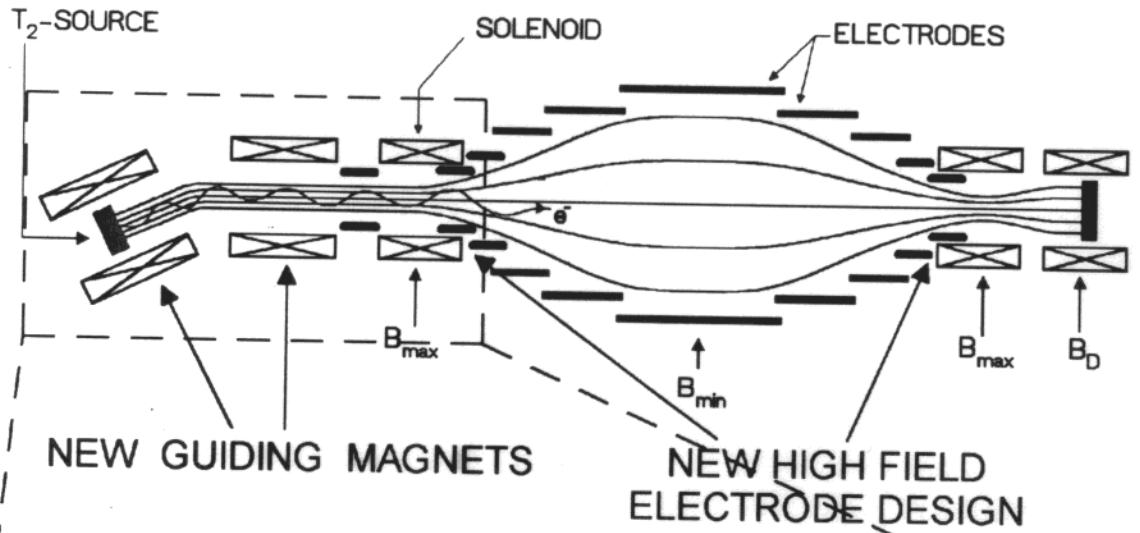
Admixture of T^0 , T^- , T_3^+ in the source $<< 10^{-4}$.

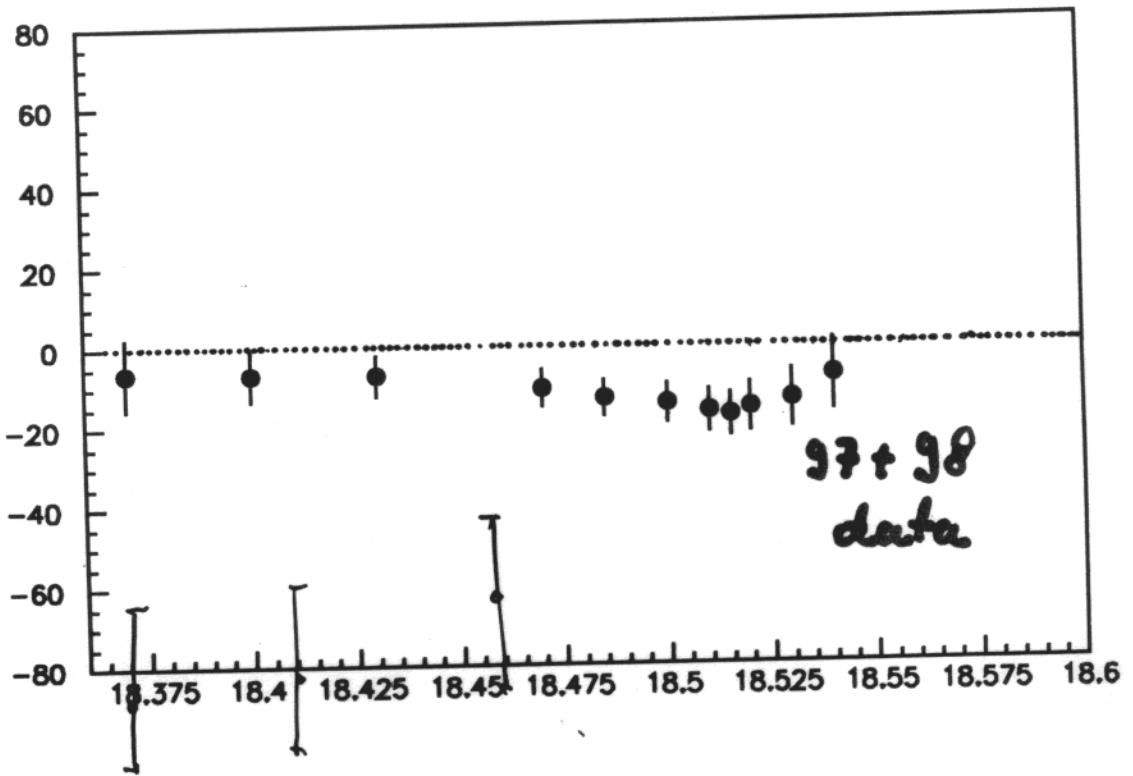
New feature - change in a week scale.

There is no rational explanation of this phenomenon by some systematics or **known** effects.

Exotic (irrational) explanations appears to be excusable in this situation.

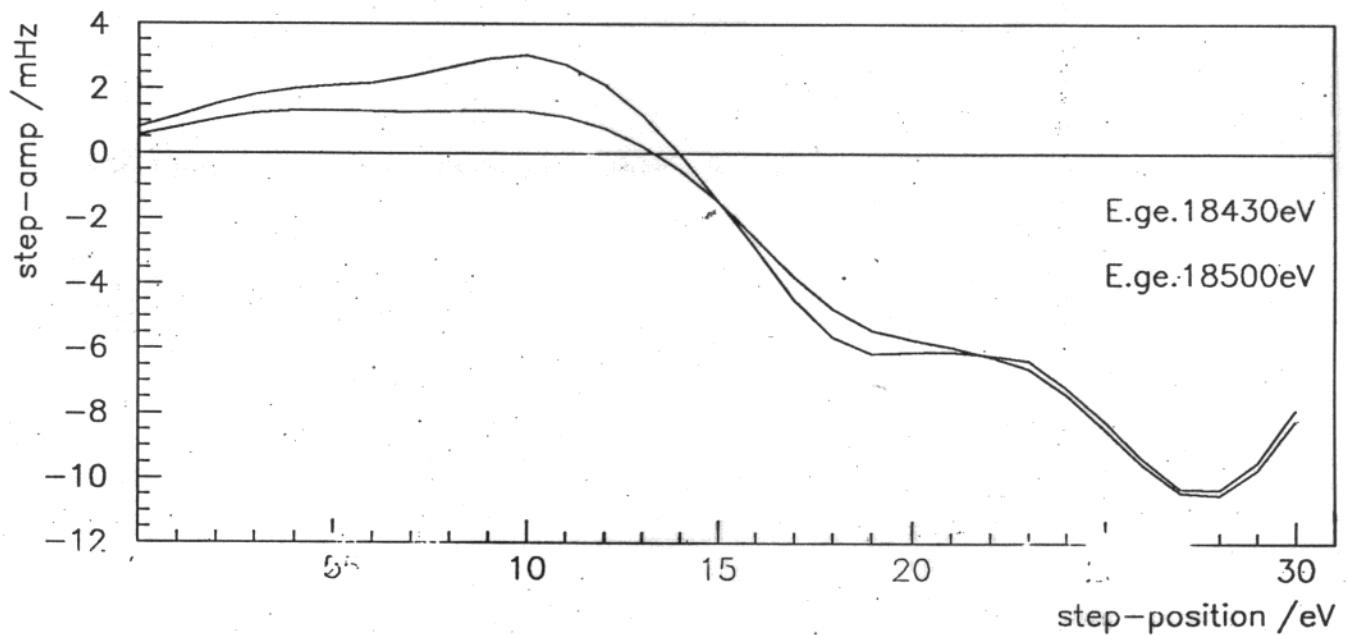
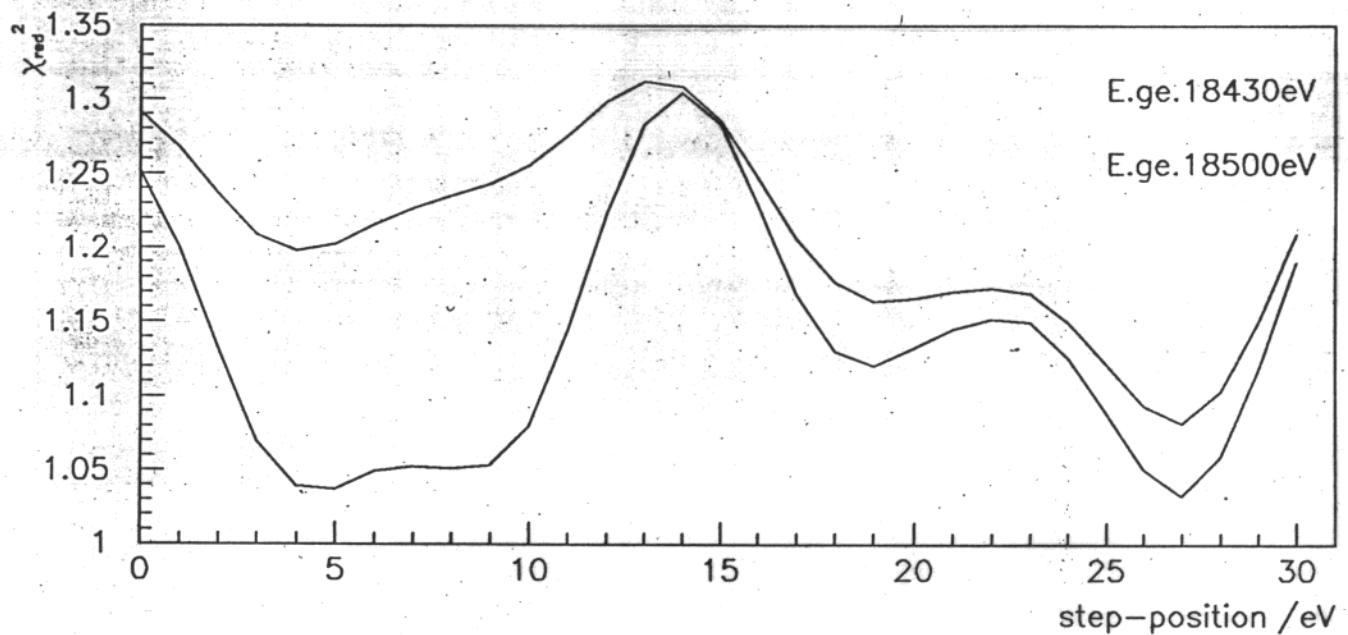
The improved Mainz Setup





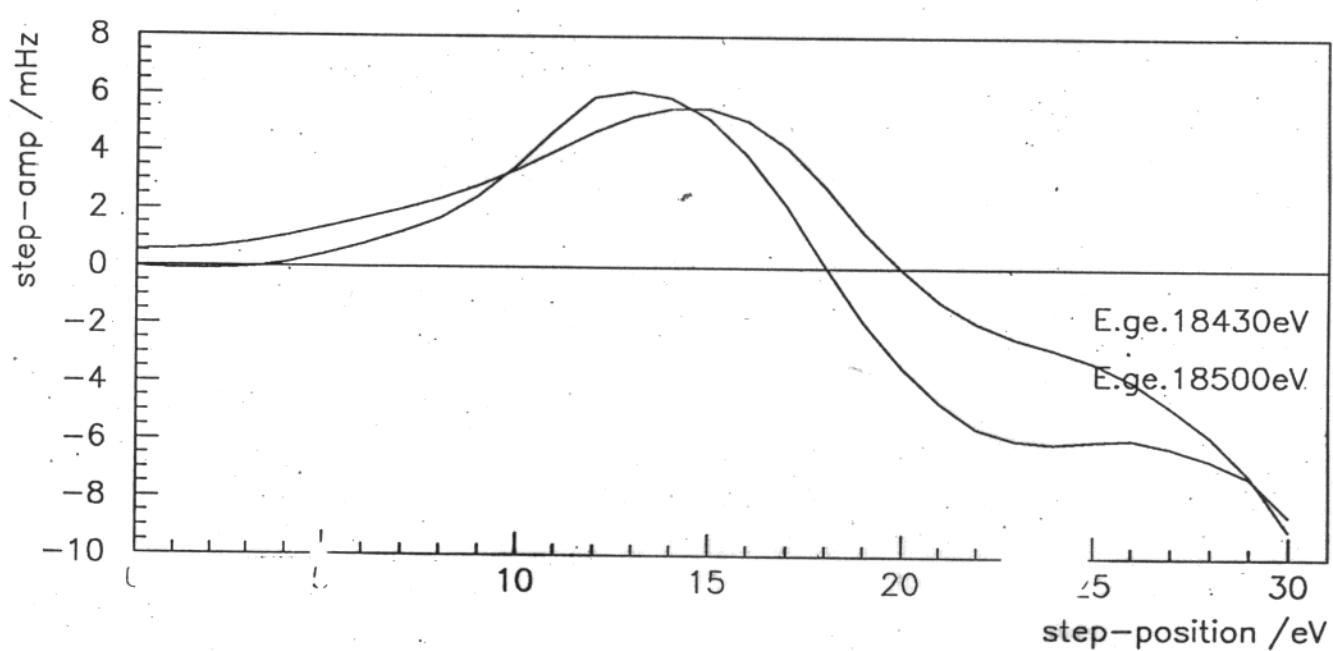
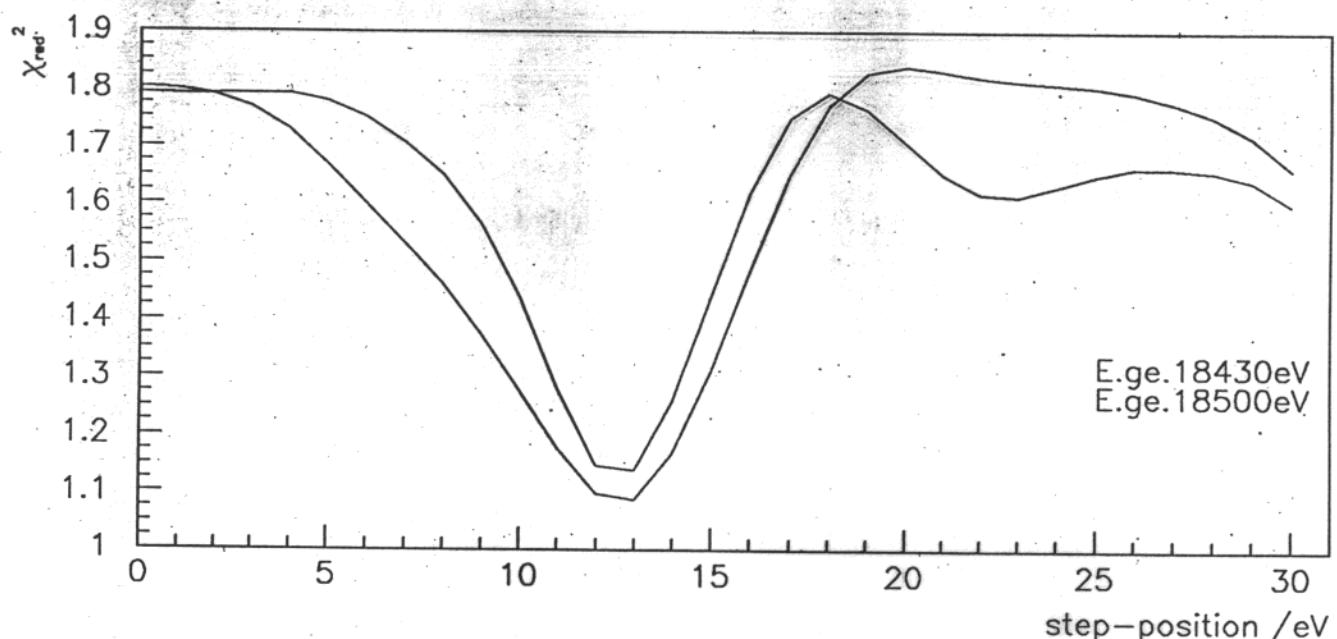
93 (Spring 98)

$m^2 = 0$ fixed



99 (summer 98)

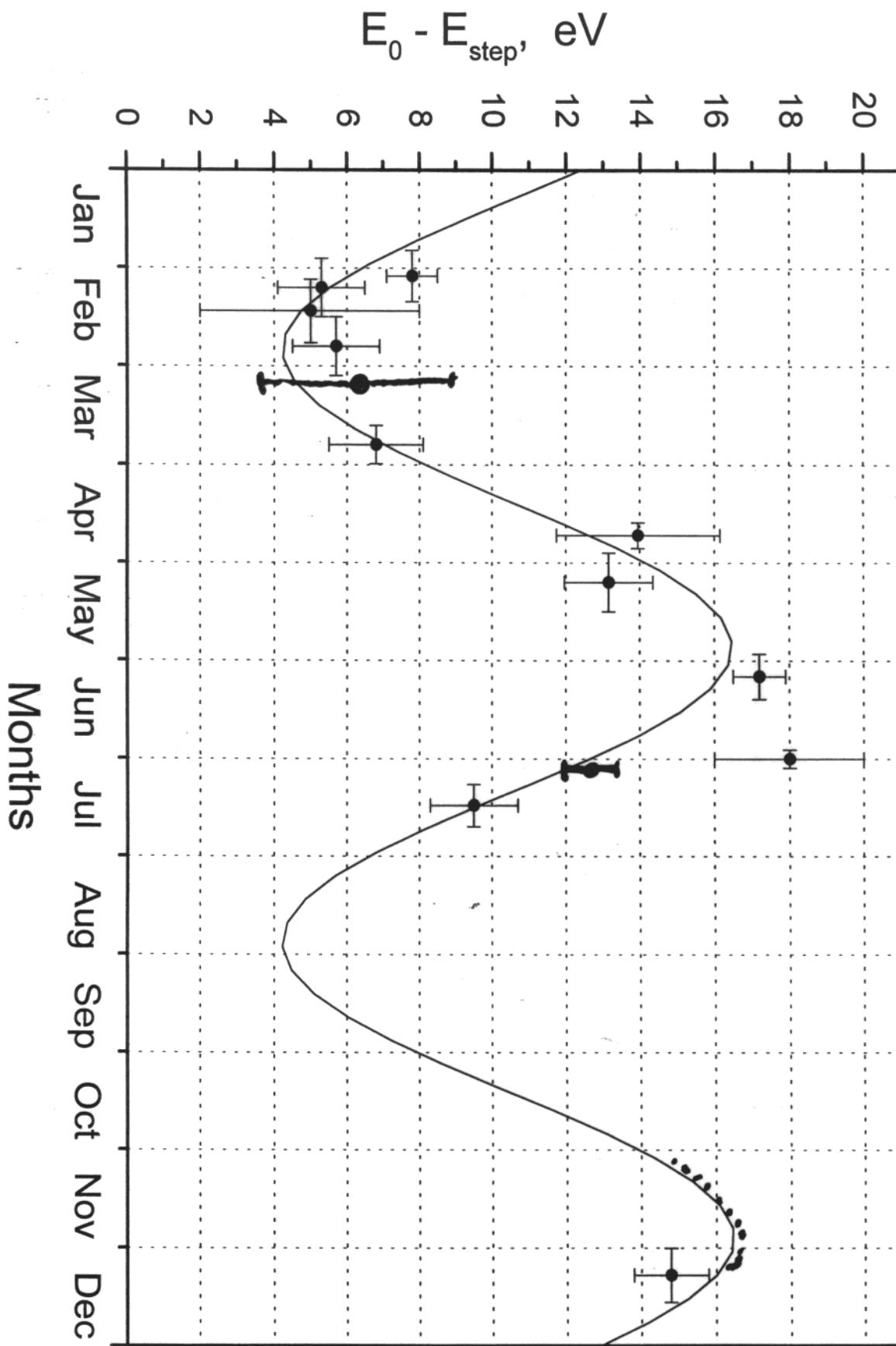
$m^2 = 0$ fixed

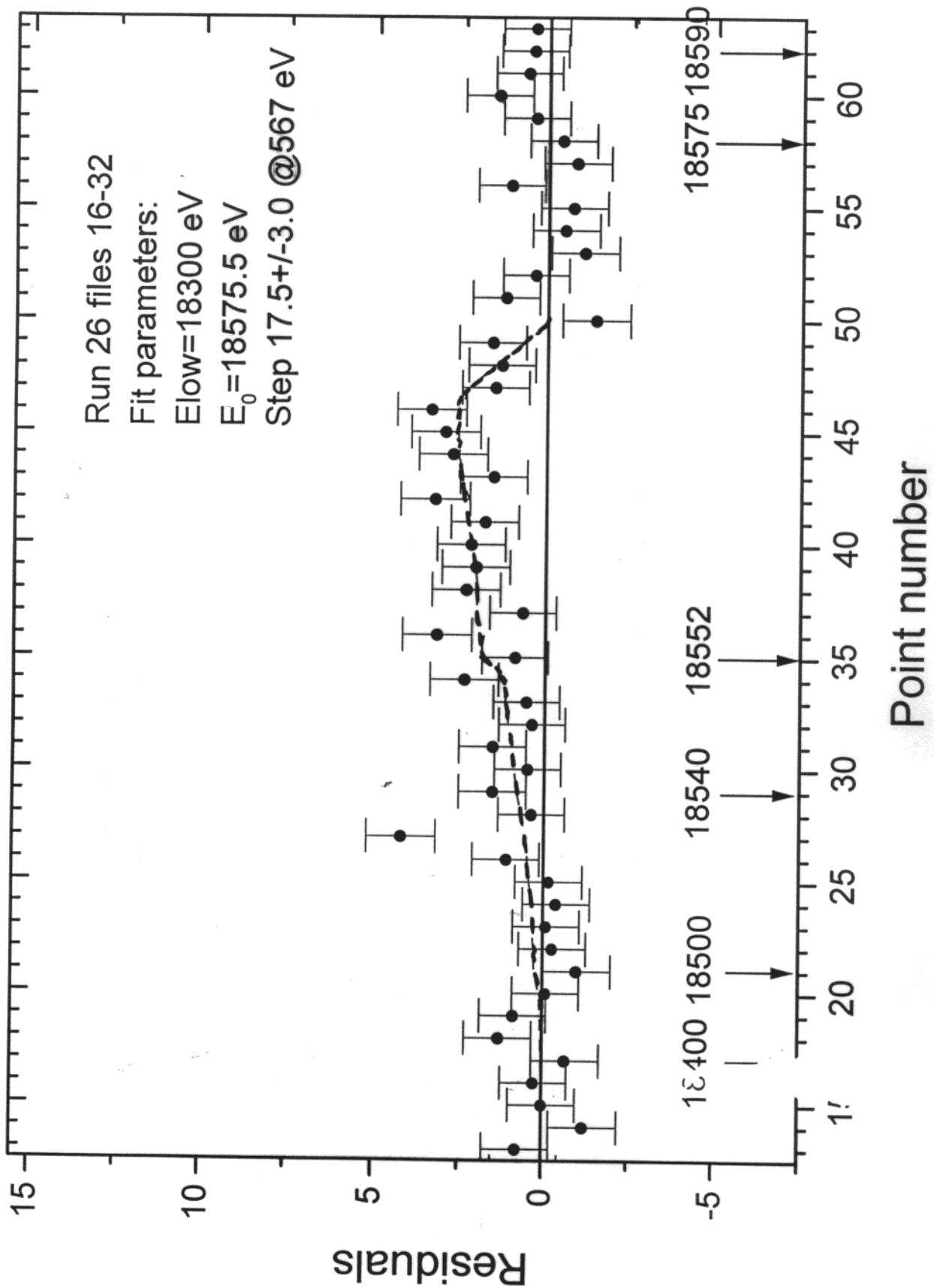


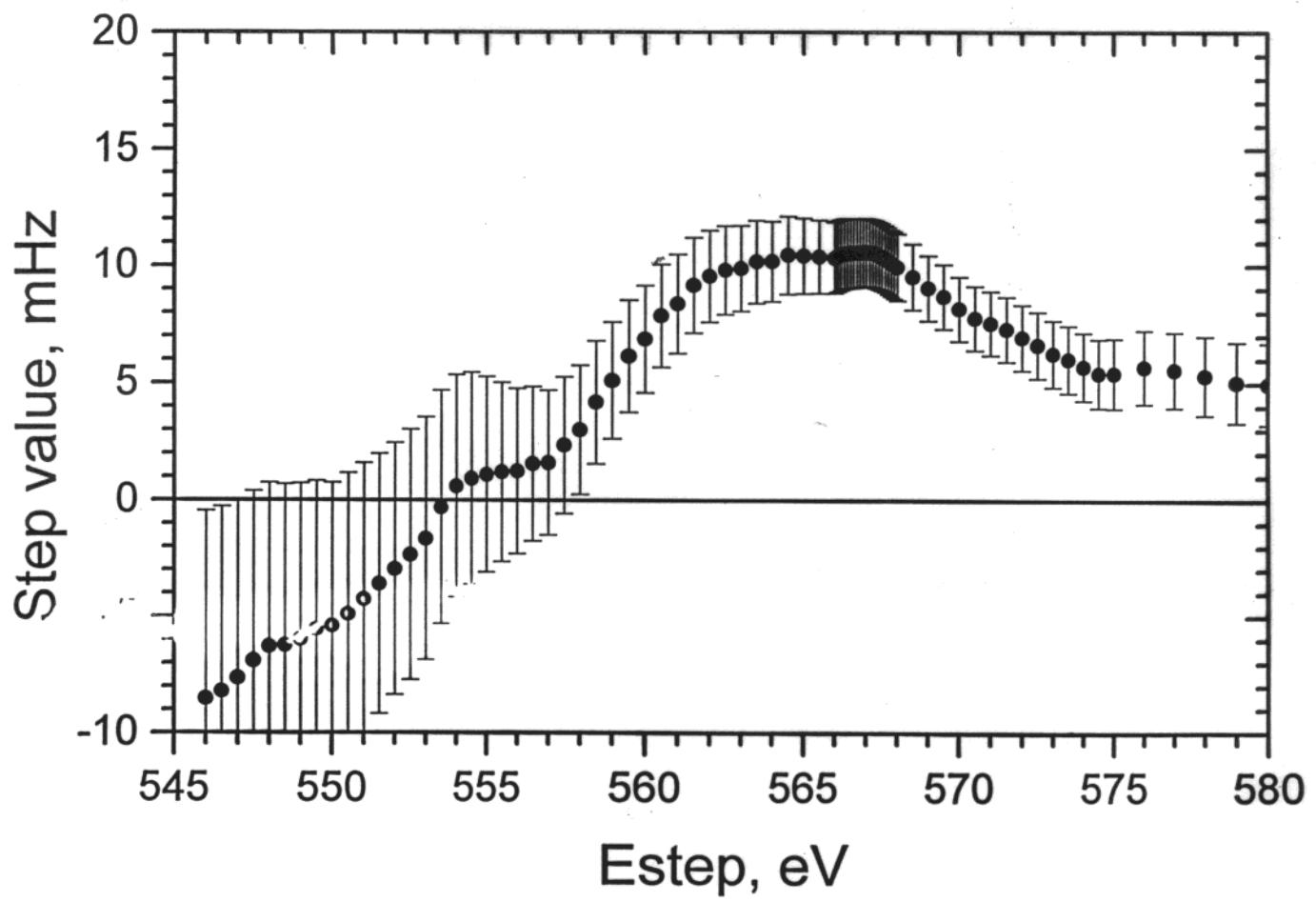
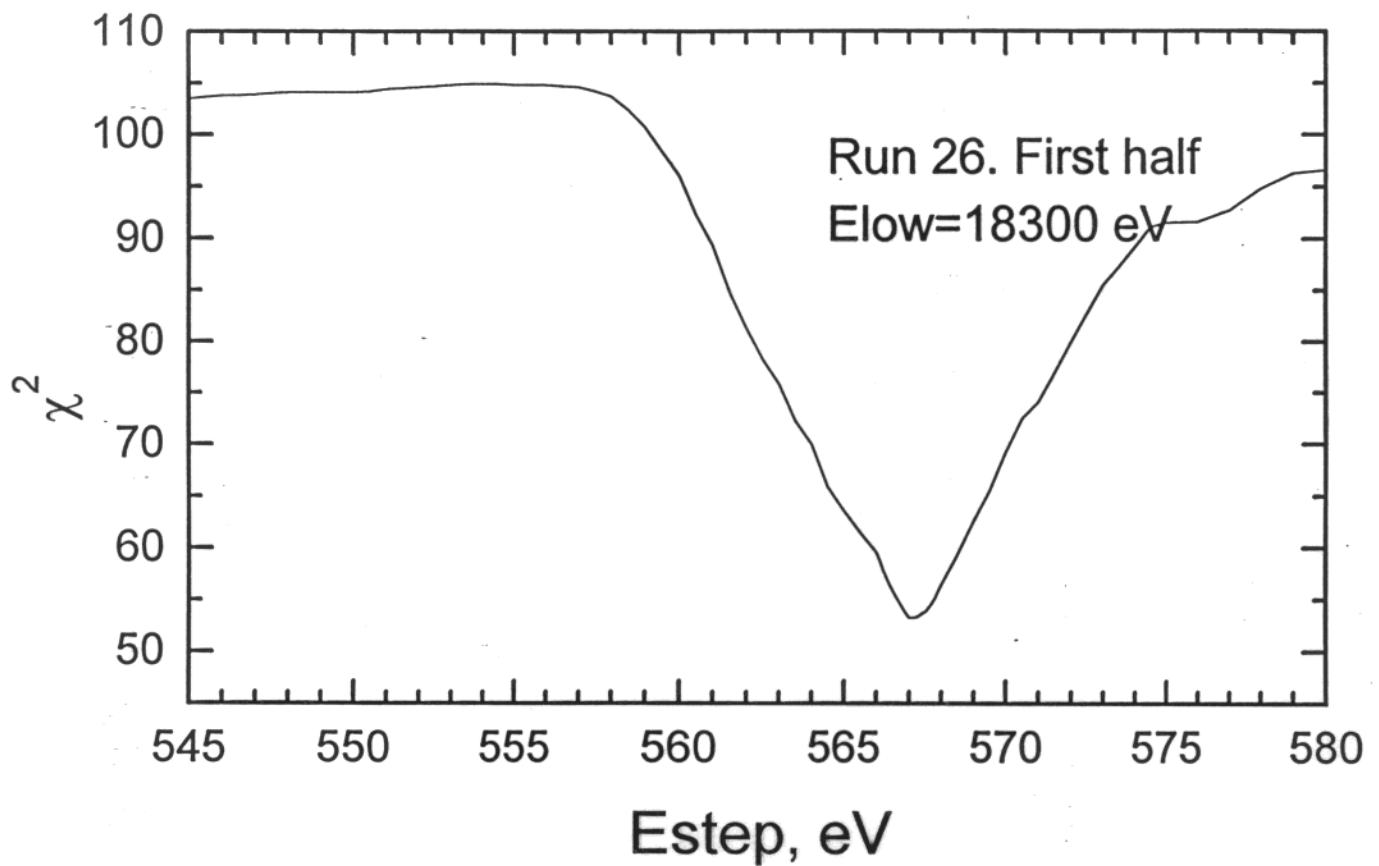
Mainz data.

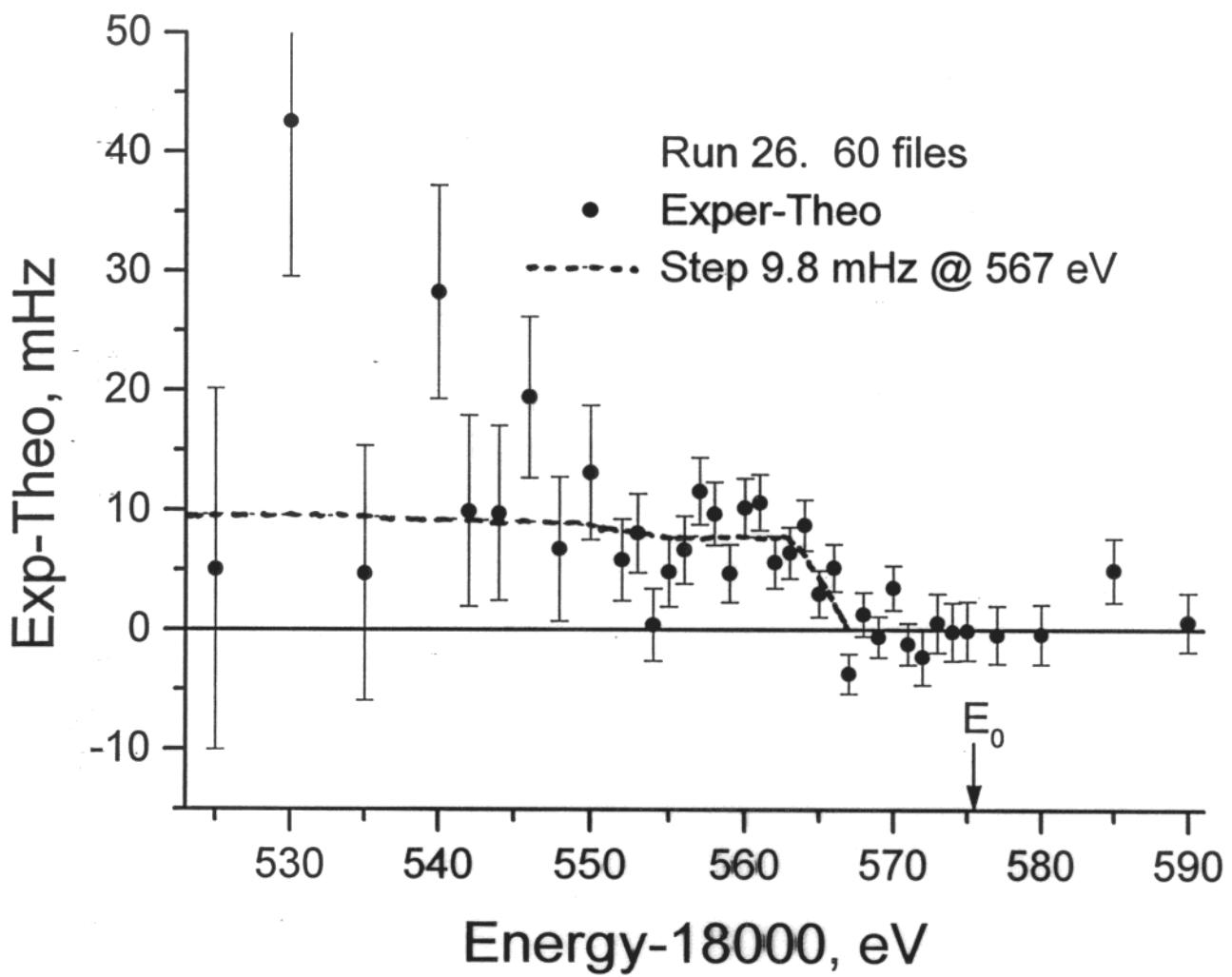
Step position vs. time. Period 0.500 year

indef.









Exotic explanation of the bump (step) by the old speculation.

Capture of the relic neutrino

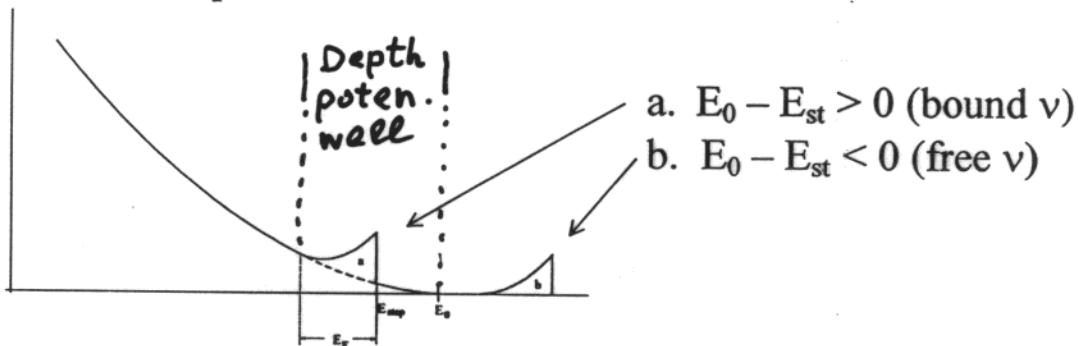


No energy threshold for ν -capture. But!

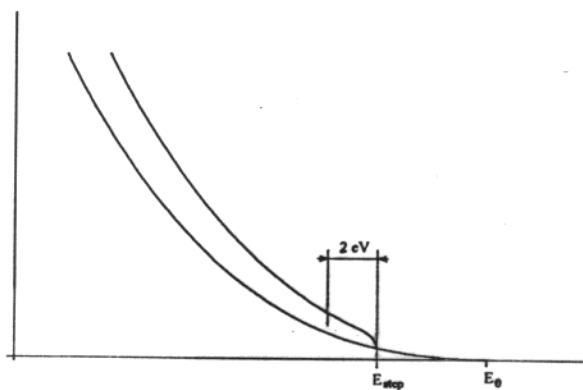
Branching ratio 10^{-10} corresponds to: $0.5 \cdot 10^{15} \nu/\text{cm}^3$
(average cosmological $\sim 10^2 \nu/\text{cm}^3$).

If ν are cold and degenerated $E_{\text{Fermi}} \approx 5 \div 6 \text{ eV}$.

Differential spectrum of electrons:



Integral Spectrum:



Modulation period 0.5 year imply the size of ν -cloud $\sim 1 \div 3 \text{ A.U.}$ and couple ν -cloud to Sun. Clustering avoid contradiction with average ν -density.

$E_0 - E_{\text{step}} > 0$ imply that E_ν is negative

Common sense interpretation ν - are in potential well.

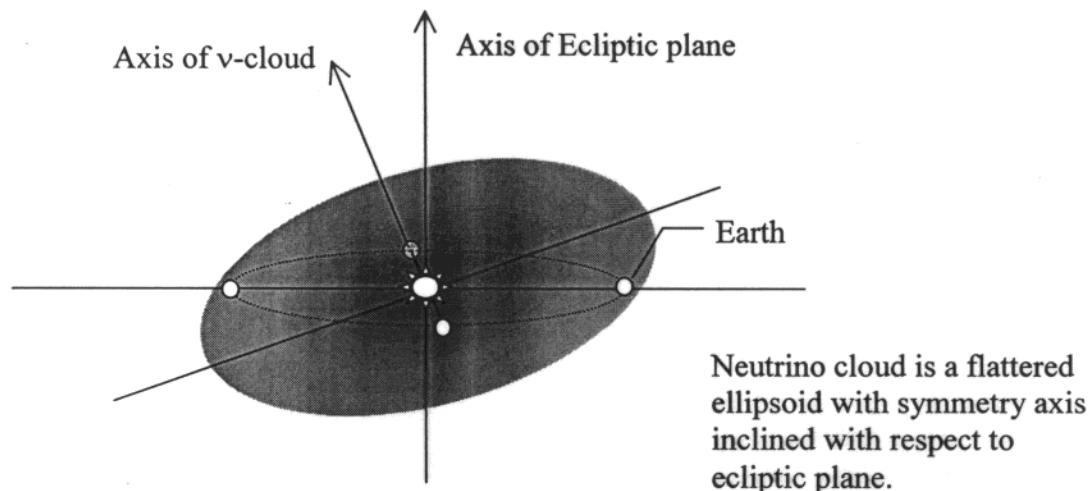
Well depth $E_0 - E_{\text{step}} + E_F \approx 20 \text{ eV} \doteq 10 \text{ eV}$

Good for coupling ν in cluster.

Origin of the potential → Mohapatra & Nussinov, P.L. 1997, ?

But contradiction with experimental observation of bump below the end-point.

Assuming inhomogeneity of potential over the ν -cloud one may visualize the origin of 0.5-year modulation.



Maxima of $E_0 - E_{\text{step}}$ corresponds to Sun rotation axis being perpendicular to direction Sun-Earth.

It is possible that axis of ν -cloud is inclined in the same direction as the Sun rotation axis. (?)

The picture looks attractive, but rises many questions:

- Is trapping of neutrino possible?
- Is negative E_ν possible?
- What interaction provides trapping?
- Massless (or small mass) ν ?

Theor. attempt

Viollier, Marx,
Stephenson
Mc.Kellar
Goldman

Present consideration (Stephenson et al. Int. Jour. Modern Physics A, Vol. 13 (16) (1998) 2765)

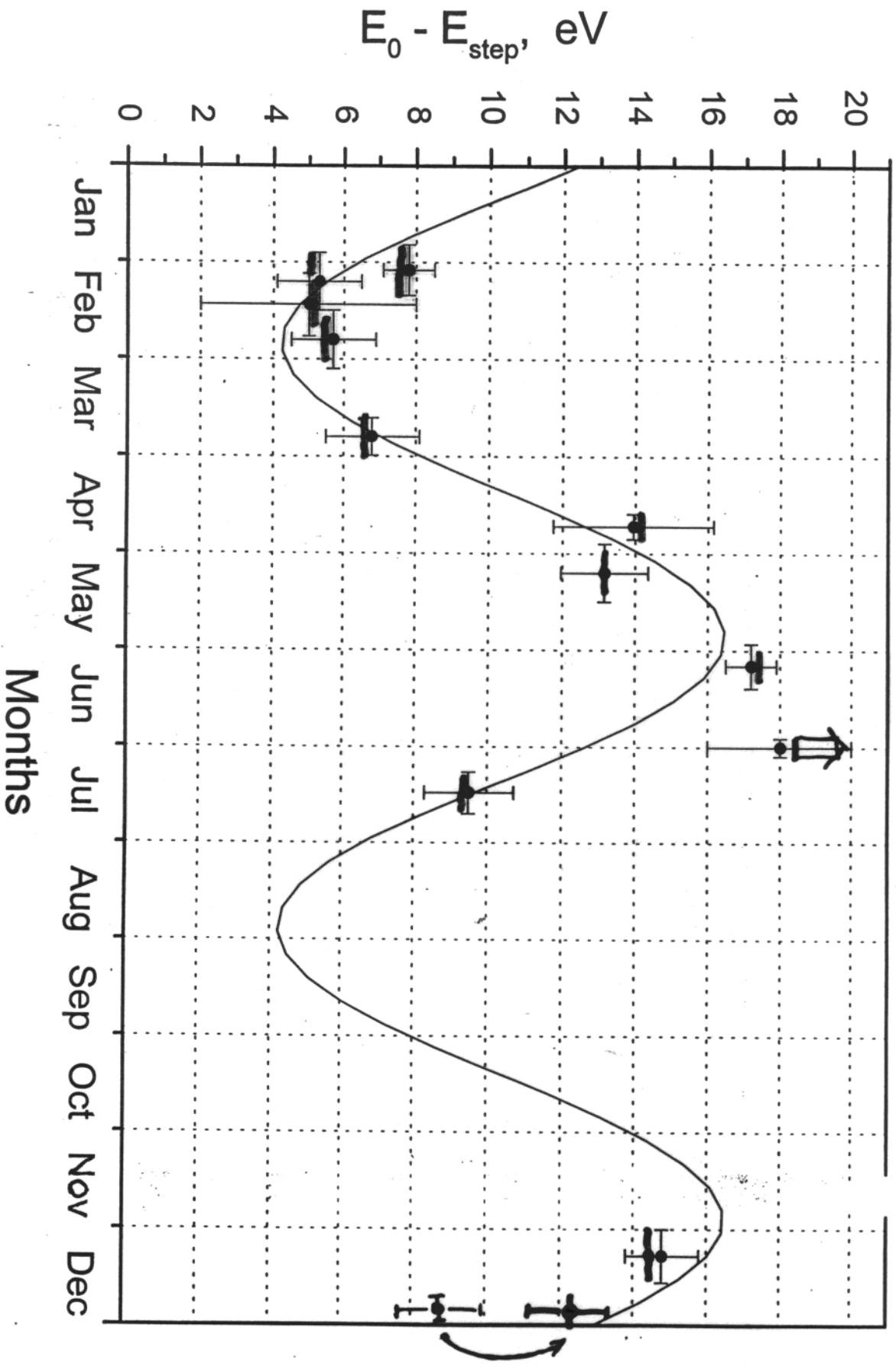
$M_\nu > U_{\text{trapping}} (\sim 20 \text{ eV})$

$(E_0 - E_{\text{step}}) < 0$

Again contradicts to experiment.

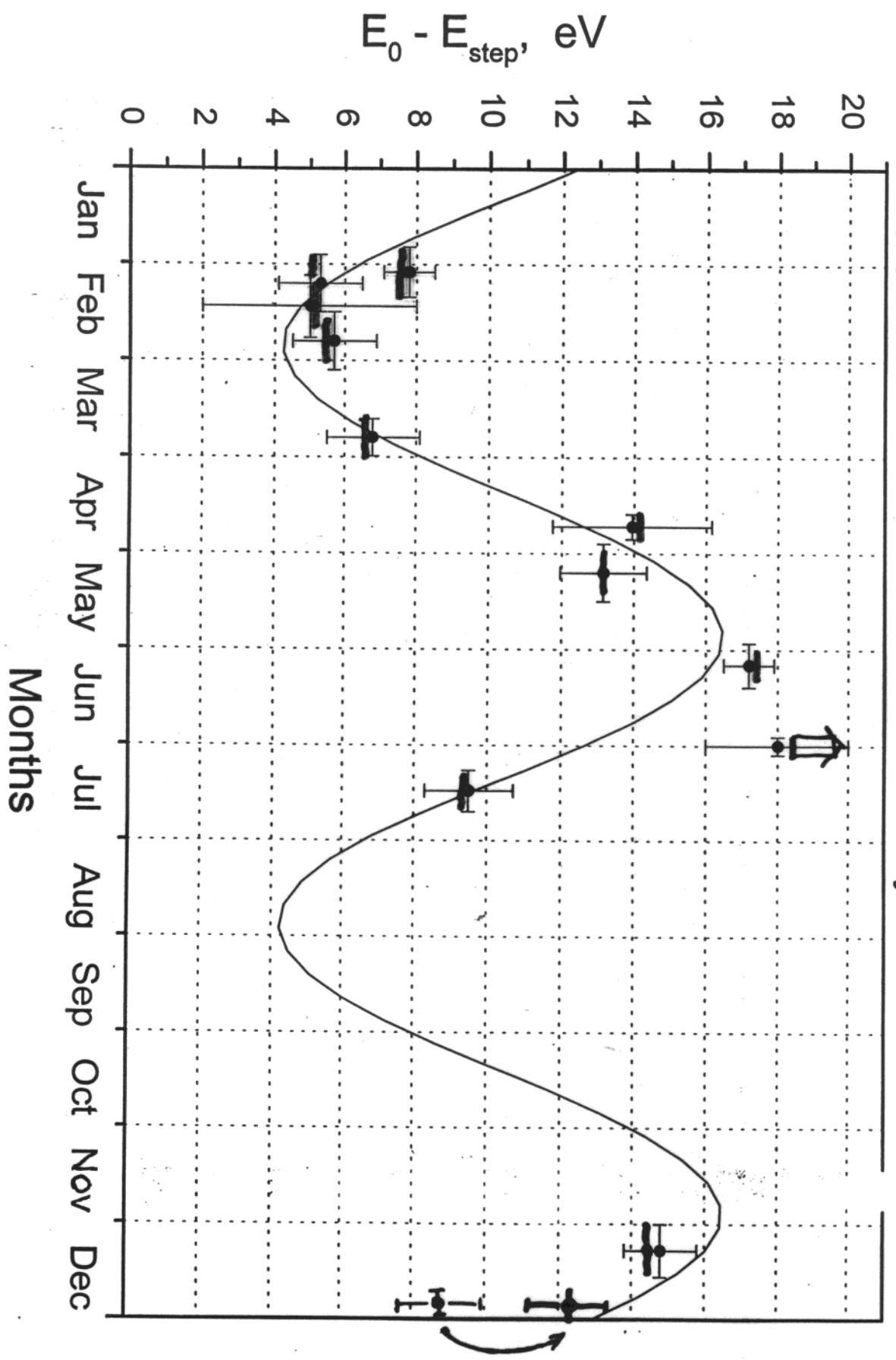
$$-V = E_0 - E_{\text{step}} + E_F$$

Step position vs. time. Period 0.500 year



$$-V = E_0 - E_{\text{step}} + E_F$$

* Step position vs. time. Period 0.500 year



Shape of β -spectrum near end-point.

Differential spectrum: $m_\nu = 0 \quad N(\varepsilon) \sim \varepsilon^2$

$$m_\nu \neq 0 \quad N(\varepsilon) \sim \varepsilon \sqrt{\varepsilon^2 - m_\nu^2}$$

$$m_\nu \ll \varepsilon \ll E_0; \quad N(\varepsilon) \sim \varepsilon^2 - m_\nu^2/2;$$

Integral spectrum: $m_\nu = 0 \quad N(\varepsilon) \sim \varepsilon^3$

$$m_\nu \neq 0 \quad N(\varepsilon) \sim (\varepsilon^2 - m_\nu^2)^{3/2}$$

$$m_\nu \ll \varepsilon \ll E_0; \quad N(\varepsilon) \sim \varepsilon^3 - 3\varepsilon m_\nu^2;$$

Maximum sensitivity:

- Differential sp. $\varepsilon = m_\nu$
- Integral sp. $\varepsilon = e_m;$
 $N(\varepsilon_m) \cong N_{bkg}$

The possible systematic biases for m_ν^2 .

1. Resolution function uncertainty. Measured by electronic gun.
Is in accordance with magnetic fields setting.
2. Energy loss spectrum and effective thickness.
Measured by means of transmission of electron through the source
in the range of E_{Loss} 0÷200 eV.
May be calculated from counting rate, luminosity of the spectrometer
and T_2 – concentration.
3. Backscattering in the source (on the rear wall).
Small, due to adiabaticity (rear wall is in the weak magnetic field).
4. Electron detection efficiency (energy dependence).
Small, but nonzero due to some backscattering of the electrons on
the detector surface with energy loss less than $E_e - E_{\text{Spectr.}}$
5. Background energy dependence.
No dependence in the range 18,600 – 19,600 V within $\pm 5\%$.
6. Trapping effect in the source. It has been calculated. Valid
only for large interval for the analysis.
7. Trapping in the spectrometer. Yet not spotted.
8. Absence of T^0 , T^- , T_3^+ in the source.
No other impurities (25 K).
Limit of abundance of atoms and ions below
 $2 \cdot 10^{-9} \cdot 3 \cdot 10^2 \cdot 10^2 \approx 10^{-4}$:
No effect up to $10^{-1} \dots 5 \cdot 10^{-2}$ relative abundance.

The m_ν problem.

Shape of the β -spectrum near end-point.

If $E_0 - E \equiv \varepsilon_\nu$; E_0 – end point energy.

Integral spectrum near end-point

$$F(E, E_0, Z \dots) \simeq A \varepsilon_\nu^3$$

$$\mp m_\nu^2 - \text{effect: } A(\varepsilon \pm \frac{3m_\nu^2}{2} \cdot \varepsilon)$$

$$\text{step function: } A \varepsilon^3 + \begin{cases} 0, & \varepsilon < \varepsilon_{step} \\ B, & \varepsilon > \varepsilon_{step} \end{cases}$$

- Efficiency correction

$$A \varepsilon^3 (1 + \alpha \varepsilon + \beta \varepsilon^2)$$

- Backward scattering

$$A \varepsilon^3 (1 + k_b \varepsilon)$$

- Trapping effect

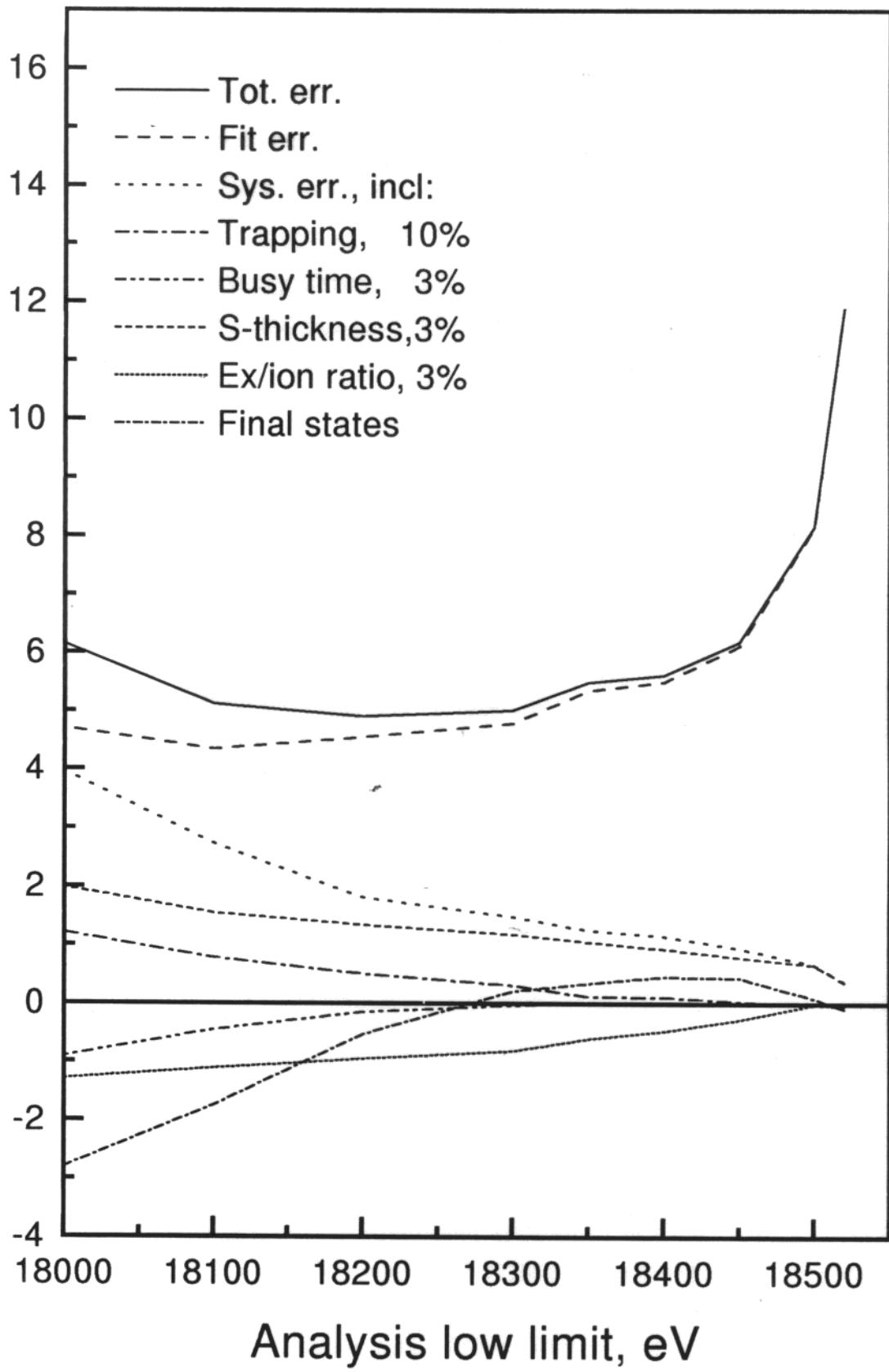
$$A \varepsilon^3 (1 + k_{tr} \varepsilon)$$

- Dead time correction

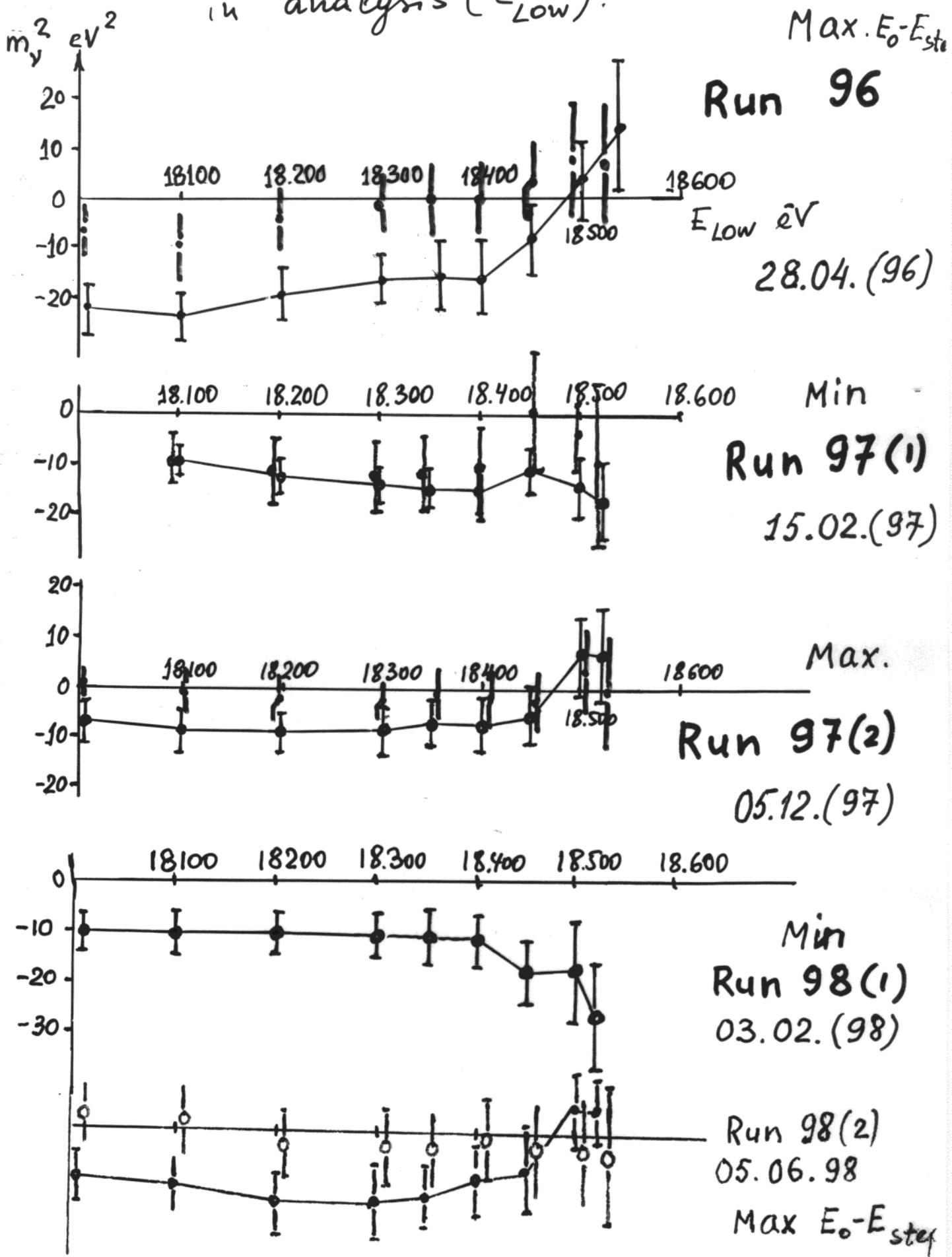
$$A \varepsilon^3 (1 + m \varepsilon^3)$$

Dependence of m_ν^2 on E_{LOW}

Statistical errors and
correction uncertainties, eV^2



Dependence of the fitted m_ν^2 on the lower boundary of the part of the spectra in analysis (E_{Low}).



Neutrino mass results.

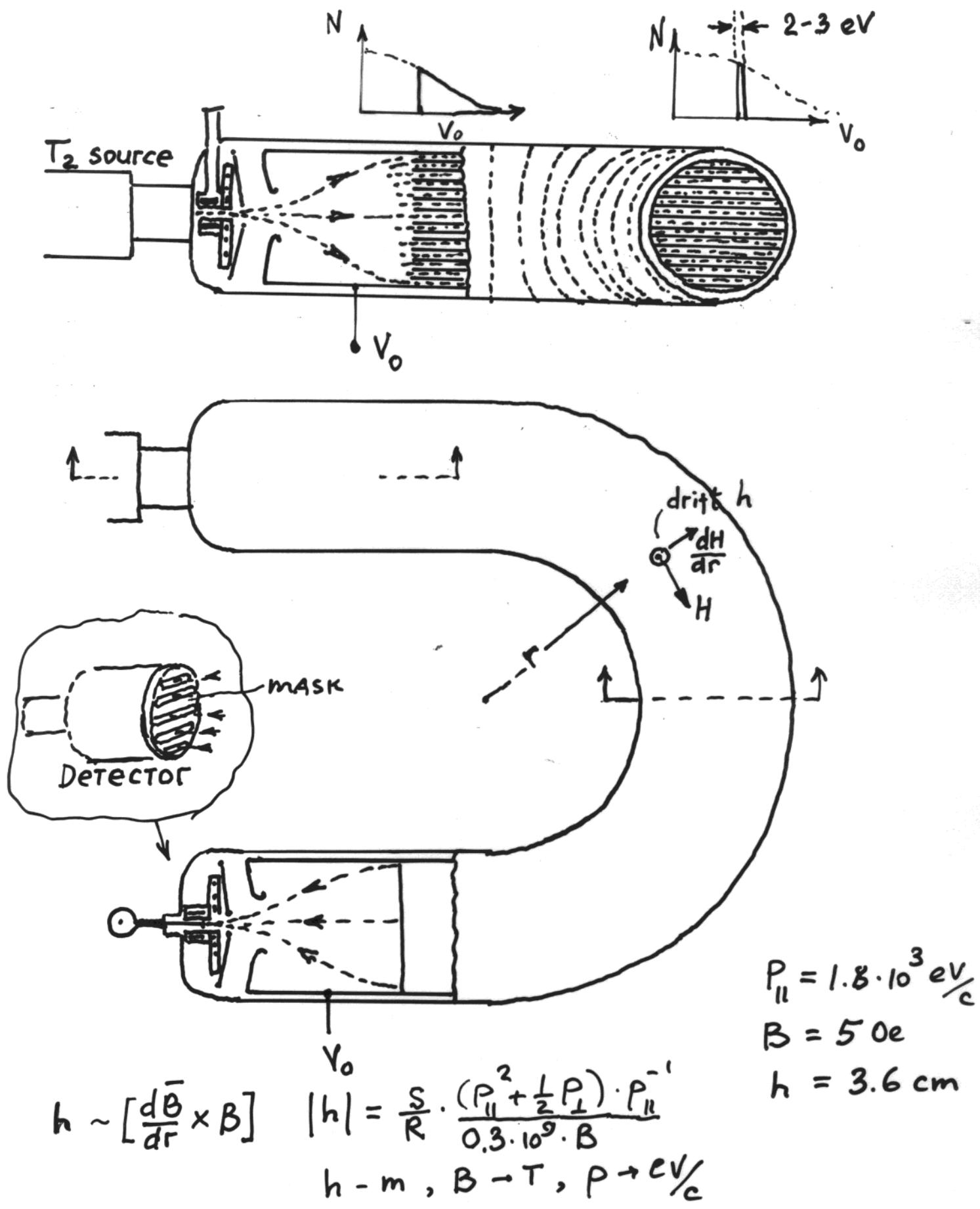
Year	Mass	
1994	$m_\nu^2 = -2.7 \pm 10.1 \text{ (fit)} \pm 4.9 \text{ (syst), } eV^2/c^4$	
1996	$m_\nu^2 = +0.5 \pm 7.1 \text{ (fit)} \pm 2.5 \text{ (syst), } eV^2/c^4$	
1997	1	$m_\nu^2 = -8.6 \pm 7.6 \text{ (fit)} \pm 2.5 \text{ (syst), } eV^2/c^4$
	2	$m_\nu^2 = -3.2 \pm 4.8 \text{ (fit)} \pm 1.5 \text{ (syst), } eV^2/c^4$
1998	1	<i>Fit for combined m_ν^2 and ΔN_{step} is uncertain</i>
	2	$m_\nu^2 = -0.6 \pm 8.1 \text{ (fit)} \pm 2.0 \text{ (syst), } eV^2/c^4$
Combined		$m_\nu^2 = -2.0 \pm 3.5 \text{ (fit)} \pm 2.1 \text{ (syst), } eV^2/c^4$
m_ν Bayesian limit: $m_\nu < 2.5 \text{ eV}/c^2$ at 95% C.L.		

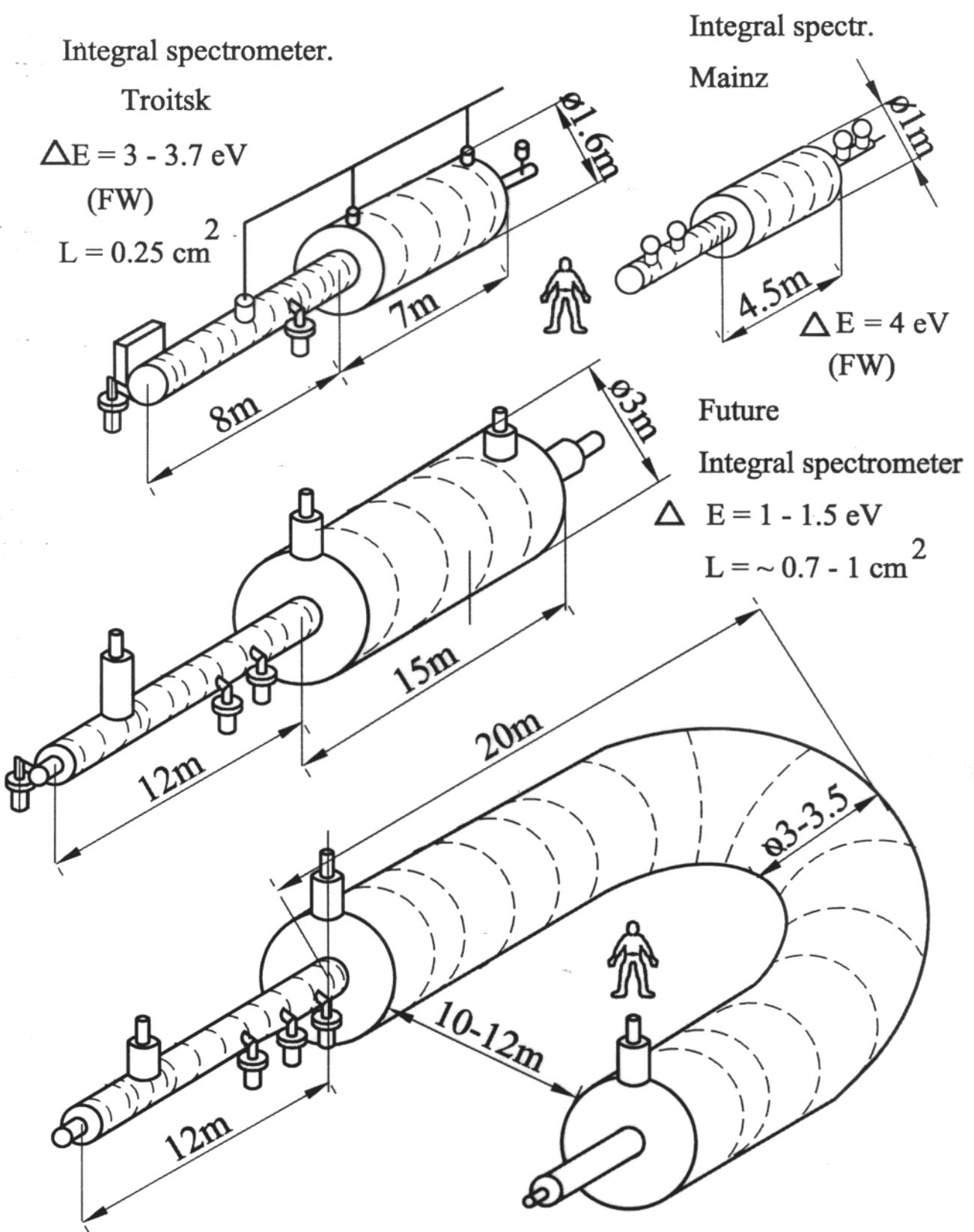
What's the further?

1. Better statistics and more measurements this year, as a proof of periodicity.
 - Improvement 2 times is possible on present set-up.
2. Synchronous measurement with Mainz group.
 - Now in progress.
3. Proof of universality of the effect:
 - Measurement of partial spectra to excited final states. $E_{ex} = 28 \div 35$ eV.
 - Practically possible with differential spectrometer.
4. Shape of the bump:
 - Needs new device.
5. Improvement of m_ν :
 - < 1.5 eV at present set-up
 - < 0.6 eV at new device.

$m_\nu \sim 1 \div 1.5$ eV may exist if LSND observation is valid.

A DIABATIC DIFFERENTIAL SPECTROMETER.

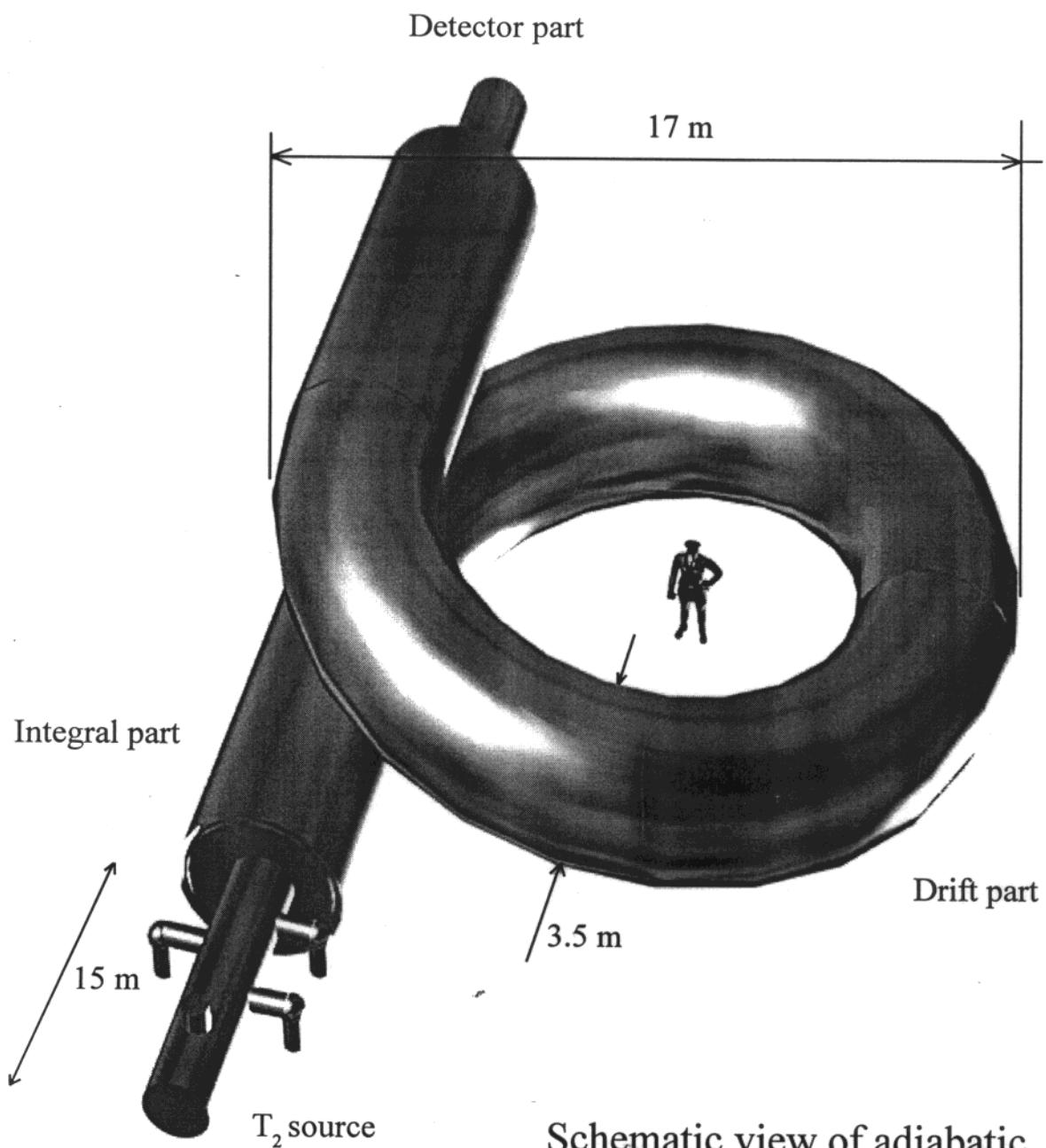




Differential adiabatic spectrometer

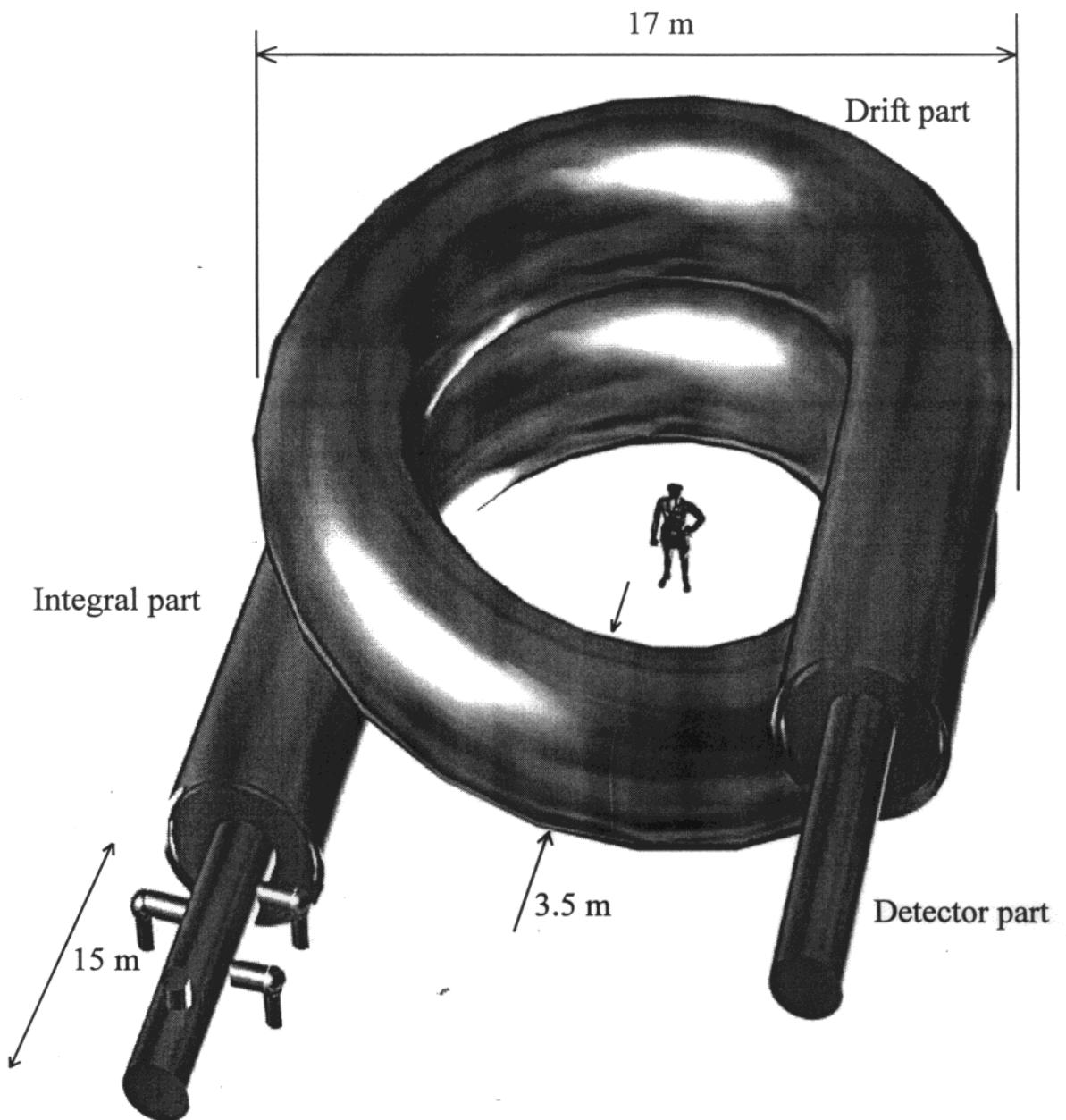
$\Delta E = 1.5 - 2 \text{ eV (FWHM)}$

$L = \sim 0.6 - 1 \text{ cm}^2$



Schematic view of adiabatic differential spectrometer with 2π drift angle

Resolution 1.5 eV (FWHM)
Luminosity $\sim 0.5 \text{ cm}^2$



Schematic view of adiabatic
differential spectrometer
with 3π drift angle

Resolution 1.5 eV (FWHM)
Luminosity $\sim 0.7 \text{ cm}^2$

Conclusion.

- “Troitsk ν -mass” set-up measured end-part of the tritium beta-spectrum during 4.5 years with resolution $3.5 \div 4.5$ eV and statistics $10^2 \div 10^3$ more than experiment before 1993.
- Shape of the spectrum proved to be in accordance with classical shape besides area ~ 15 eV below end-point, where small bump (10^{-10}) relative intensity was observed, periodically moving within $5 \div 15$ eV with period 0.5 year.
- Main feature of the effect may be phenomenologically interpreted as capture of relic neutrino from the cloud around the Sun if to neglect the origin of the cloud. This effect produce significant interference to neutrino mass deduction but being accounted for allows to obtain upper limit $m_\nu < 2.5$ eV/c².
- New facility is needed.