# NEUTRINO MASS AND ANOMALY IN THE TRITIUM BETA-SPECTRUM

presented V.M.Lobashev
Institute for Nuclear Research
of the Russian Academy of Sciences,
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"Troitsk $\nu$ -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

# 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

$\sim p_\nu^2$ *if* $m_\nu = 0$

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

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

No lepton or flavor quantum number dependence is supposed.

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

| | |
|---|---|
| $\nu_e$<br>$m_{\nu_e} < 2.5eV$<br>$(recent \quad result)$ | $n \to p + e + \nu_e;$<br>$T_2 \to (THe^3)^+ + e + \bar{\nu};$<br>$N(E)_e;\ P_e;$<br>$E_0 = 18{,}573\ eV$ |
| $\nu_\mu$<br>$m_{\nu_\mu} < 0.17MeV$ | $\pi^+ \to \mu^+ + \nu_\mu$<br>$m_\pi;\quad m_\mu;\quad P_\mu;$ |
| $\nu_\tau$<br>$m_{\nu_\tau} < 18MeV$ | $\tau \to \underbrace{5\pi}_{\text{all charged}} + \nu_\tau$<br>$m_\tau;\quad P_\pi;$ |

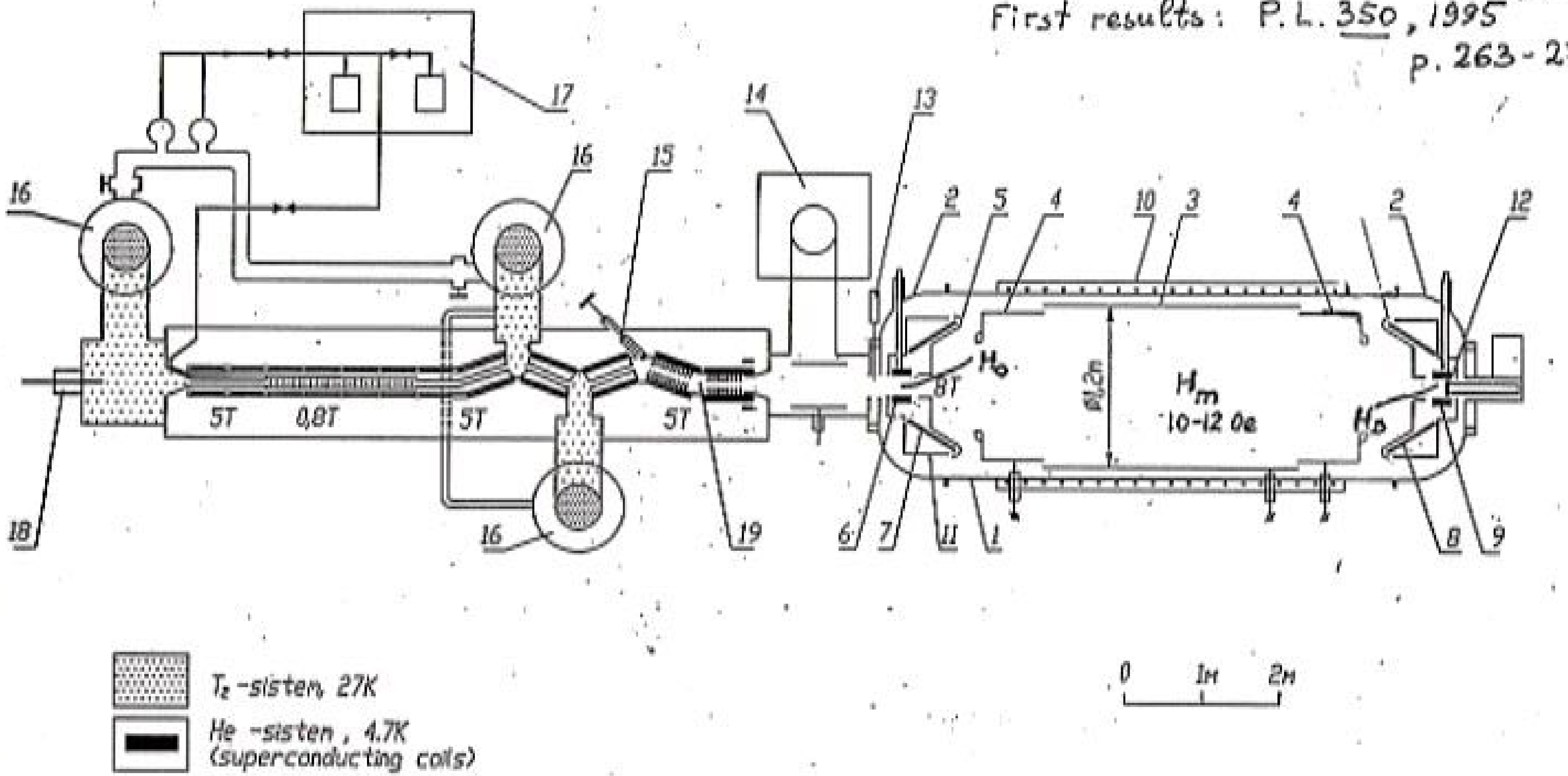
Advantage of T-decay:

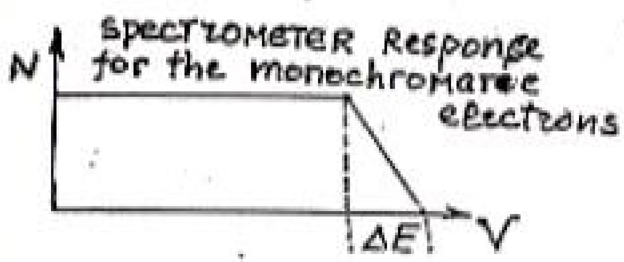
1. Low $E_0$.
2. High specific activity ($T_{1/2} = 12.26$ y).
3. Low Z.
4. Exact calculation of final state spectrum.
5. Purity from other radioactive contamination.
   Next on $E_0$ $Ni^{63}$: $E_0 = 67.0$ keV; $T_{1/2} = 92$ y.

'int INR P-0291(198

Proposal 1982 ; Λ A240, 305-310

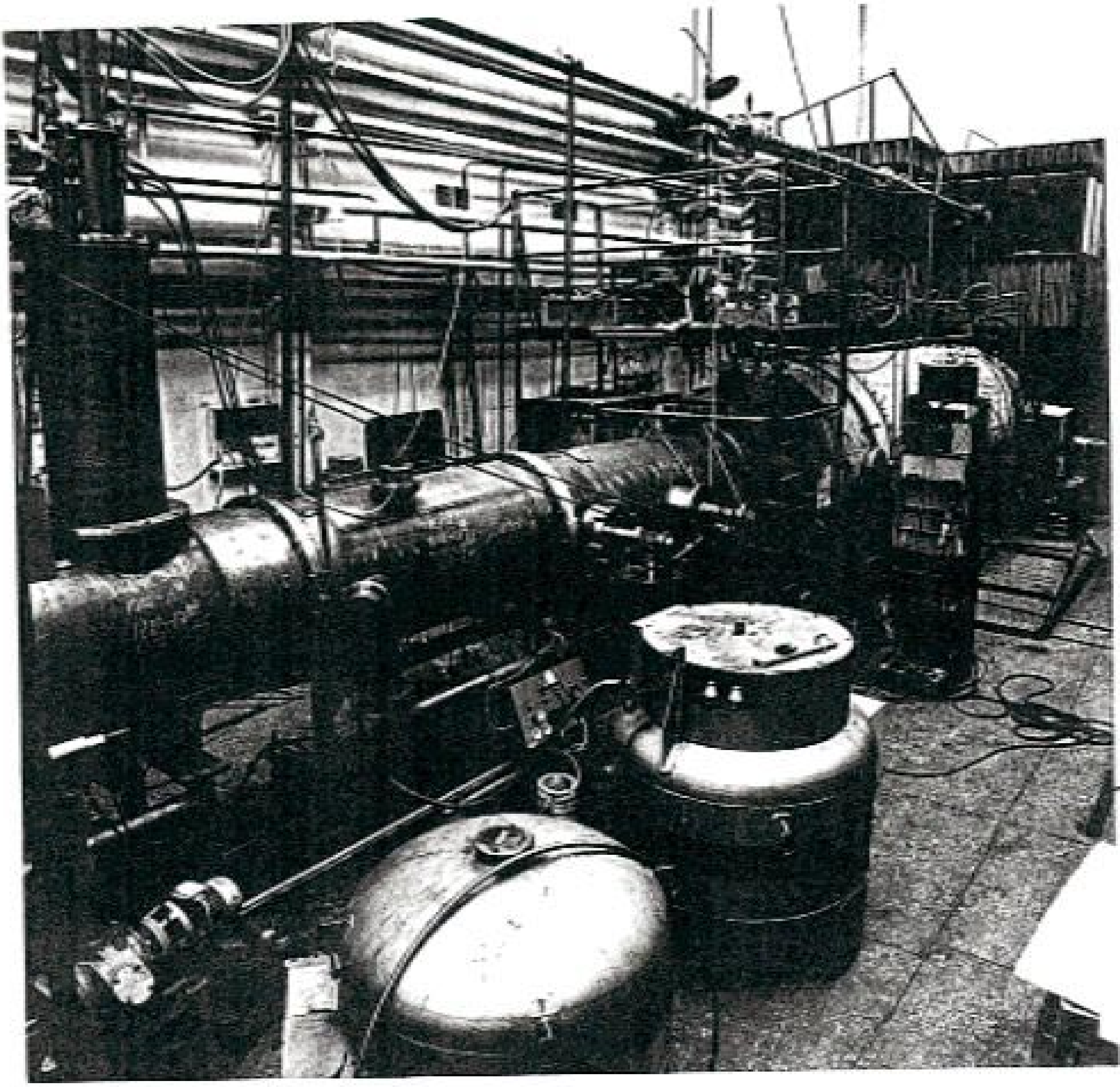
First results: P.L. 350, 1995 (1985)
p. 263-271



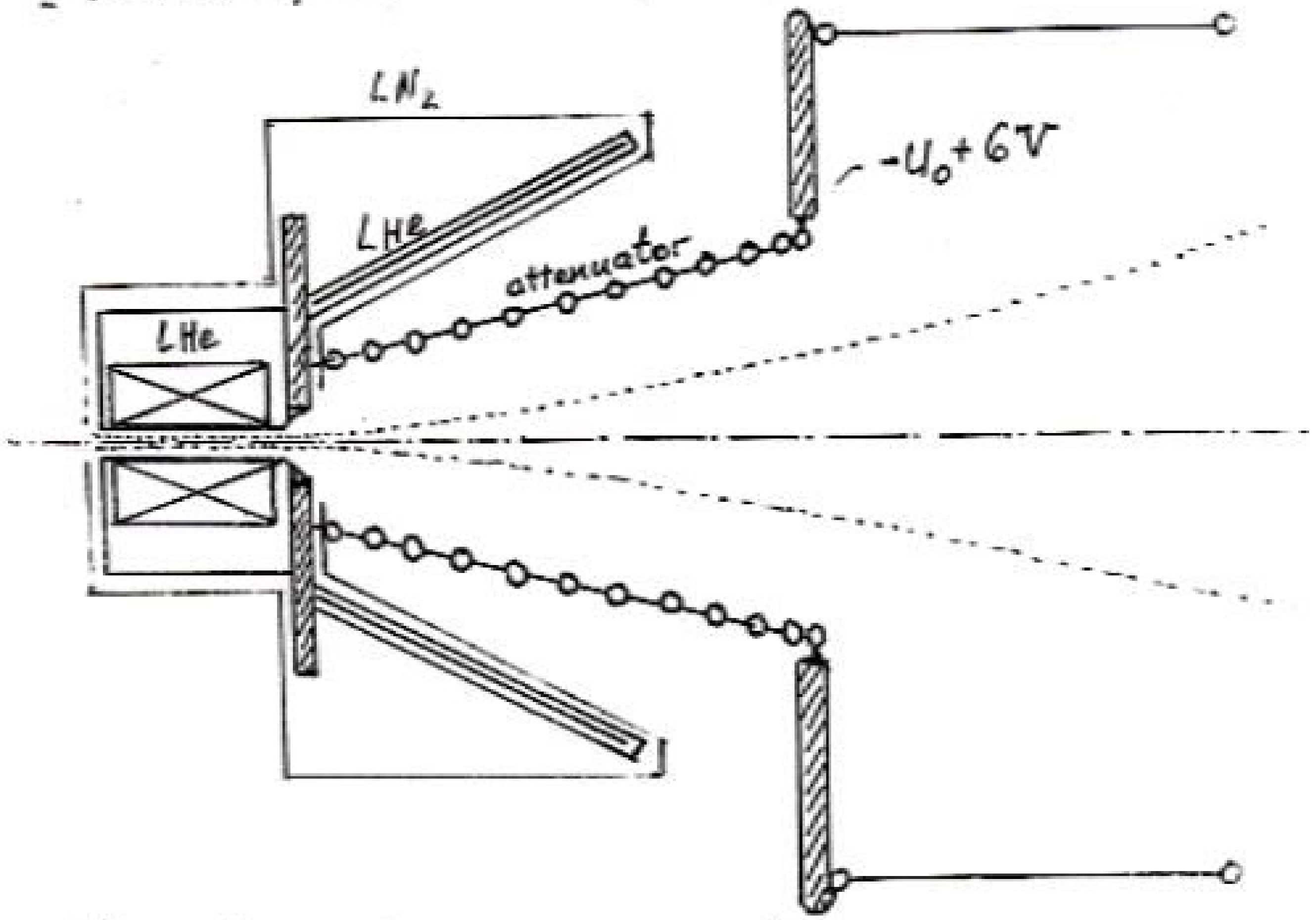




$$\Delta E = \frac{H_m}{H_o} \cdot E_o \quad ; \quad L = S_D \cdot \frac{H_D}{H_o} \cdot \frac{1}{4}$$

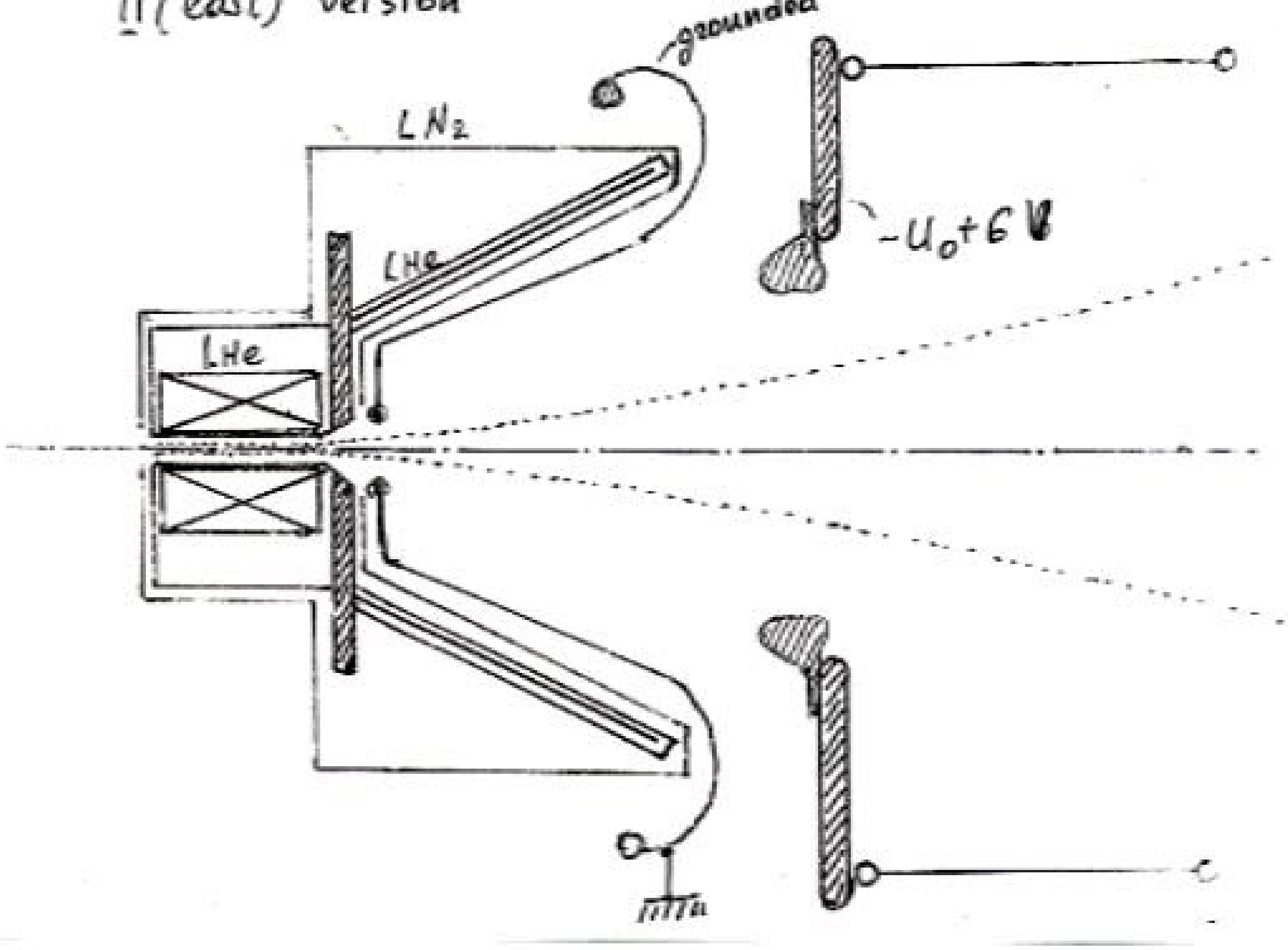
$E_o = 18.6$ keV ; $\Delta E = 3.5-4$ eV (FW).



I version of electrode system




II (last) version



## Experimental spectrum corrections.

1. Search and elimination of tritium decay

   in spectrometer volume.

   5÷20 sec bunch of pulses (1÷3 $hour^{-1}$). Cut-off level ~$3 \cdot 10^{-4}$.
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 photoexitation, 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.

# 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 ~$10^3$ sec. H.V. was returned to reference point (18,000 or 18,175 V).
- Maximum count rate ~ $6 \cdot 10^3$ $sec^{-1}$.
- Spectrum was measured for 1÷2 hours (cycle).
- Background ~12÷30 mHz independent of the spectrometer potential. Measured in the range 18,600÷19,600 V.
- Periods of running :

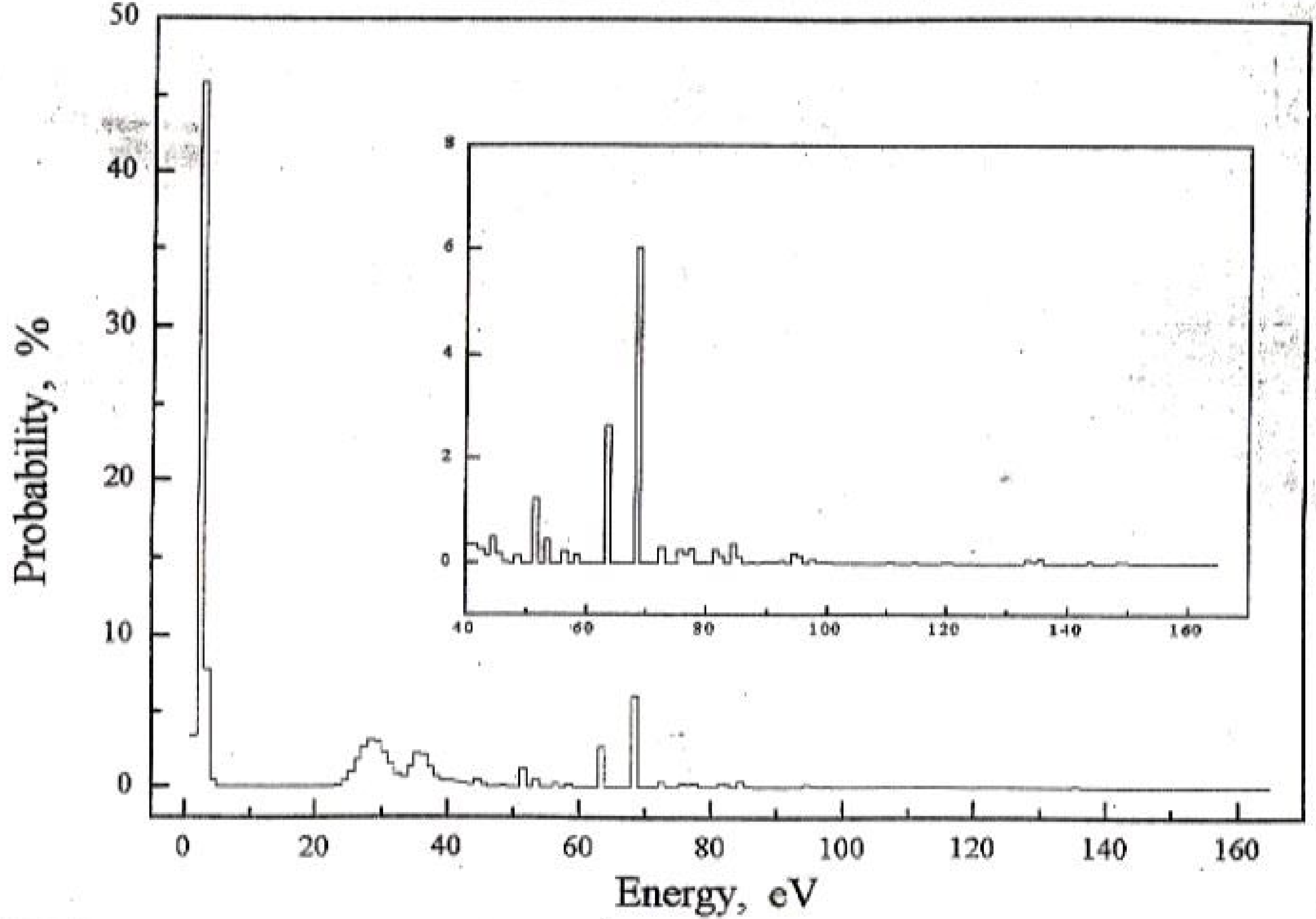
| | | |
|---|---|---|
| 1994 | January-February<br>March<br>July | 3 X 12 days |
| 1996 | April - May | 24 days |
| 1997 | February - March<br>June<br>December | 40 days<br>10 days<br>20 days |
| 1998 | February<br>June | 15 days<br>15 days |

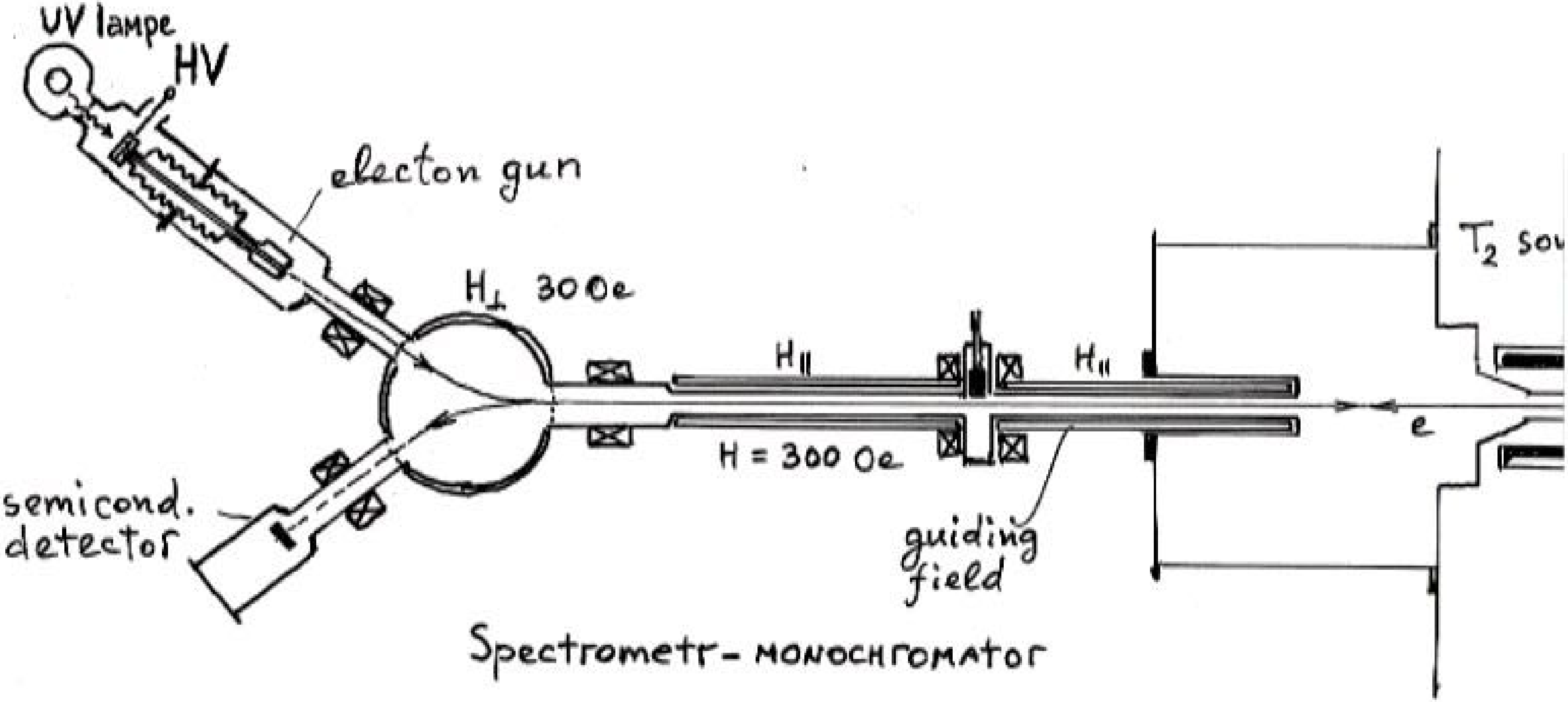
Altogether ~180 days / 4 years.

+10 more days December 98

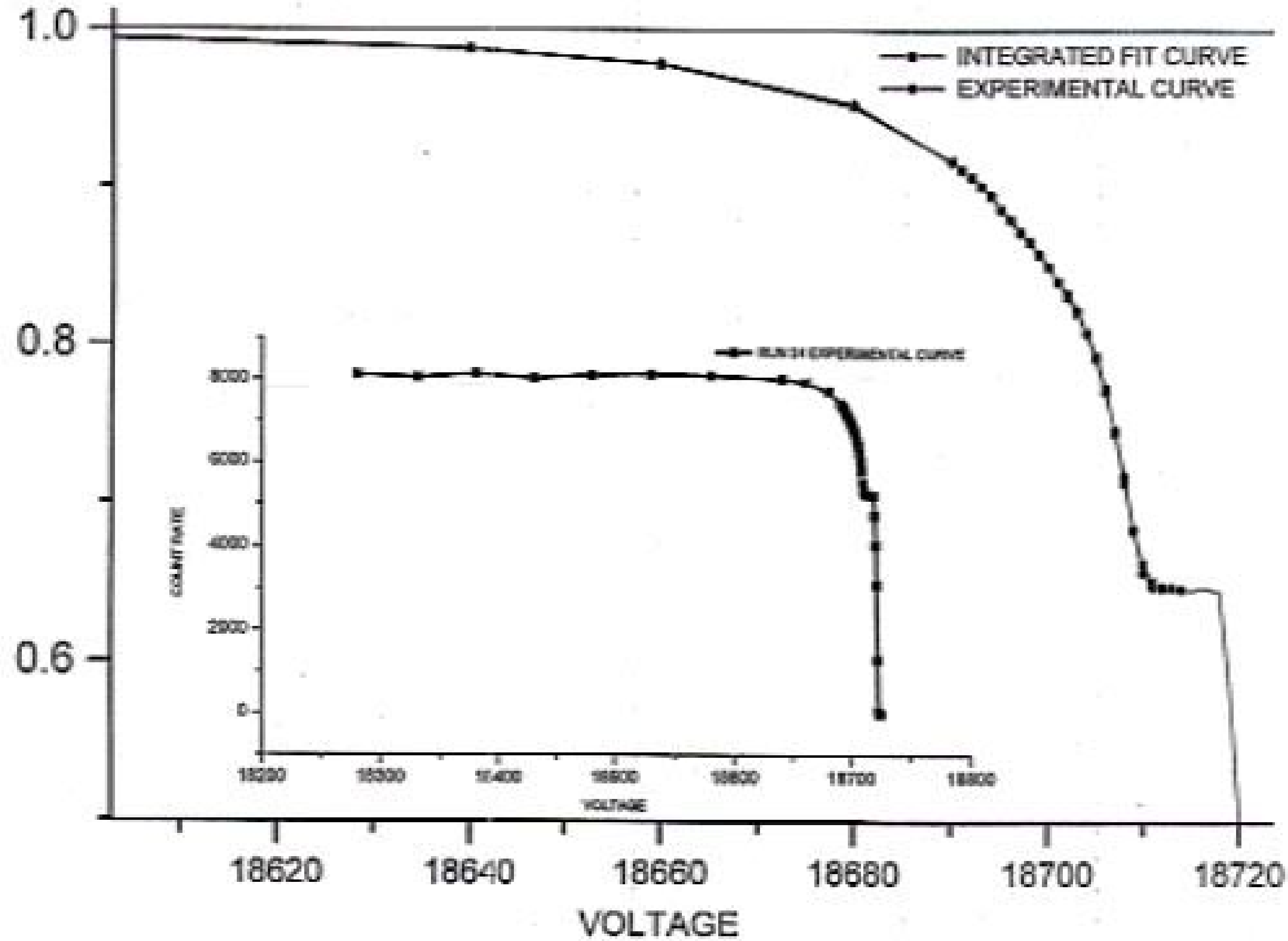
+20 " " April-May 99

# Spectrum of final states

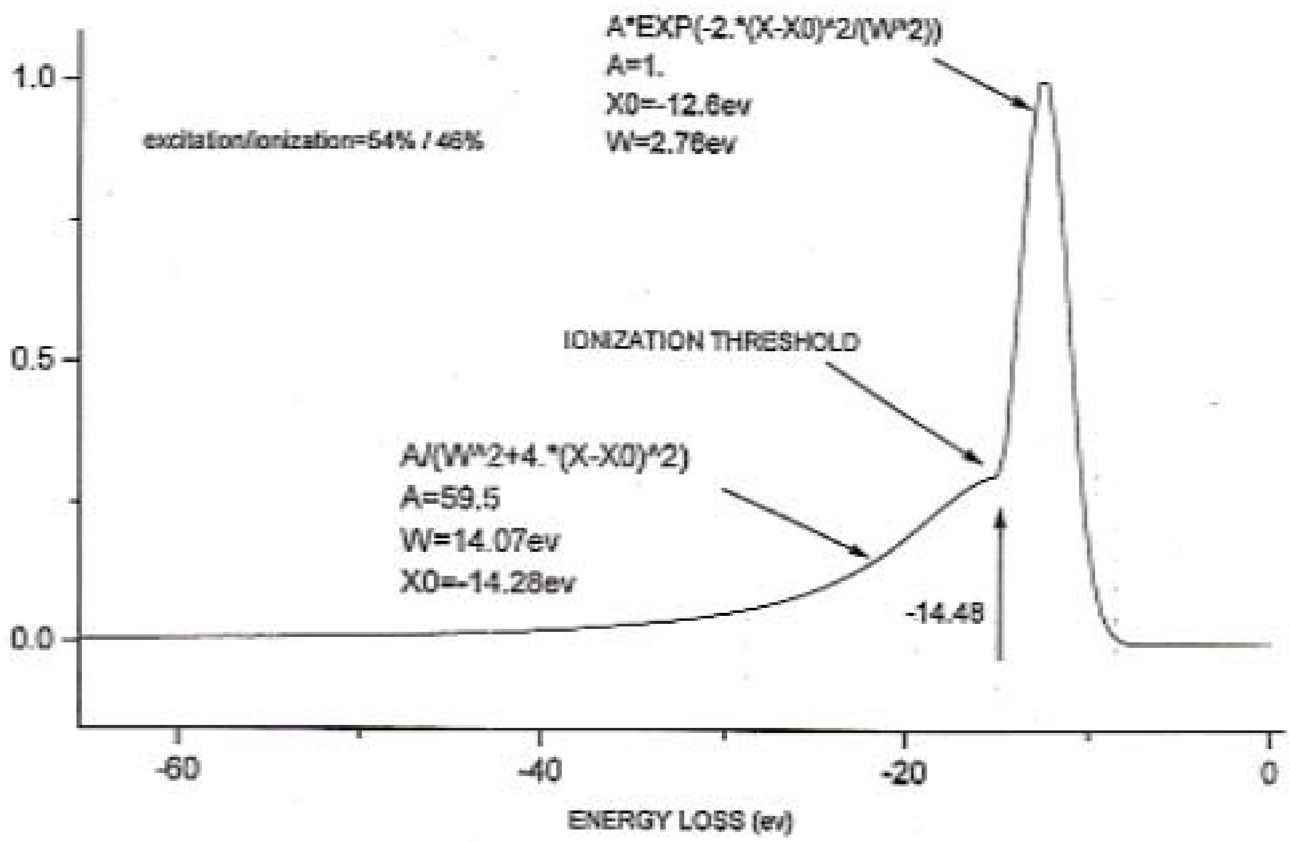




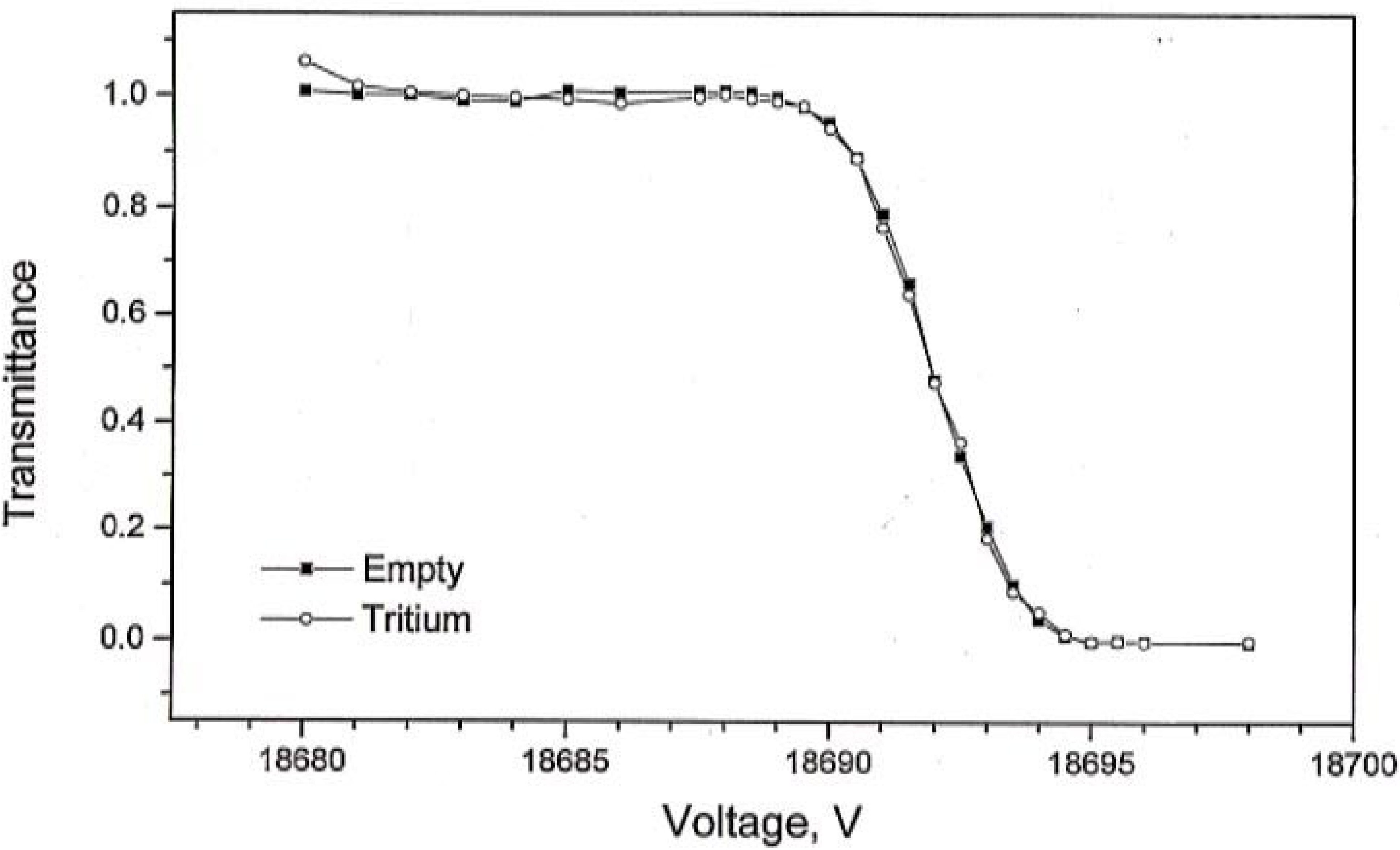

Spectrometr - monochromator
for injection of electron into the source

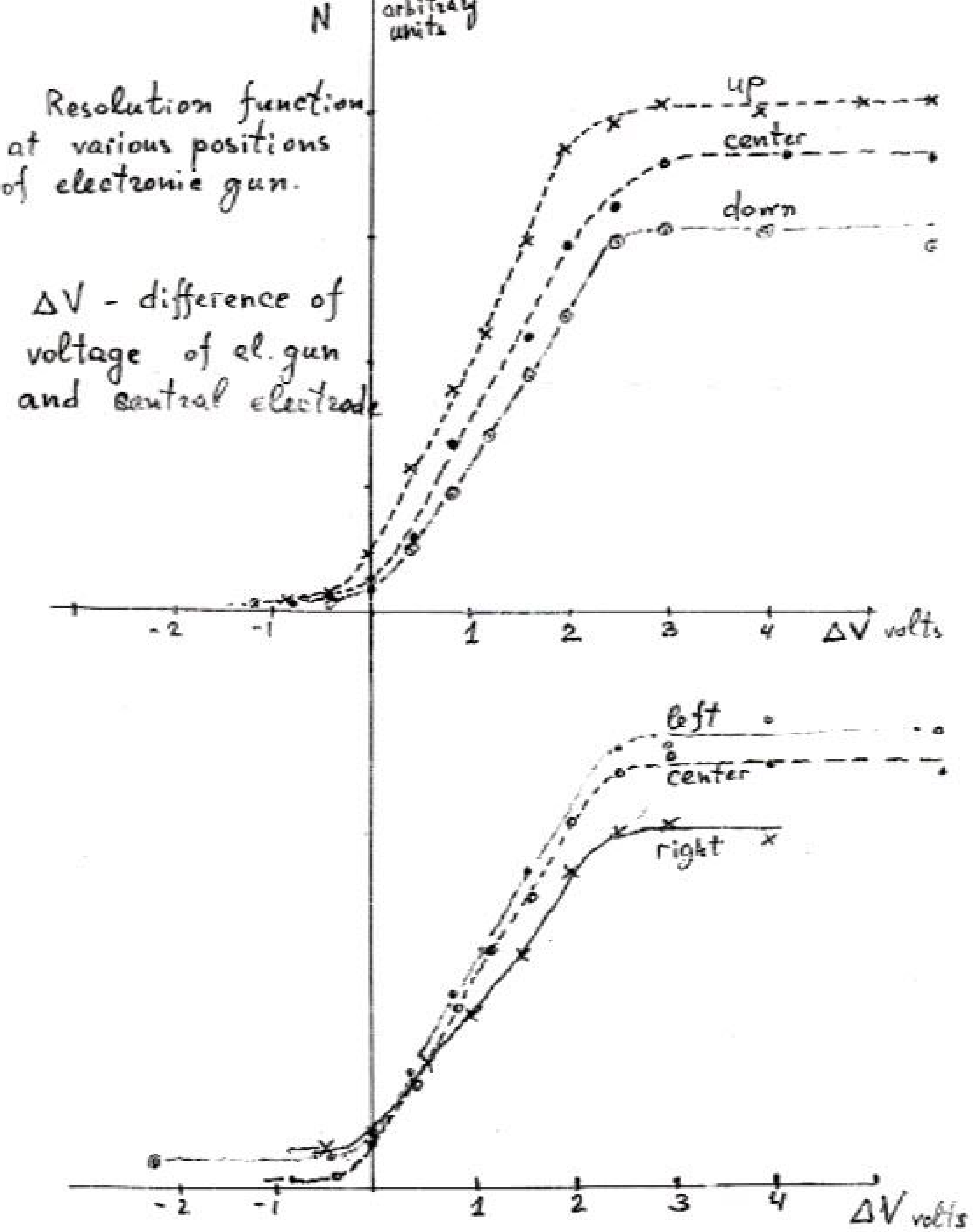


1.0
0.8
0.6
INTEGRATED FIT CURVE
EXPERIMENTAL CURVE
18620
18640
18660
18680
18700
18720
VOLTAGE

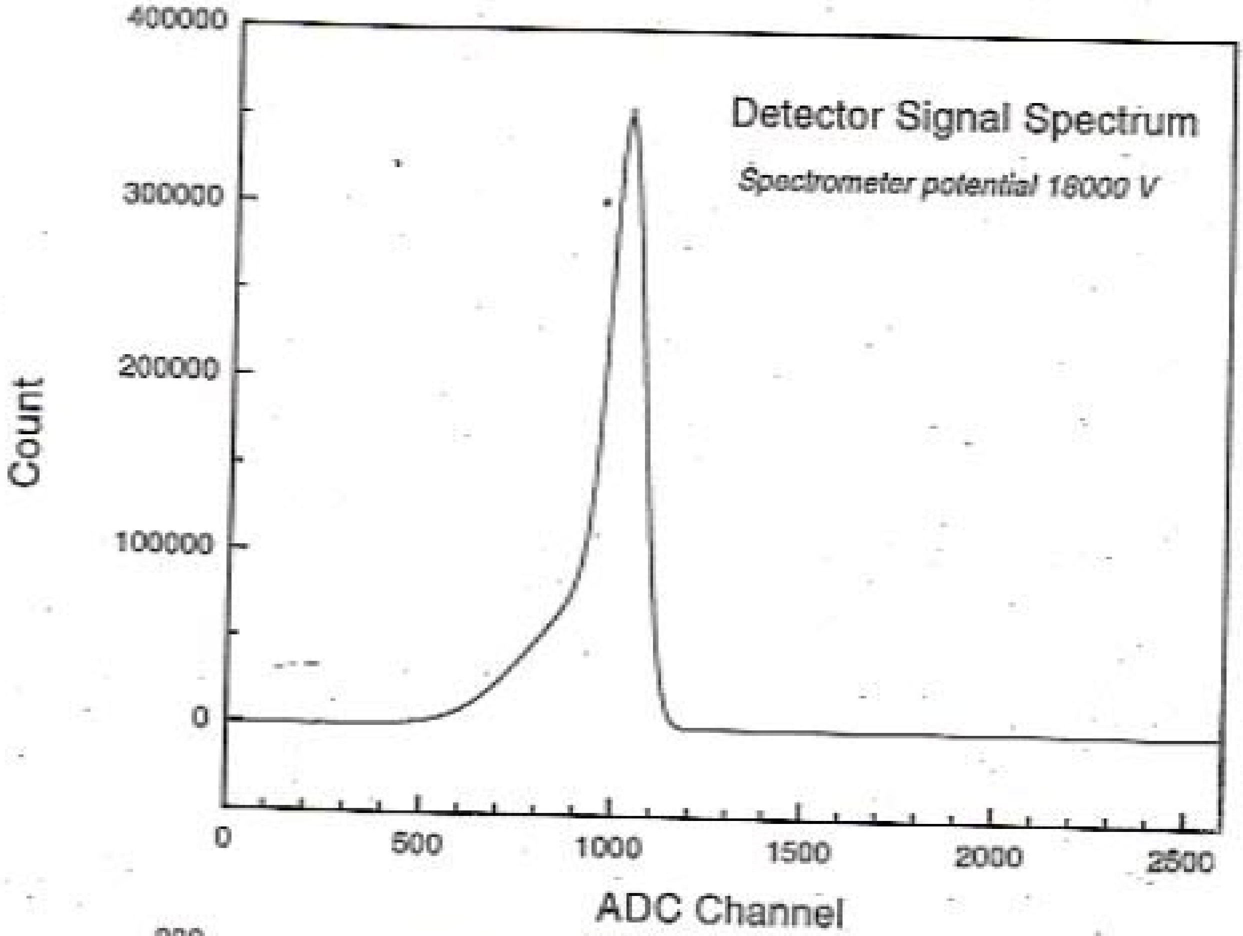
A*EXP(-2.*(X-X0)^2/(W^2))
A=1.
X0=-12.6ev
W=2.76ev
excitation/ionization=54% / 46%
IONIZATION THRESHOLD
A/(W^2+4.*(X-X0)^2)
A=59.5
W=14.07ev
X0=-14.28ev
-14.48
1.0
0.5
0.0
-60
-40
-20
0
ENERGY LOSS (ev)

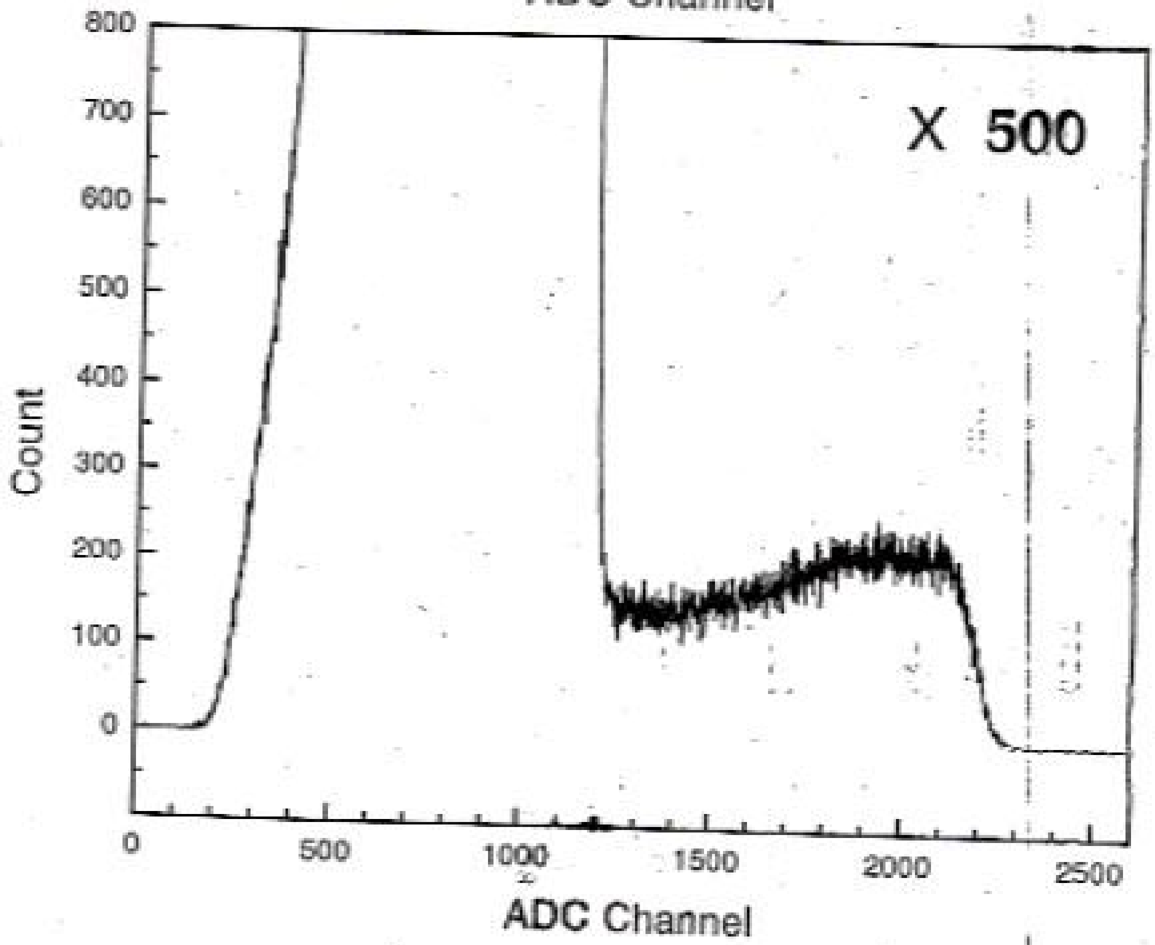

Transmittance
1.0
0.8
0.6
0.4
0.2
0.0
Empty
Tritium
18680
18685
18690
18695
18700
Voltage, V

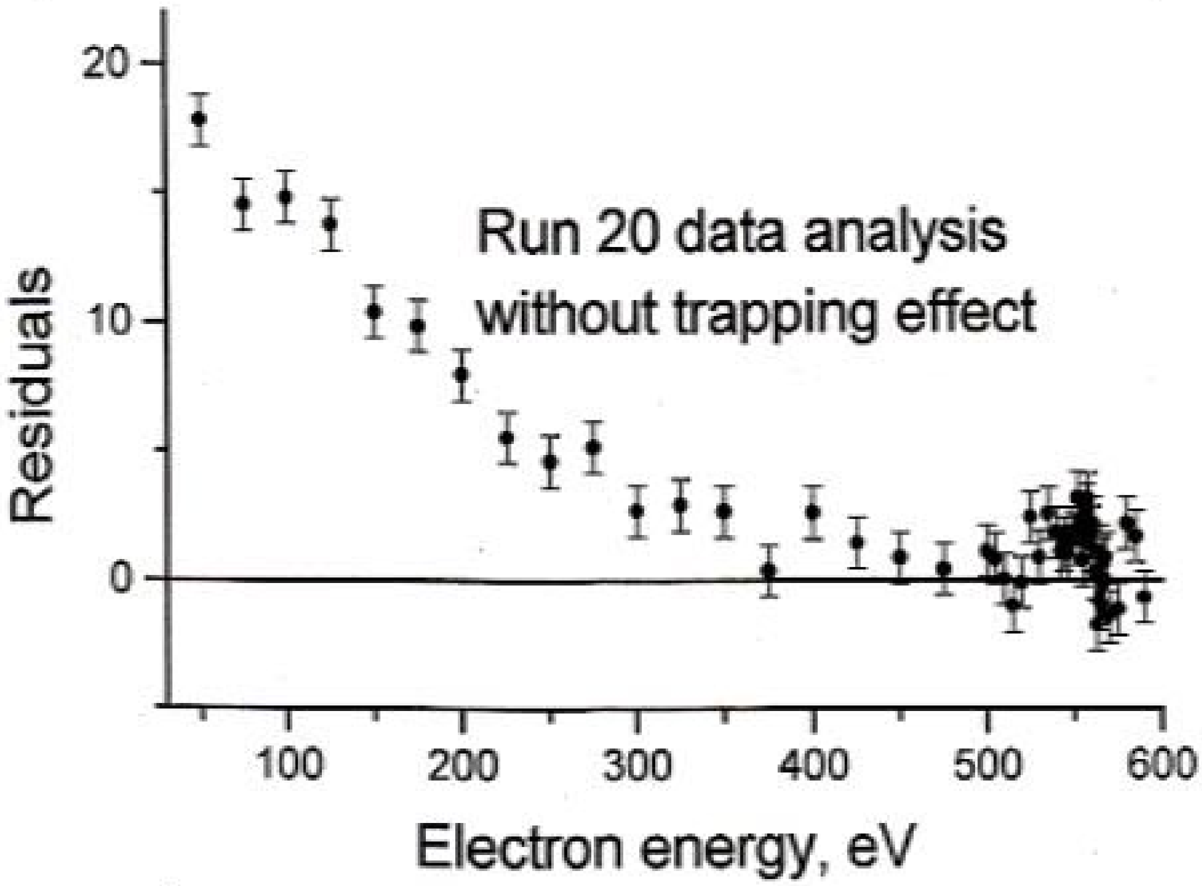



calculated FW 2.5 eV

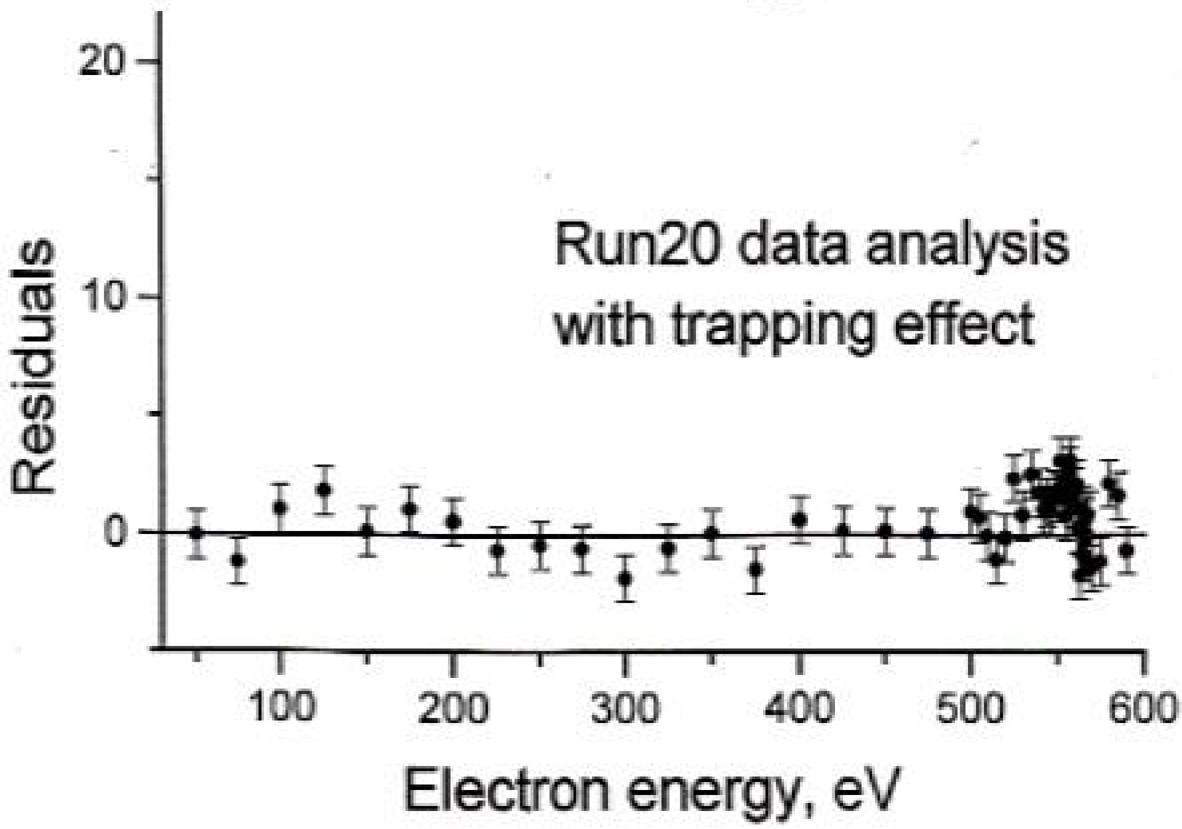
measured FW 2.6 - 2.8 eV


Detector Signal Spectrum
Spectrometer potential 18000 V
Count
ADC Channel
400000
300000
200000
100000
0
0
500
1000
1500
2000
2500


X 500
Count
ADC Channel
800
700
600
500
400
300
200
100
0
0
500
1000
1500
2000
2500



20
10
0
Residuals
Run 20 data analysis
without trapping effect
100
200
300
400
500
600
Electron energy, eV

20
10
0
Residuals
Run20 data analysis
with trapping effect
100
200
300
400
500
600
Electron energy, eV

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:

$m_\nu^2$ + basic

$E_{step}$, $N_{step}$ } Step function + basic

All of them variable.

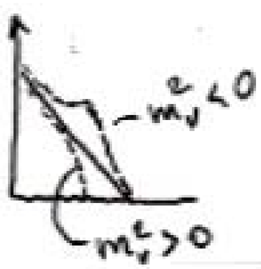
Some correction factors + basic + $m_\nu^2$ for regression coefficient determination.

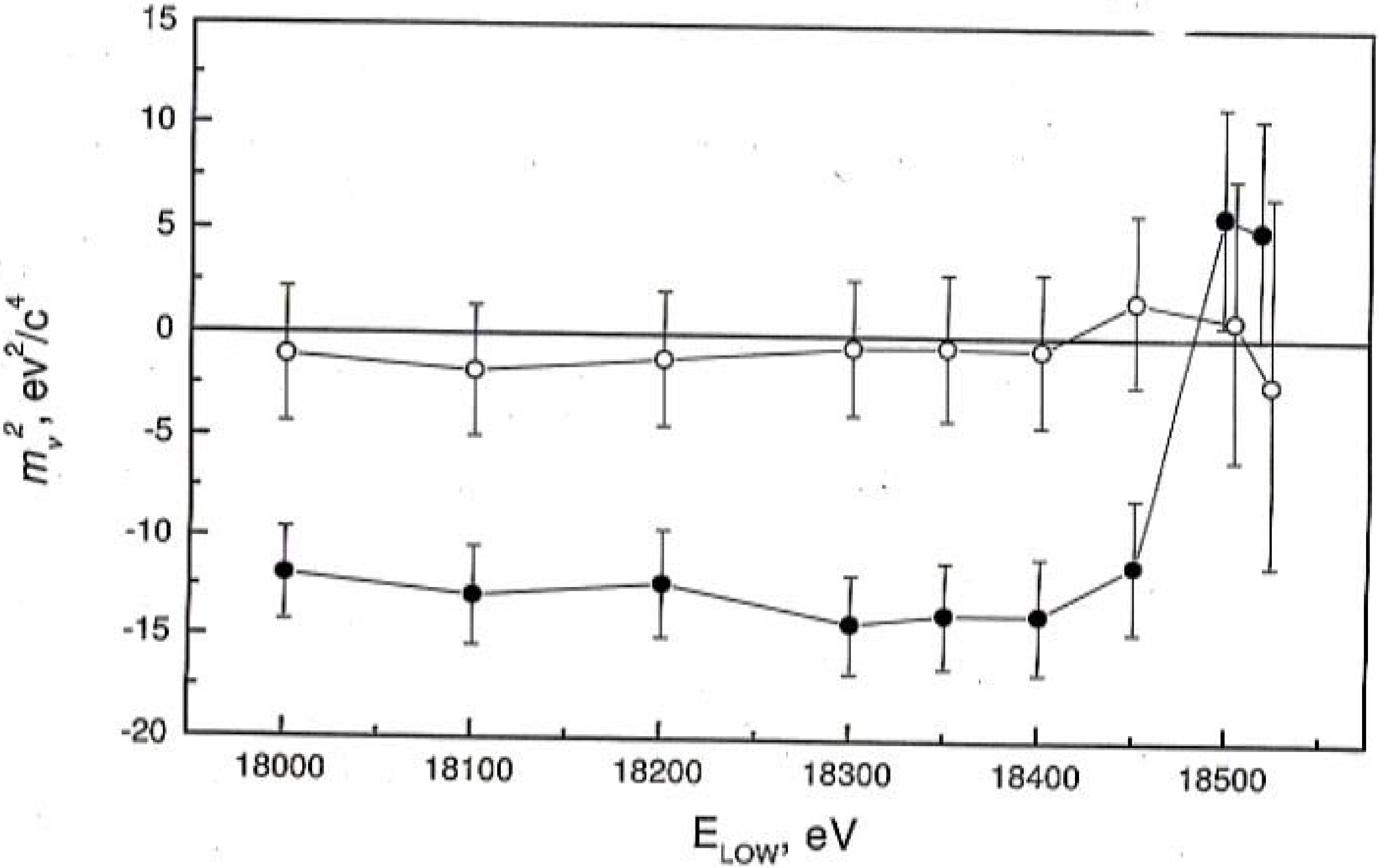
Fit by MINUIT package.

Neutrino mass effect approximation:

$$\varepsilon\sqrt{\varepsilon^2 - m_\nu^2 c^4} \qquad m_\nu^2 \geq 0$$

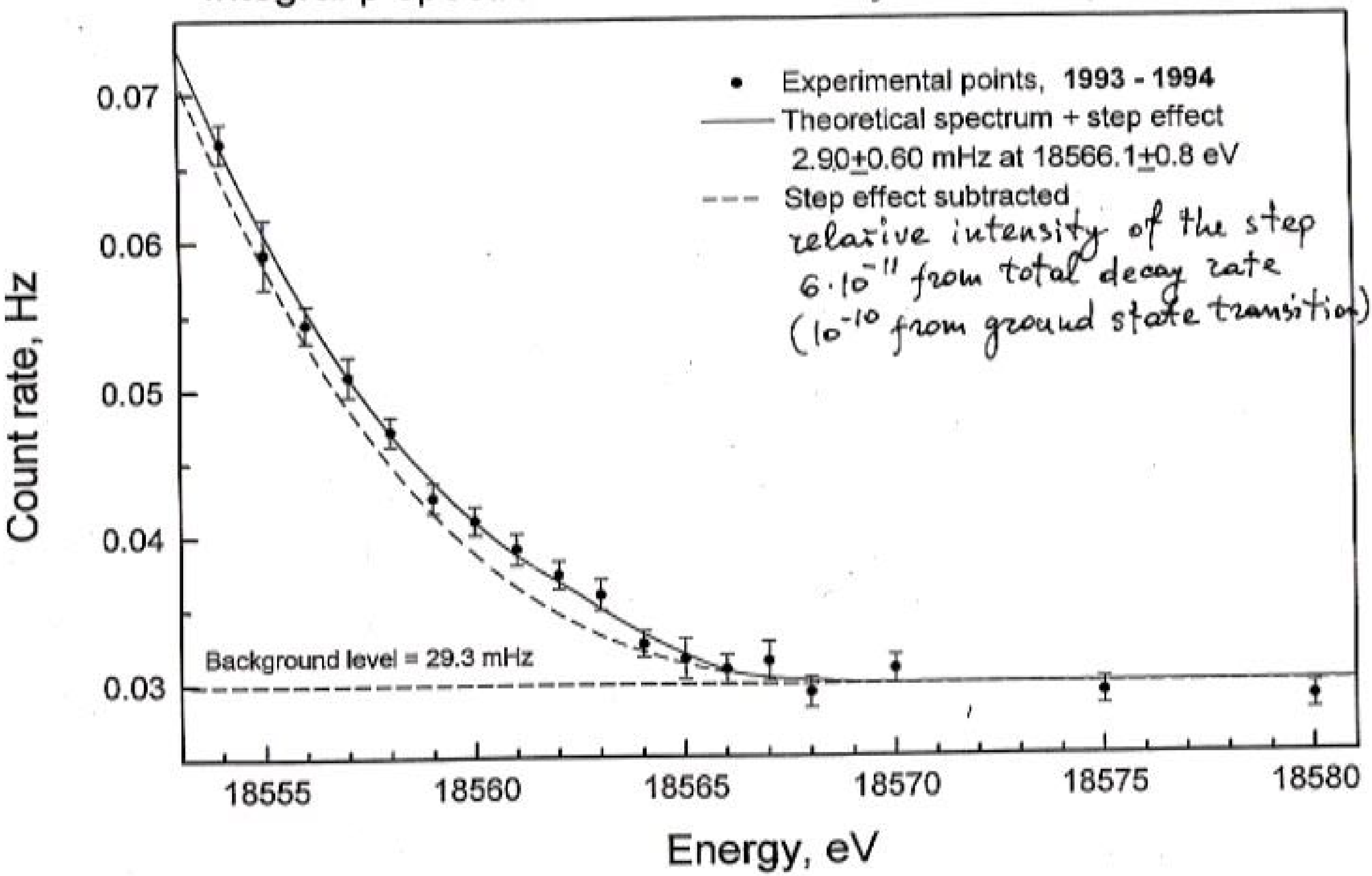
$$2\varepsilon^2 - \varepsilon\sqrt{\varepsilon^2 - |m_\nu^2| c^4} \qquad m_\nu^2 < 0$$

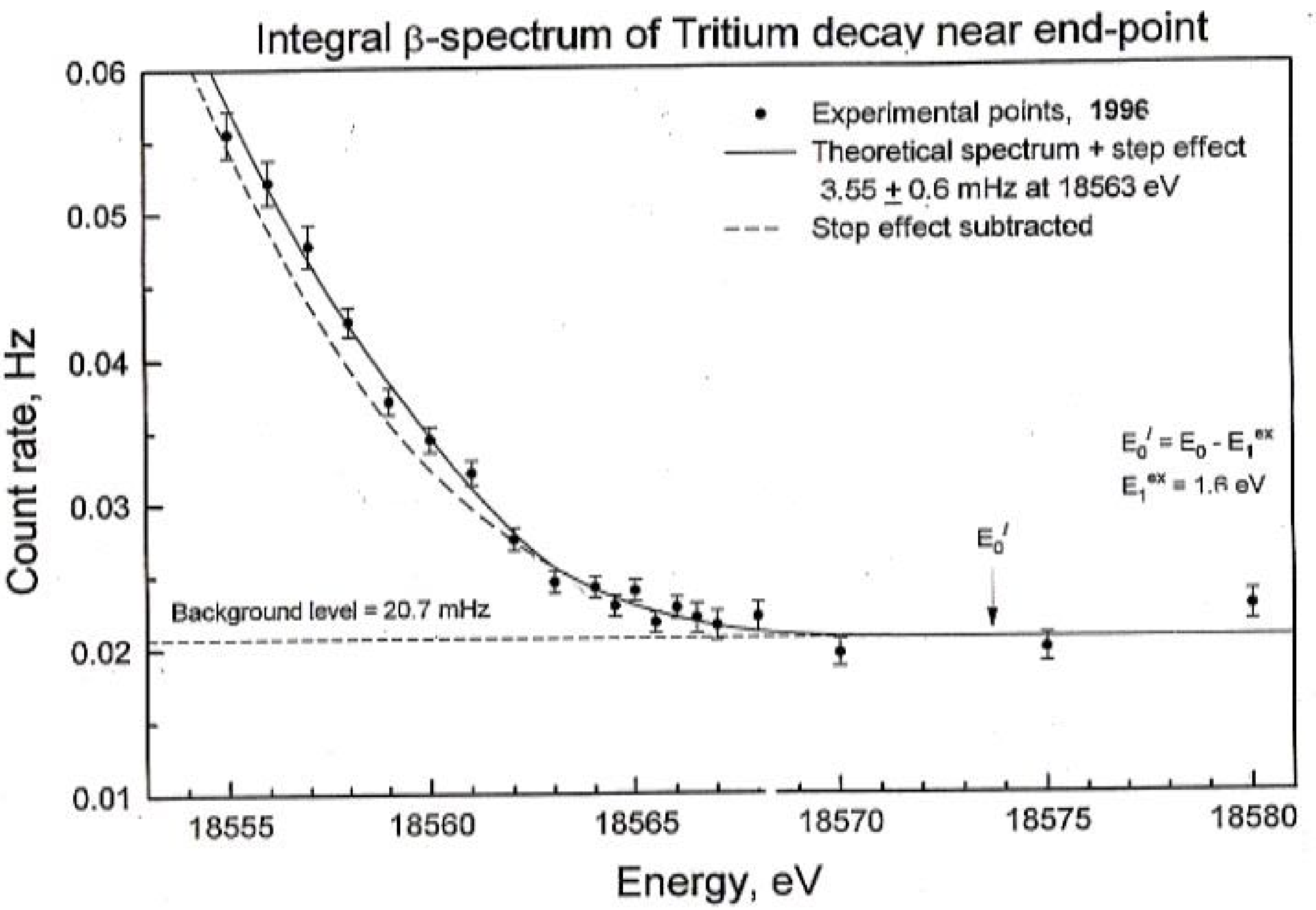




15
10
5
0
-5
-10
-15
-20
$m_\nu^2$, eV$^2$/c$^4$
18000
18100
18200
18300
18400
18500
$E_{LOW}$, eV

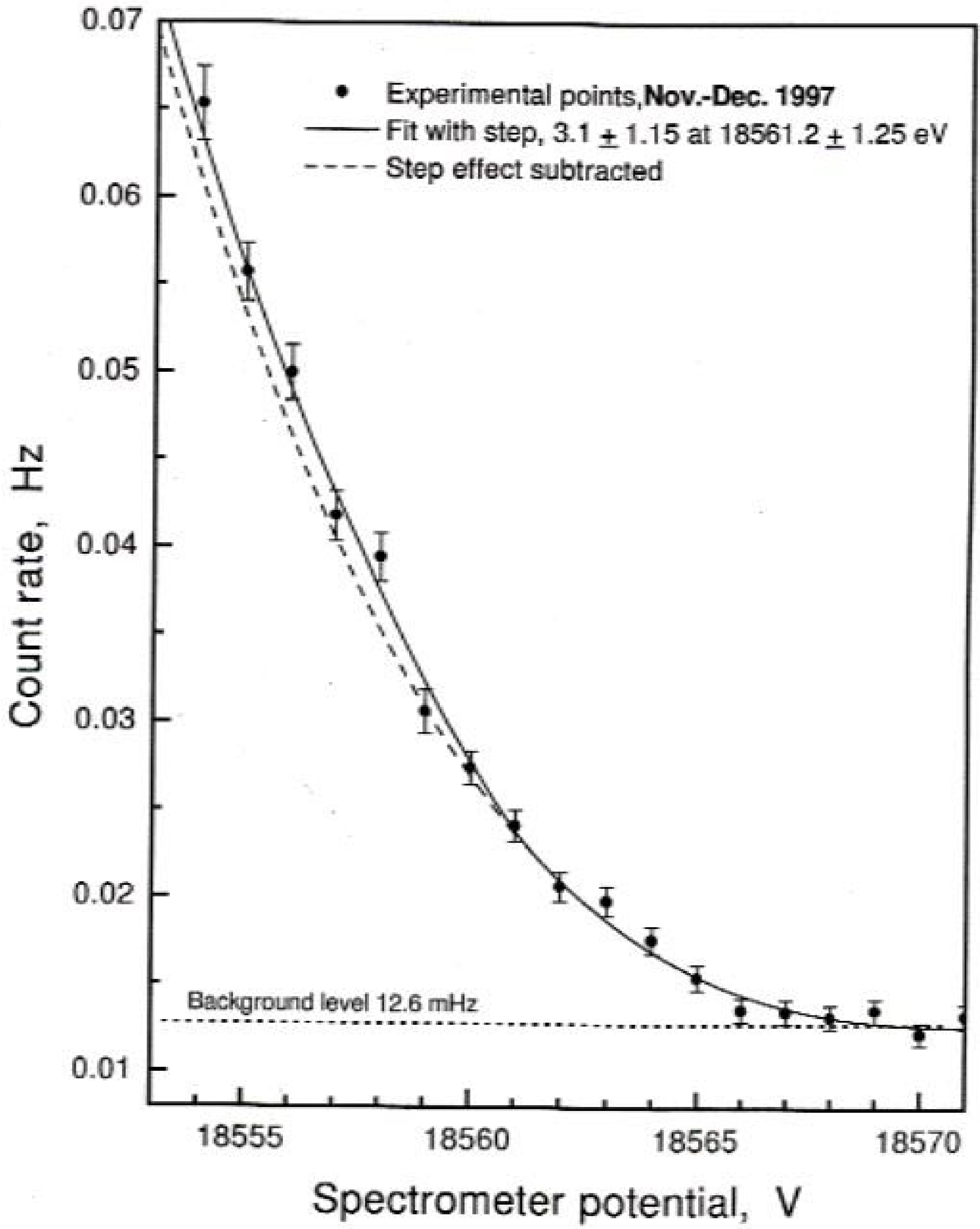
Integral β-spectrum of Tritium decay near end-point



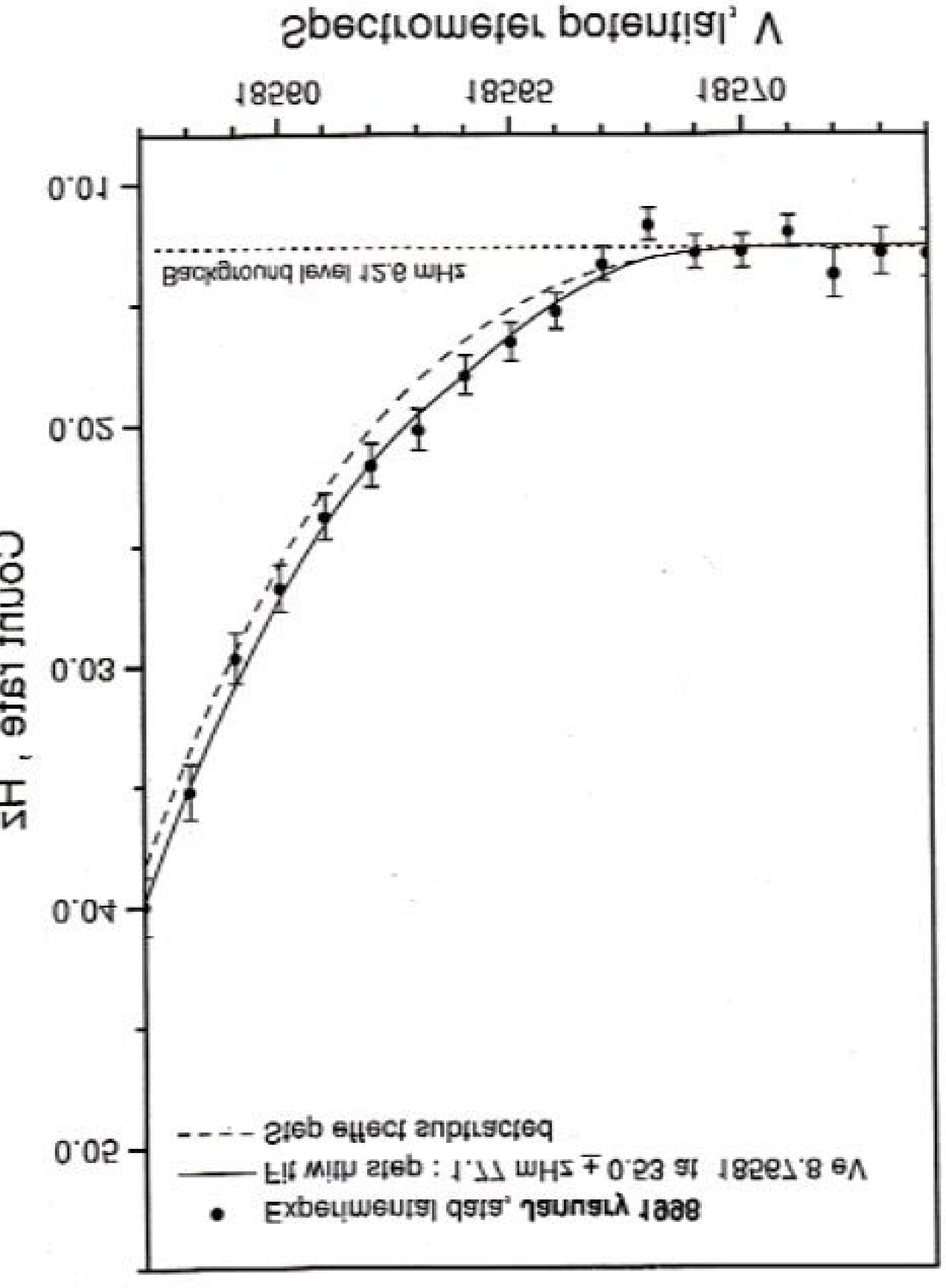


Integral β-spectrum of Tritium decay near end-point
0.06
0.05
0.04
0.03
0.02
0.01
Count rate, Hz
Experimental points, 1996
Theoretical spectrum + step effect
3.55 ± 0.6 mHz at 18563 eV
Stop effect subtracted
E0′ = E0 - E1ex
E1ex = 1.6 eV
E0′
Background level = 20.7 mHz
18555
18560
18565
18570
18575
18580
Energy, eV

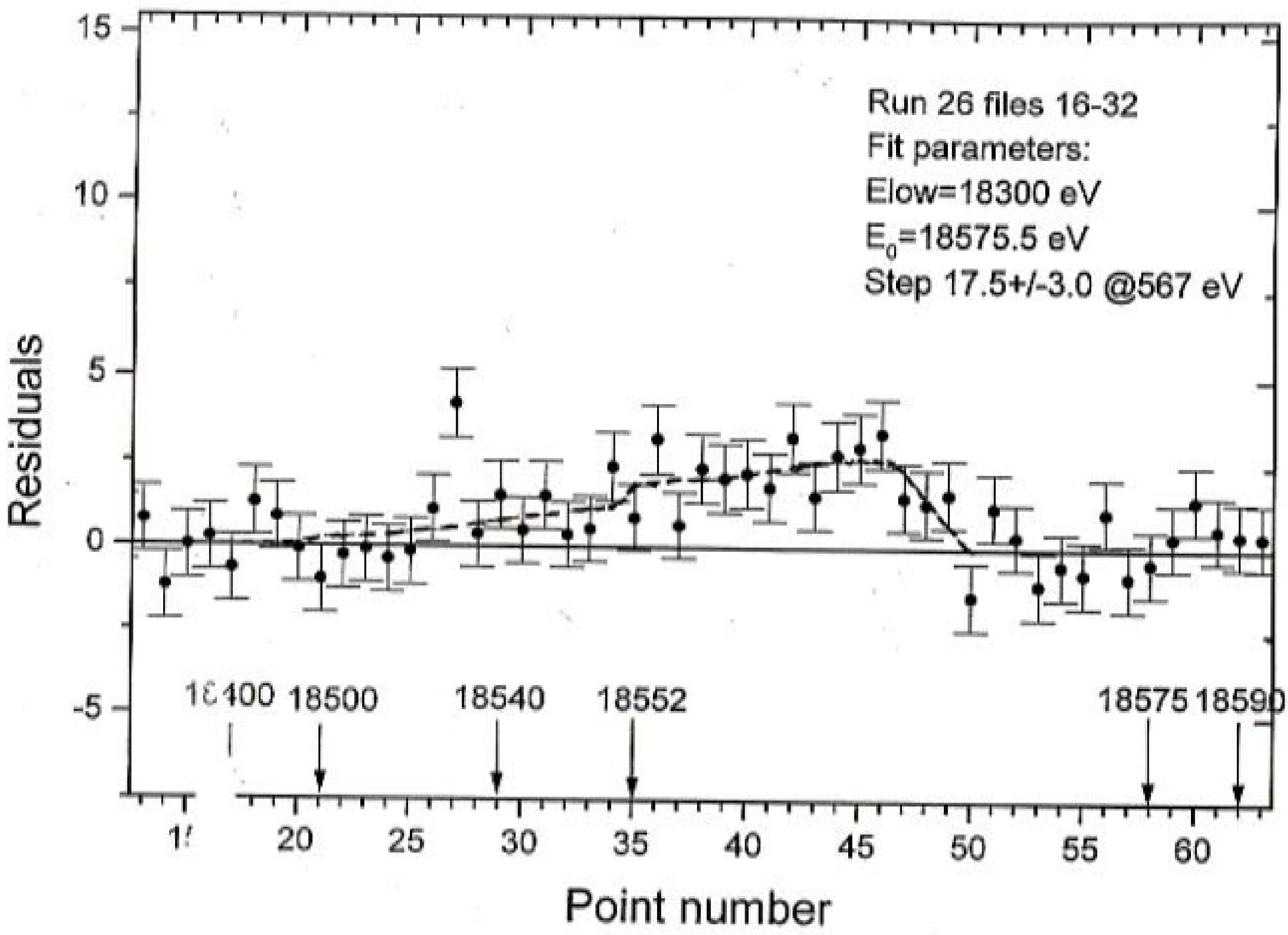

37

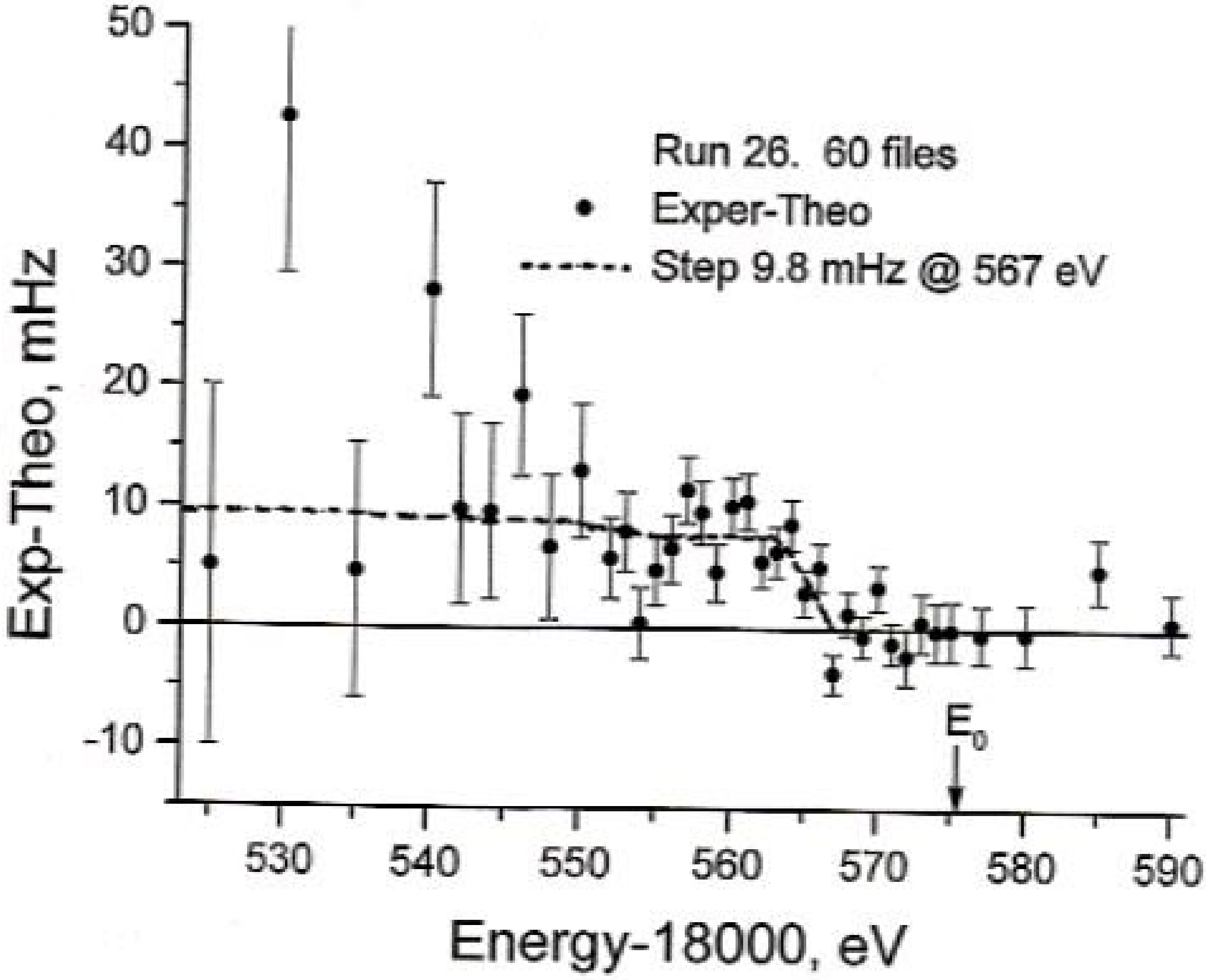


Experimental points, Nov.-Dec. 1997
Fit with step, 3.1 ± 1.15 at 18561.2 ± 1.25 eV
Step effect subtracted
Background level 12.6 mHz
Count rate, Hz
0.07
0.06
0.05
0.04
0.03
0.02
0.01
18555
18560
18565
18570
Spectrometer potential, V

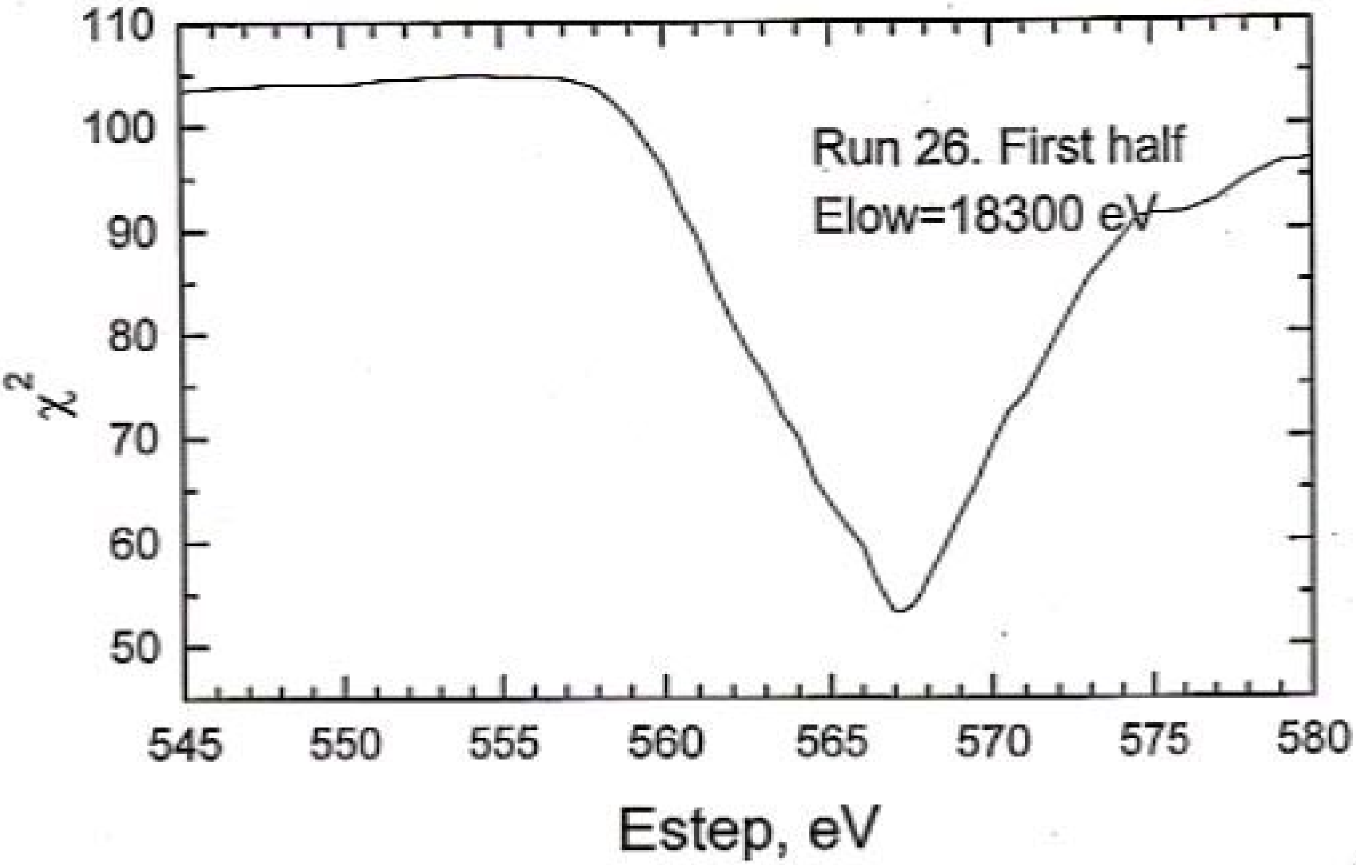


Spectrometer potential, V
18560
18565
18570
Count rate , Hz
0.01
0.02
0.03
0.04
0.05
Background level 12.6 mHz
Step effect subtracted
Fit with step : 1.77 mHz ± 0.53 at 18567.8 eV
Experimental data, January 1998

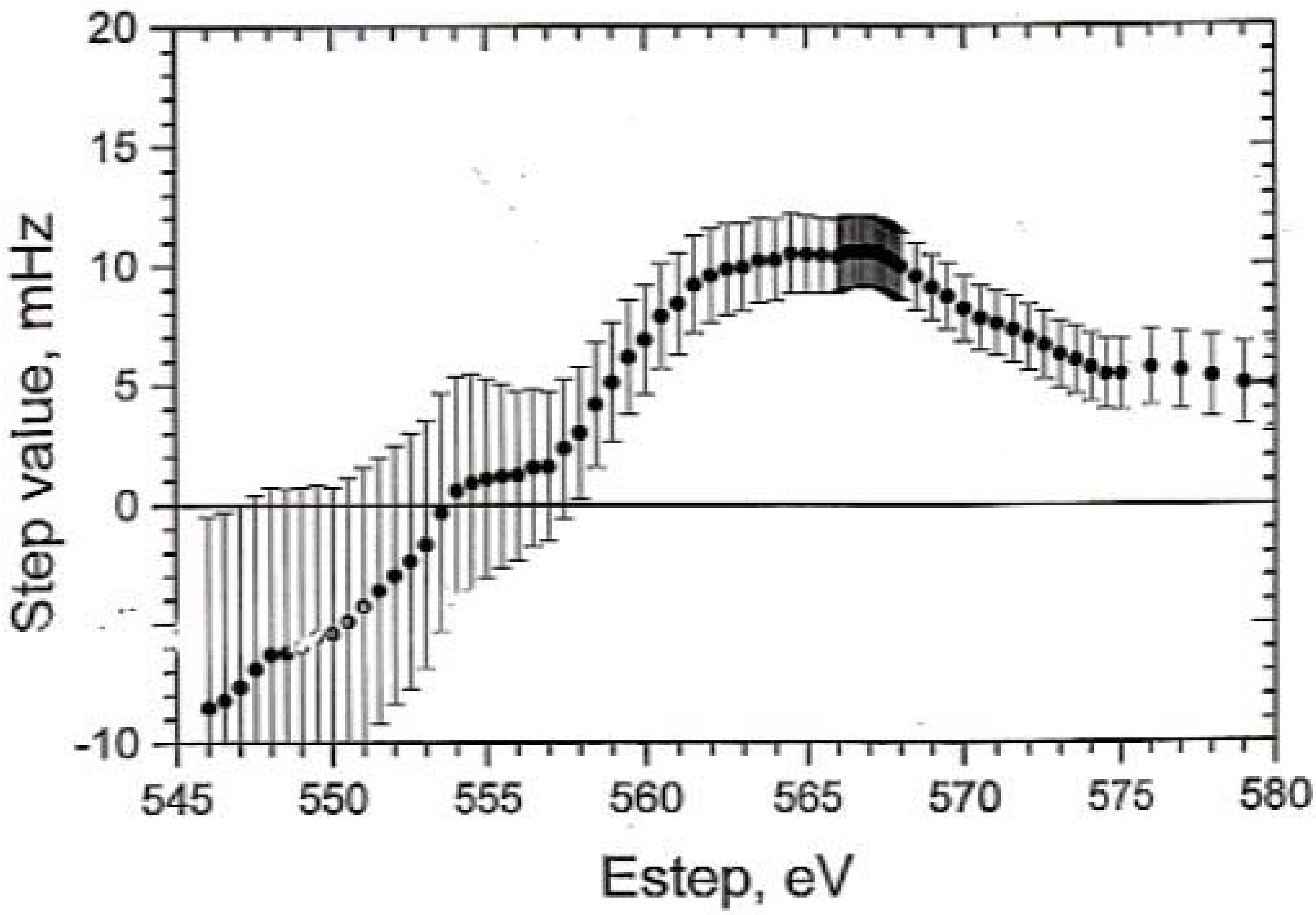

Run 26 files 16-32
Fit parameters:
Elow=18300 eV
$E_0$=18575.5 eV
Step 17.5+/-3.0 @567 eV
Residuals
Point number
18500
18540
18552
18575
18590



Run 26. 60 files
Exper-Theo
Step 9.8 mHz @ 567 eV
Exp-Theo, mHz
Energy-18000, eV
$E_0$
50
40
30
20
10
0
-10
530
540
550
560
570
580
590



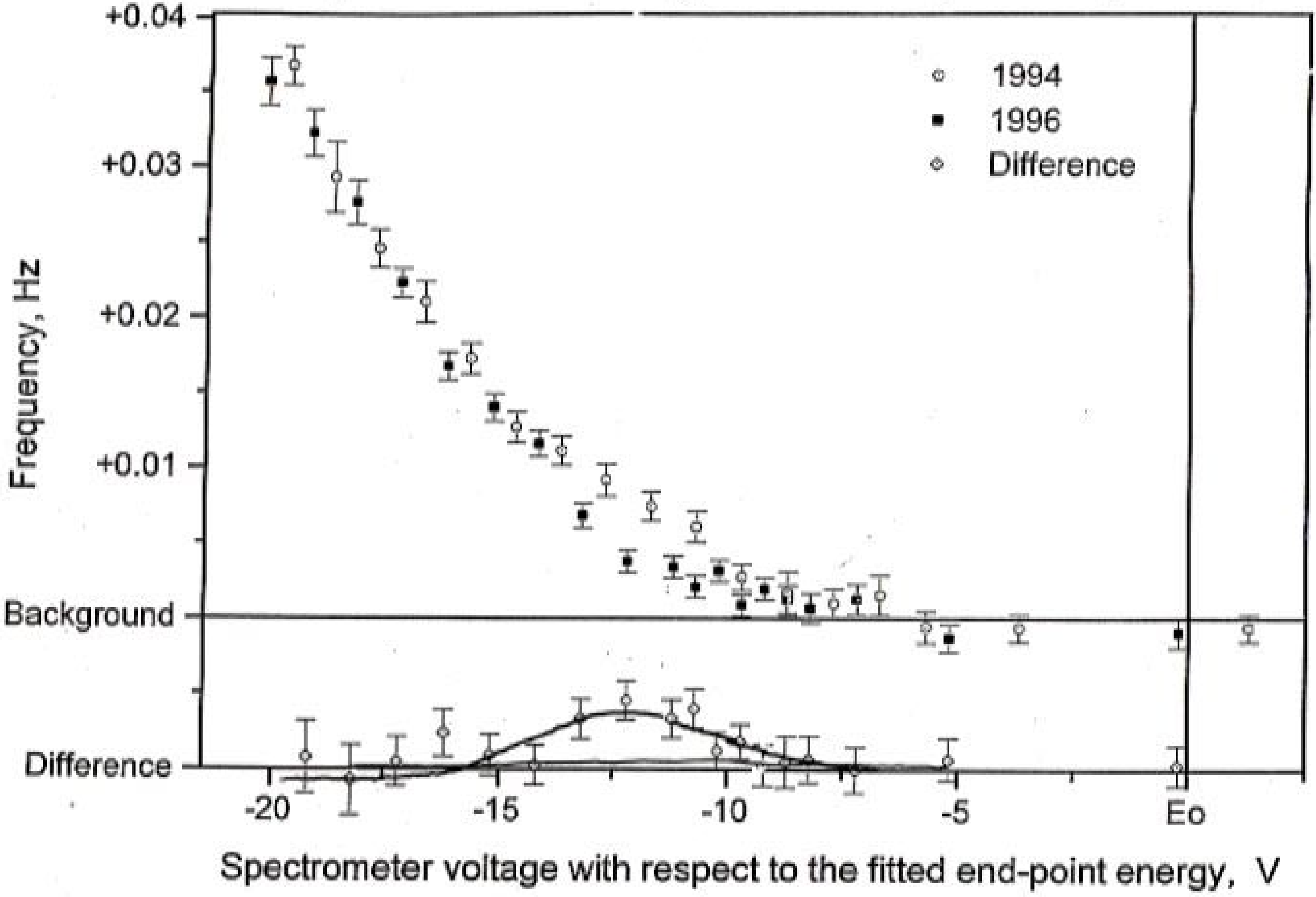
Run 26. First half
Elow=18300 eV
χ2
Estep, eV

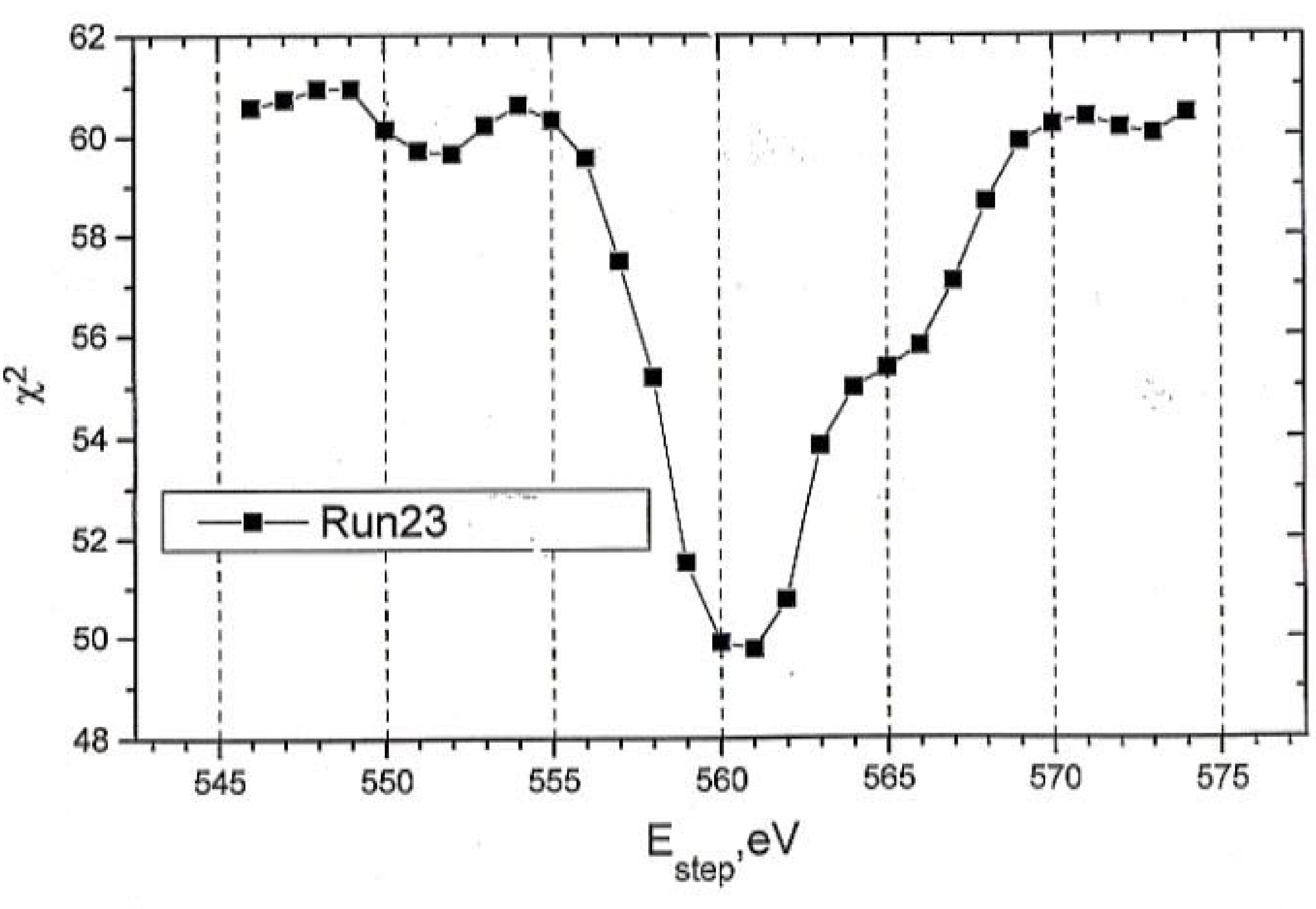



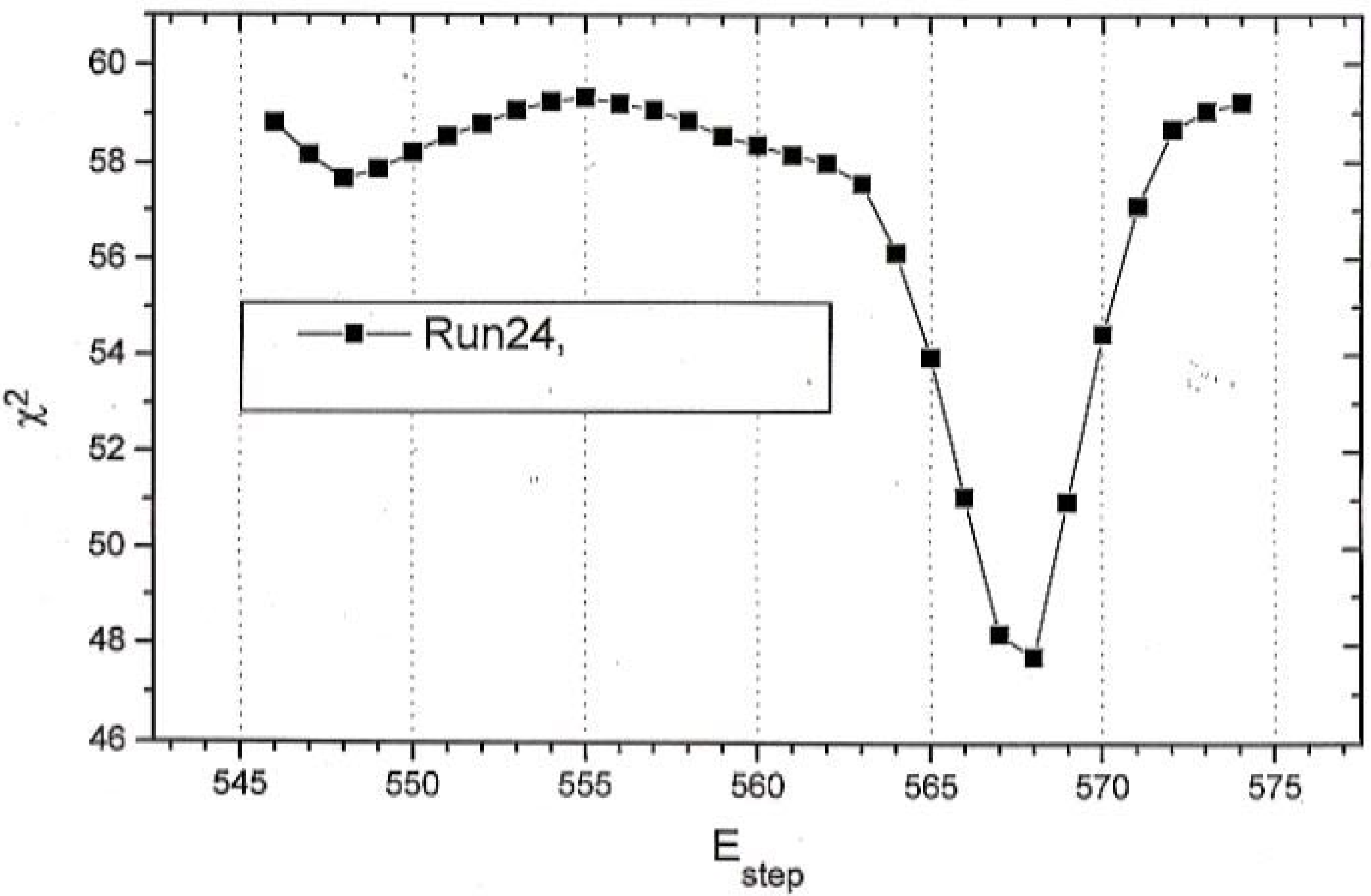
Step value, mHz
Estep, eV

Comparison of measurements 1994 and 1996

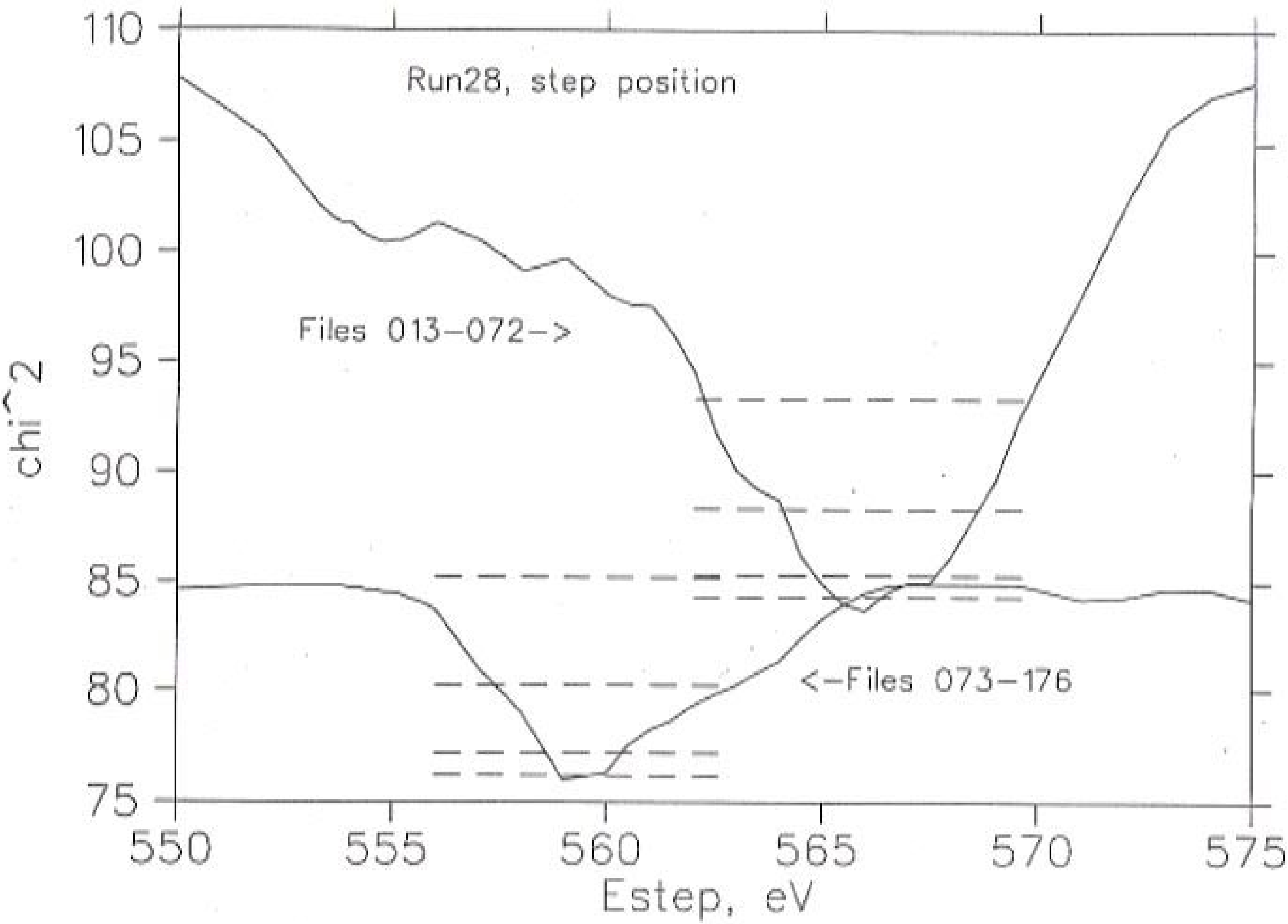
Spectra are matched in $E_0$ point and on integral intensity

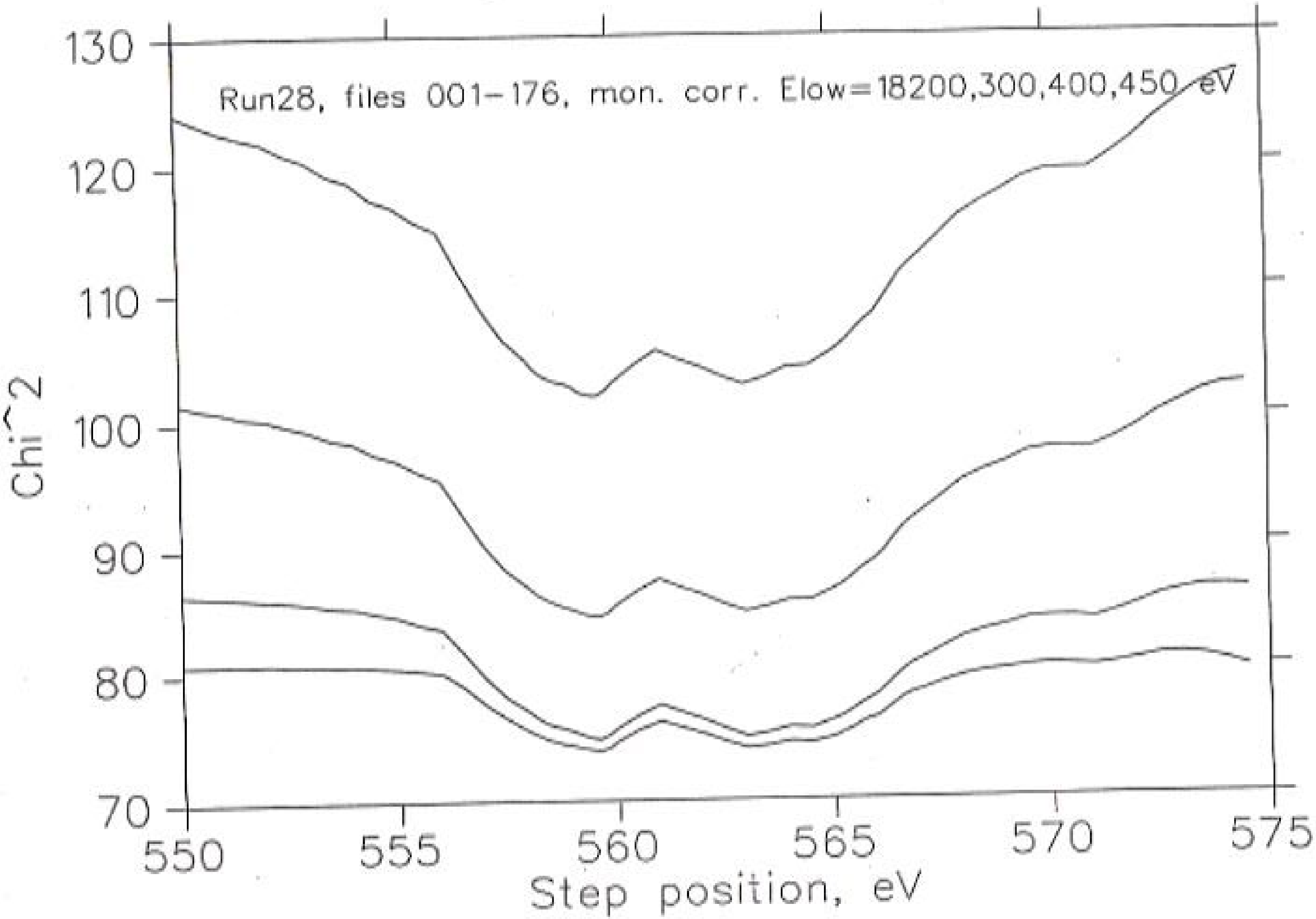


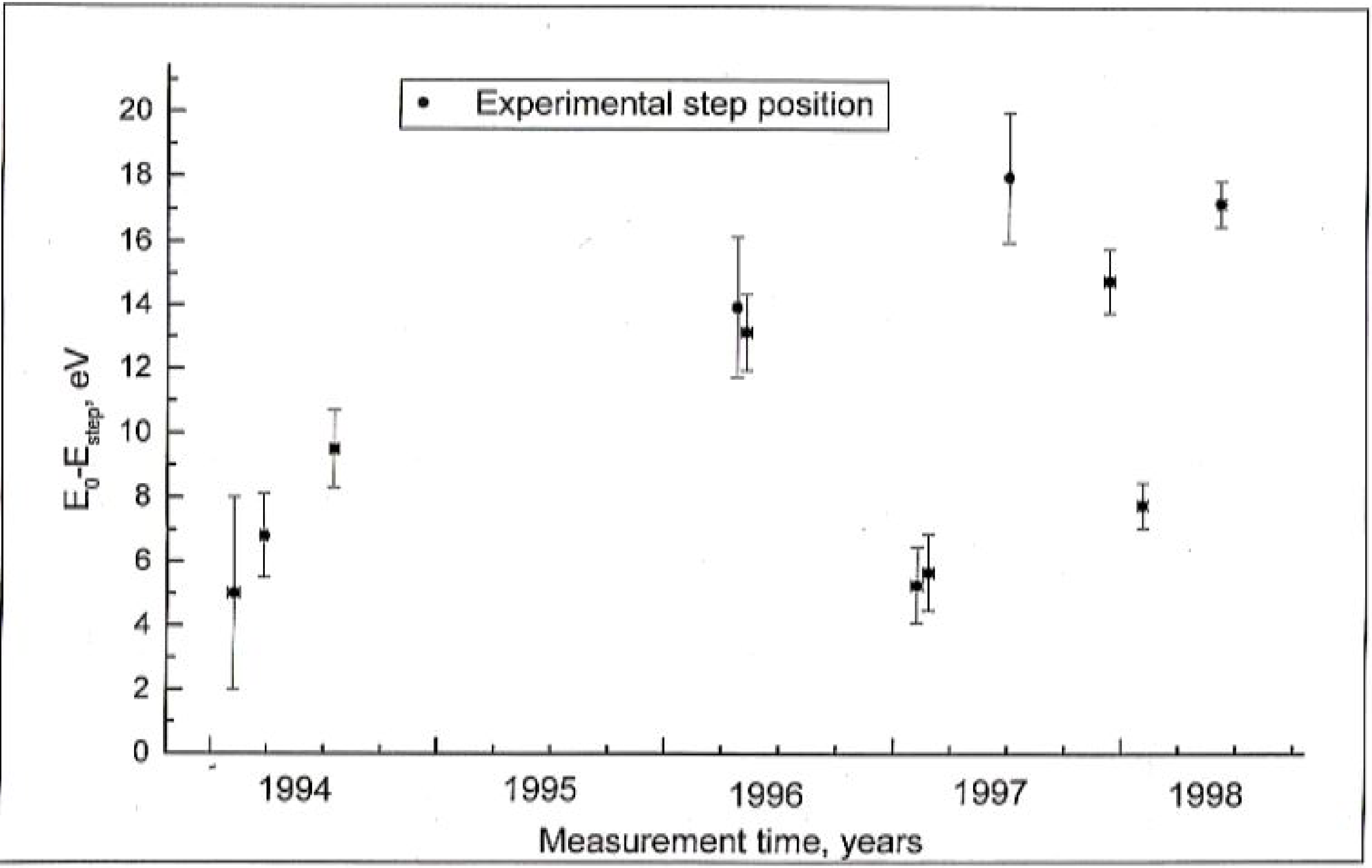

62
60
58
56
54
52
50
48
χ2
Run23
545
550
555
560
565
570
575
Estep,eV



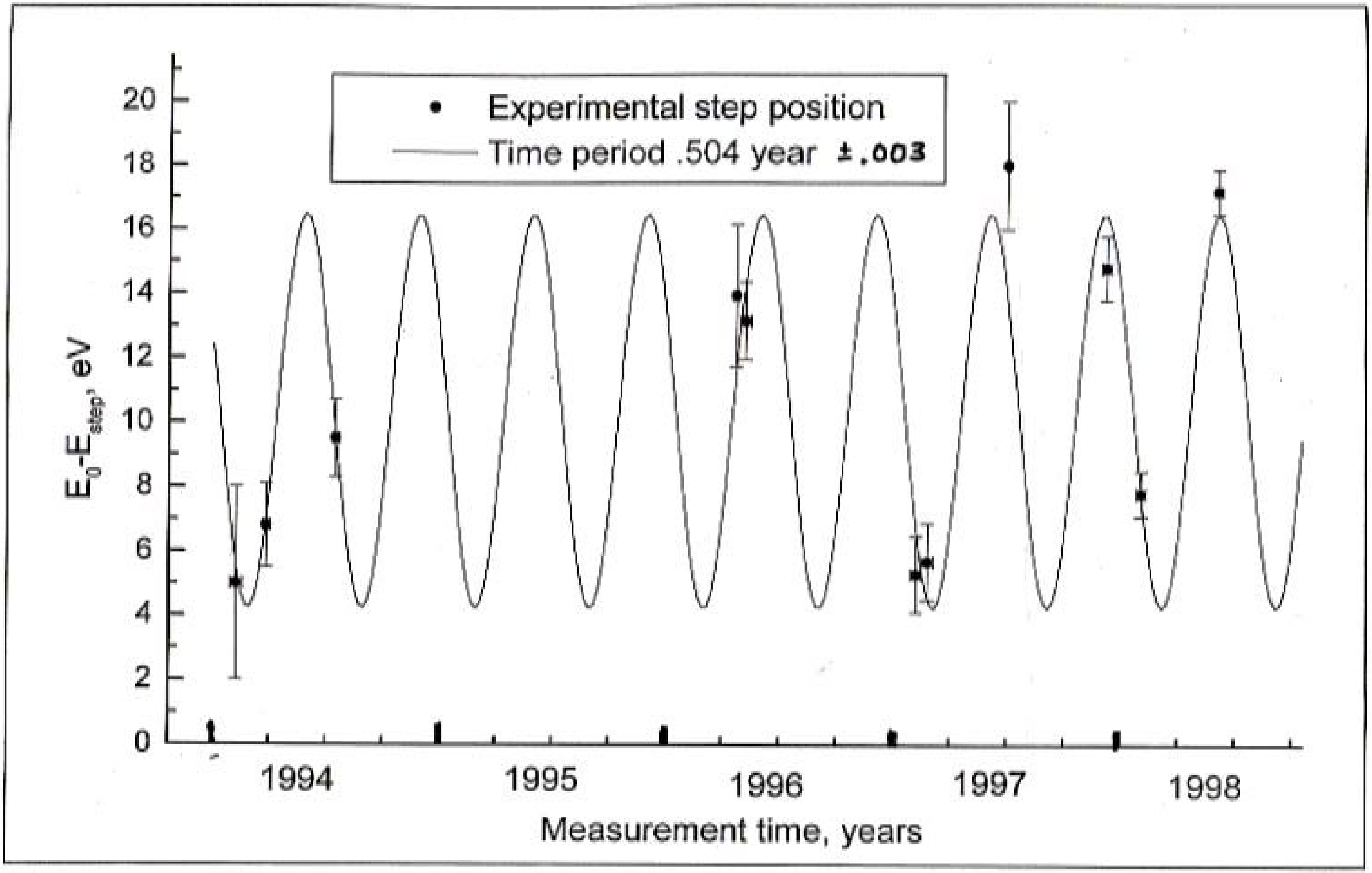
Run24,
60
58
56
54
52
50
48
46
$\chi^2$
545
550
555
560
565
570
575
$E_{step}$

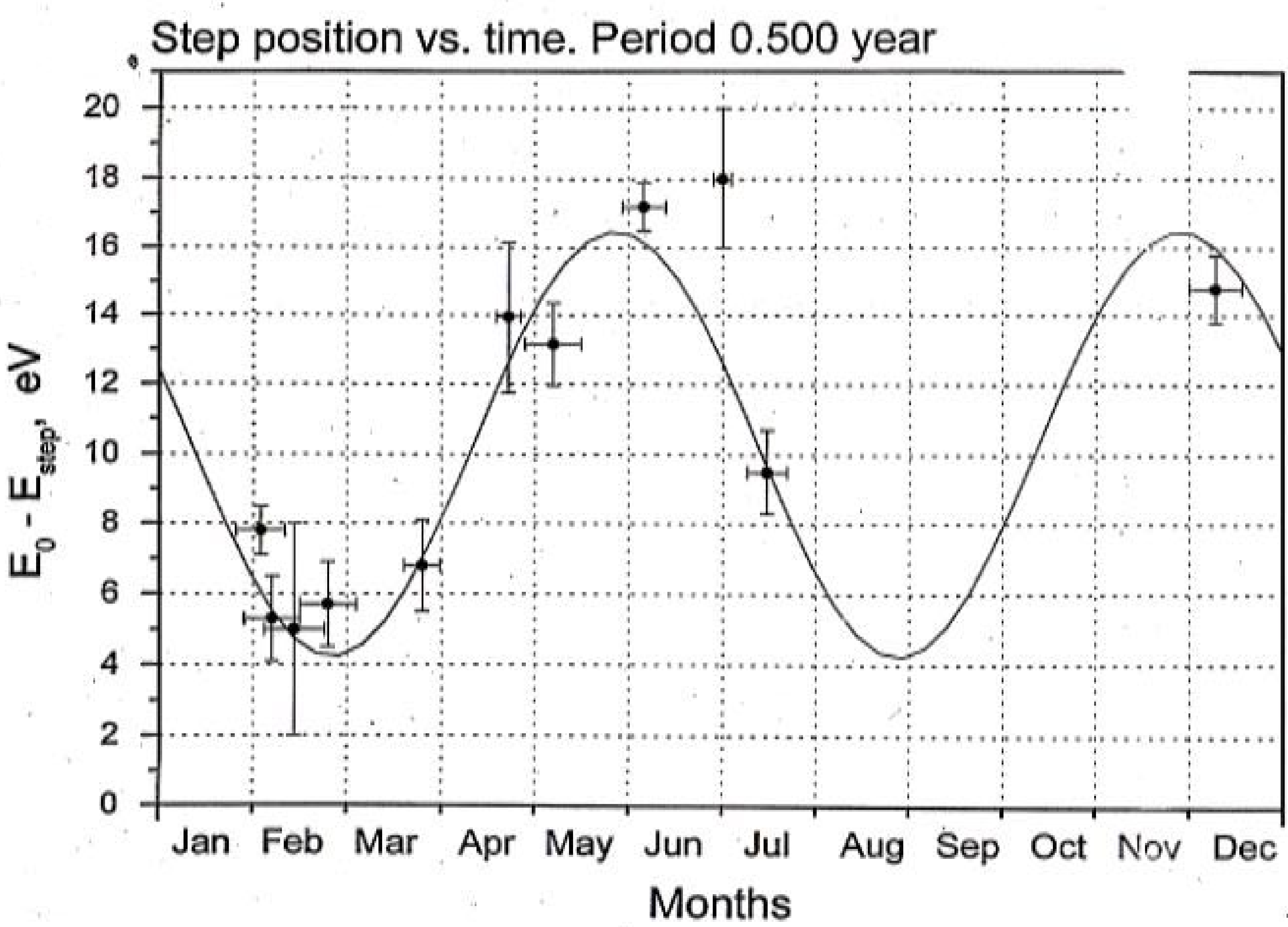

Run28, step position
Files 013-072->
<-Files 073-176
chi^2
Estep, eV
110
105
100
95
90
85
80
75
550
555
560
565
570
575


Run28, files 001-176, mon. corr. Elow=18200,300,400,450 eV
Chi^2
130
120
110
100
90
80
70
550
555
560
565
570
575
Step position, eV

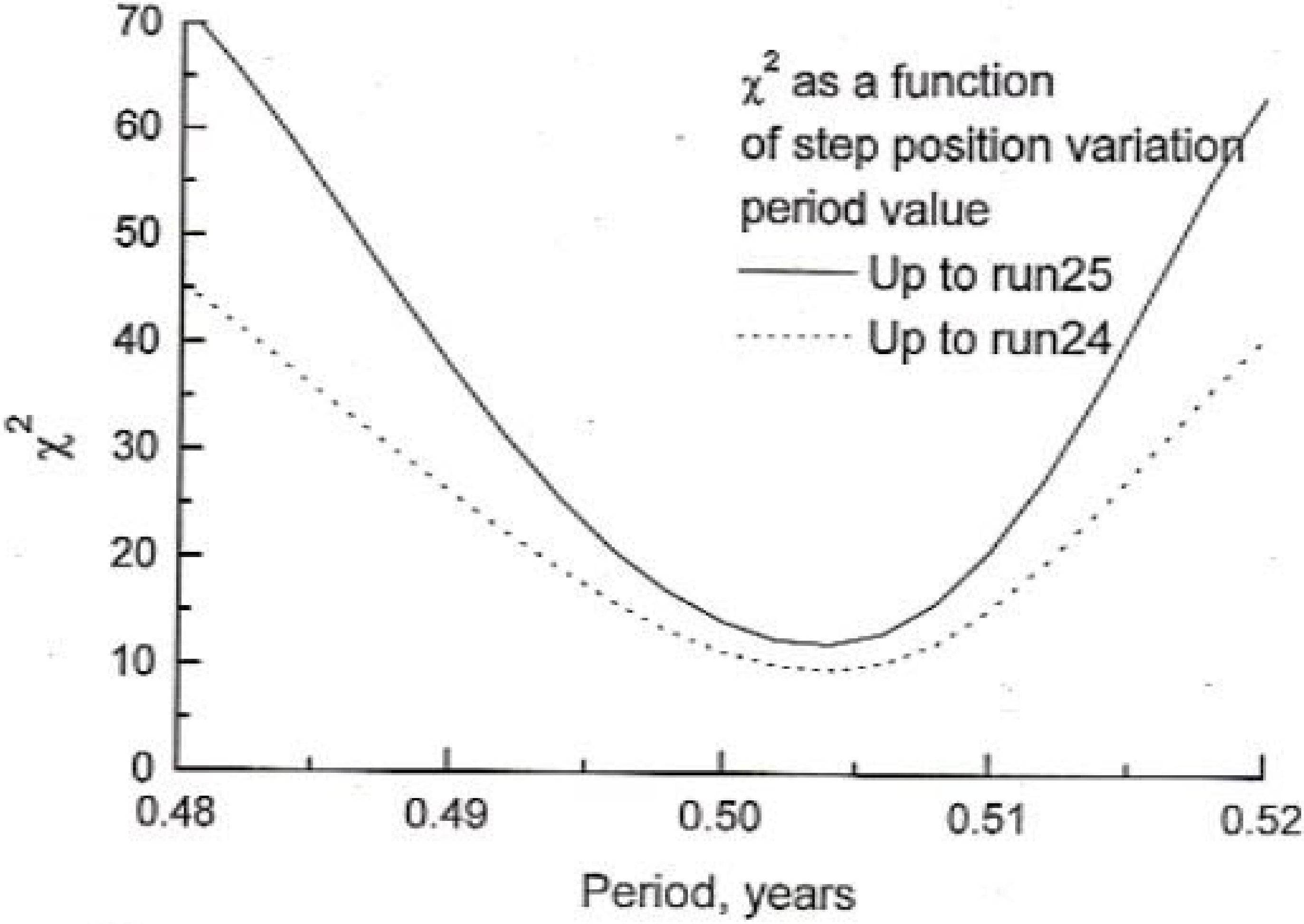


Experimental step position
E0-Estep, eV
0
2
4
6
8
10
12
14
16
18
20
1994
1995
1996
1997
1998
Measurement time, years

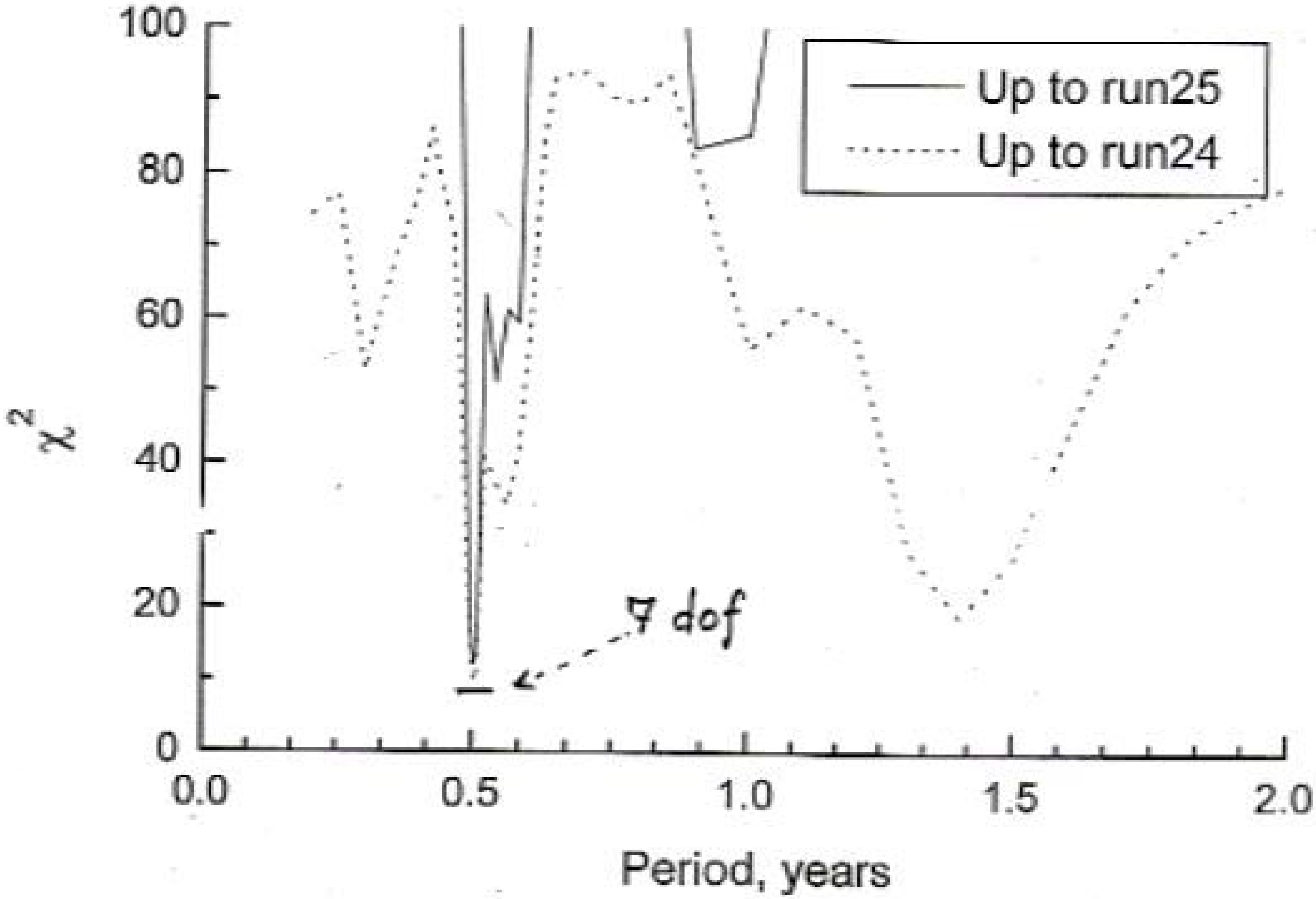

Experimental step position
Time period .504 year ±.003
$E_0$-$E_{step}$, eV
0
2
4
6
8
10
12
14
16
18
20
1994
1995
1996
1997
1998
Measurement time, years



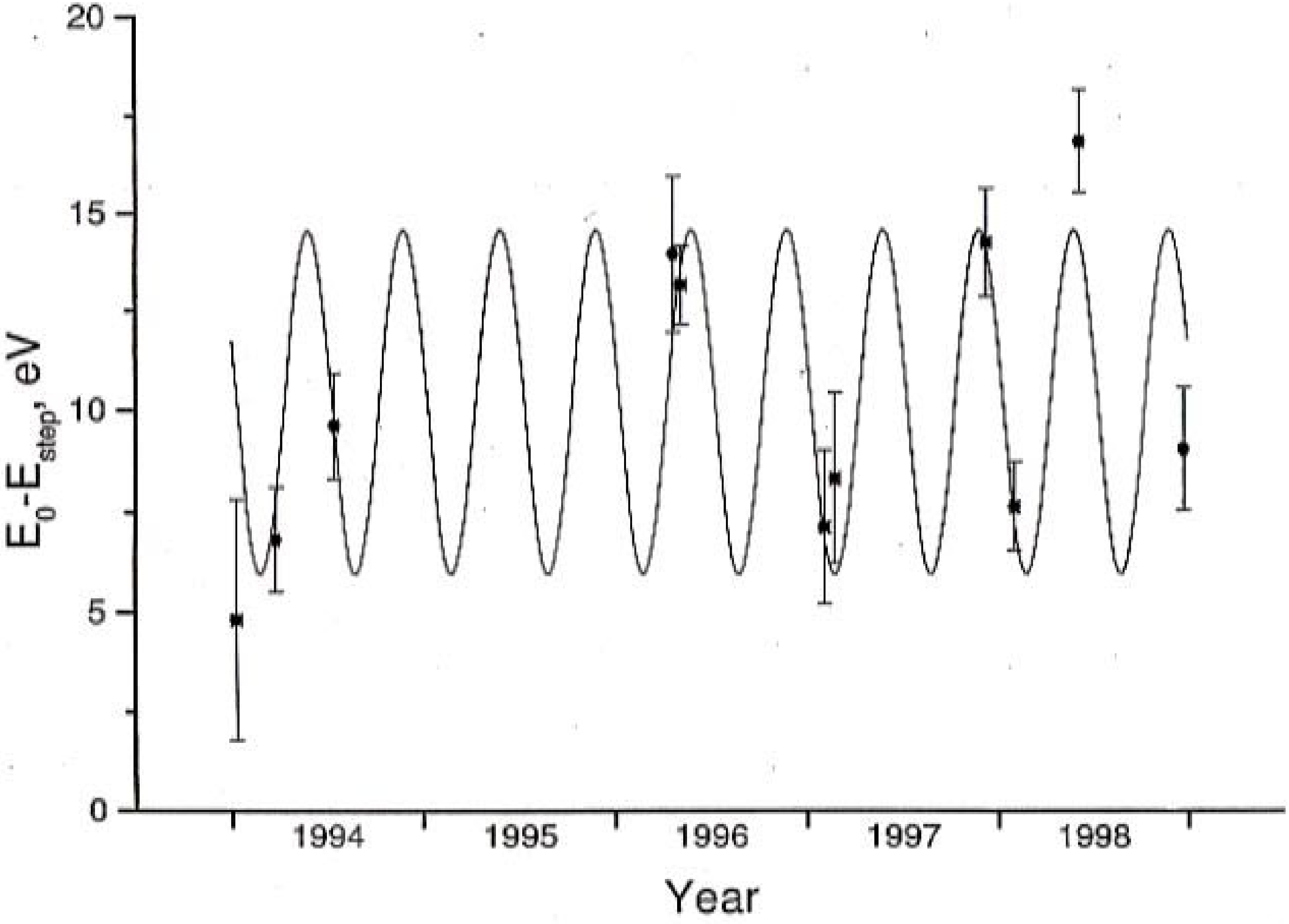
Step position vs. time. Period 0.500 year
$E_0 - E_{step}$, eV
0
2
4
6
8
10
12
14
16
18
20
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Months



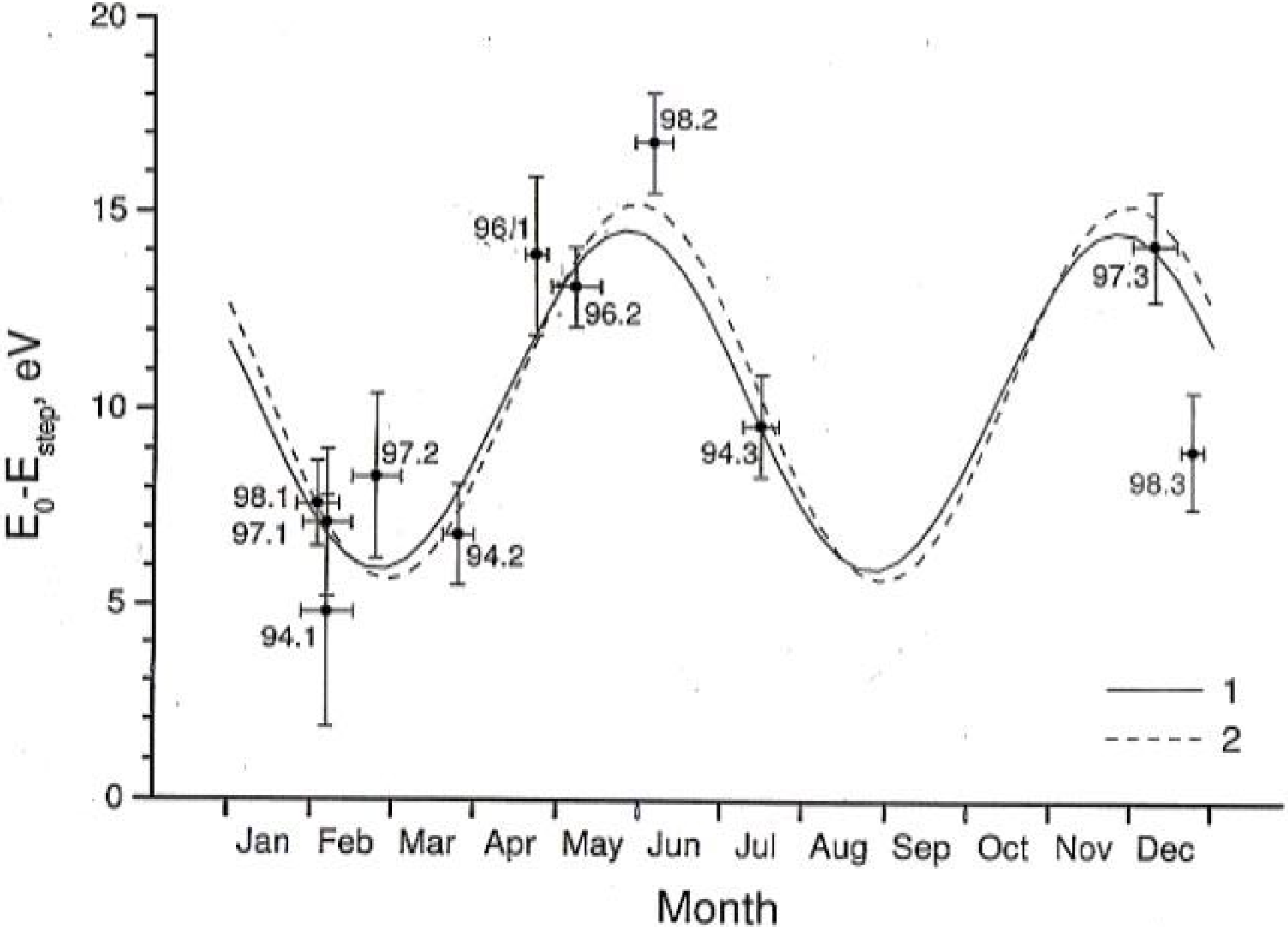
$\chi^2$ as a function
of step position variation
period value
Up to run25
Up to run24
$\chi^2$
Period, years

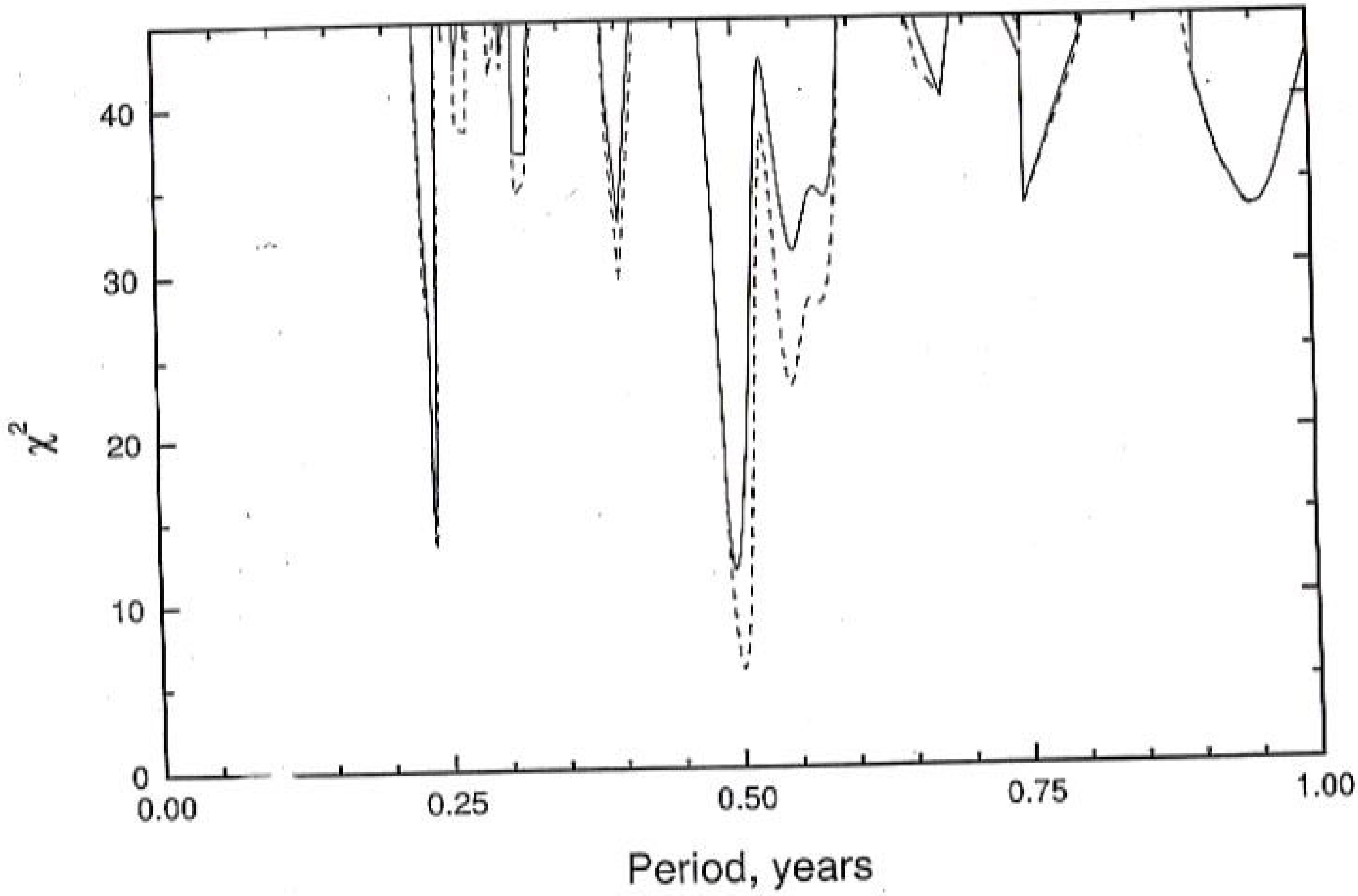
Up to run25
Up to run24
7 dof
$\chi^2$
Period, years



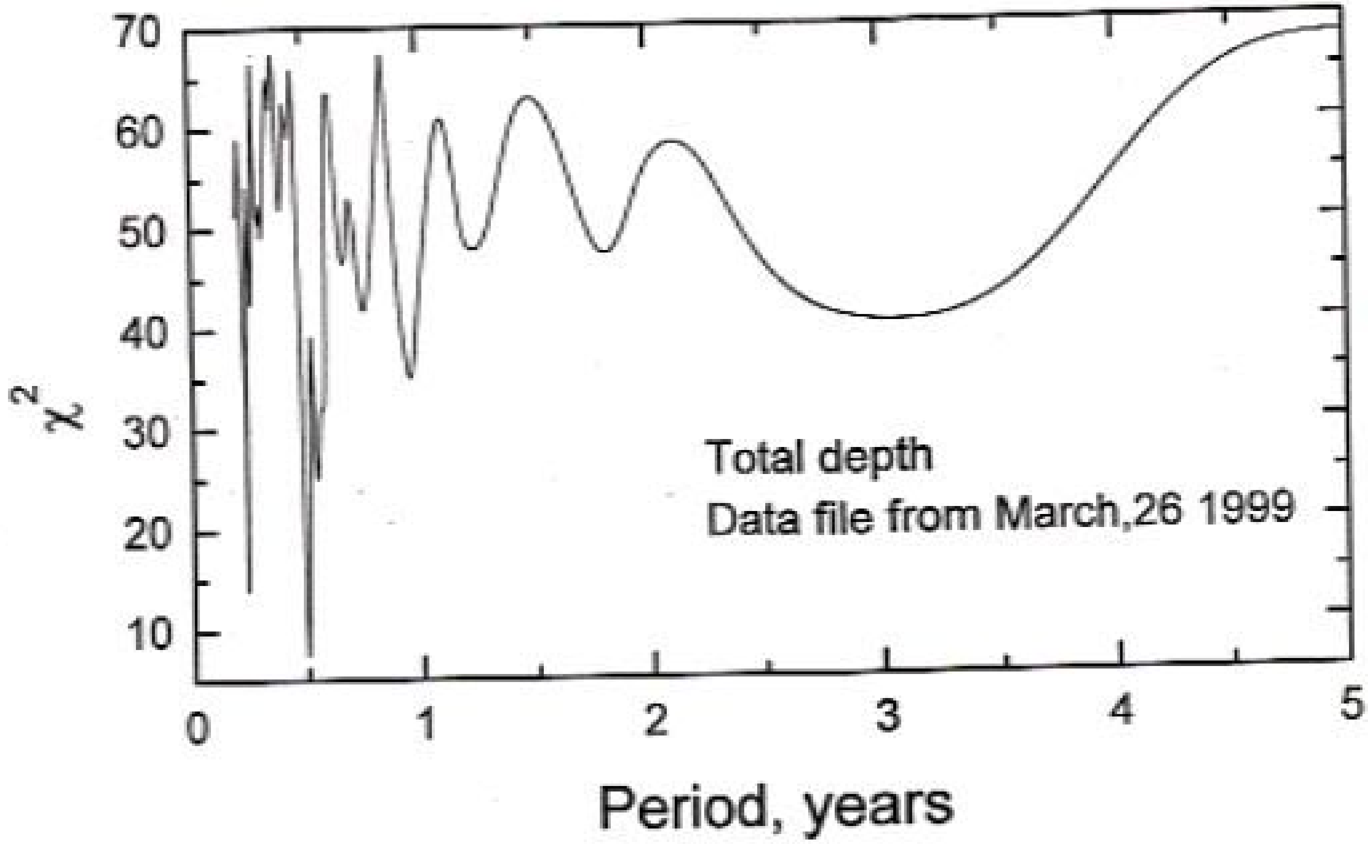
$E_0$-$E_{step}$, eV
0
5
10
15
20
1994
1995
1996
1997
1998
Year



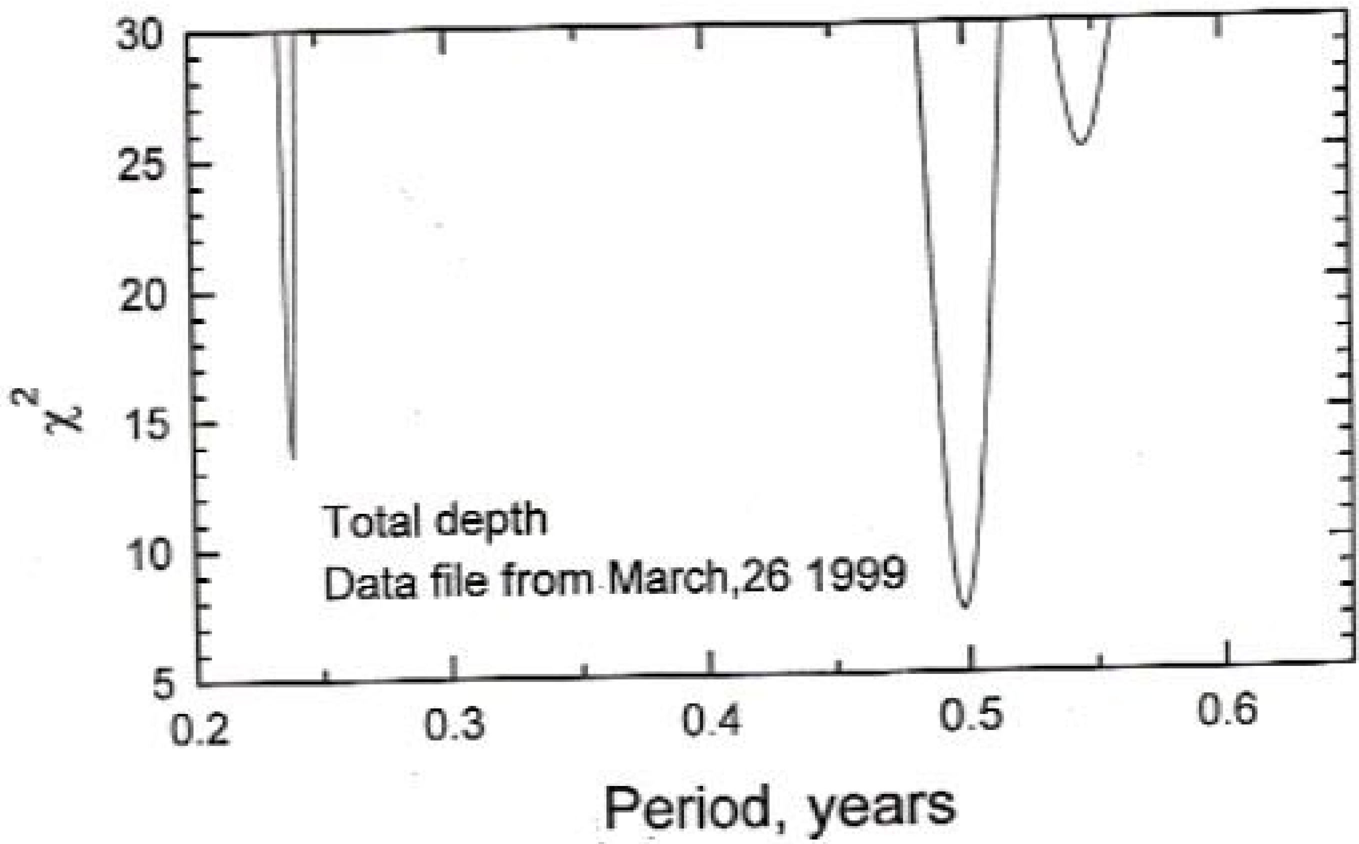
$E_0$-$E_{step}$, eV
0
5
10
15
20
98.1
97.1
94.1
97.2
94.2
96/1
96.2
98.2
94.3
97.3
98.3
1
2
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month



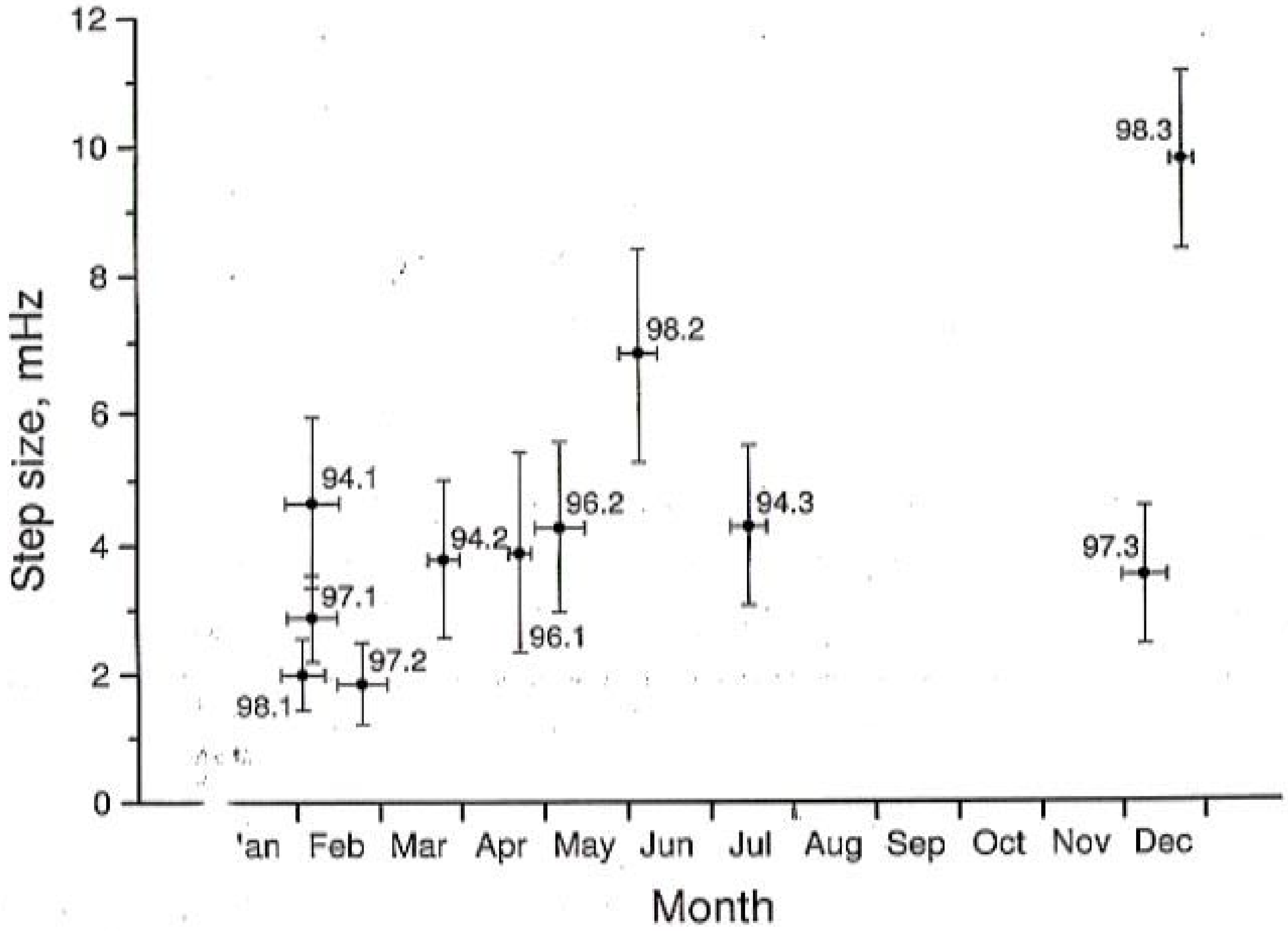
40
30
20
10
0
$\chi^2$
0.00
0.25
0.50
0.75
1.00
Period, years

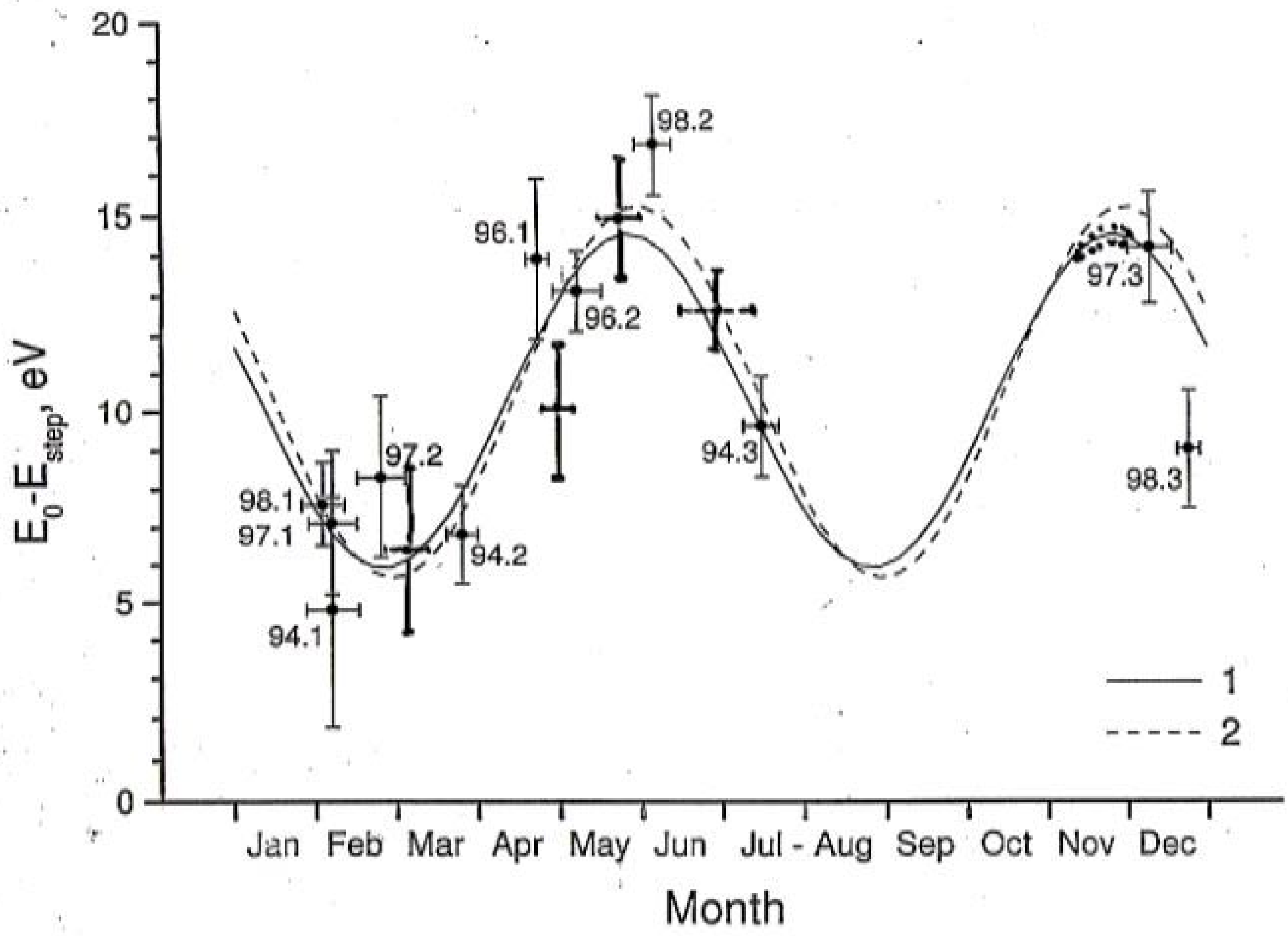


70
60
50
40
30
20
10
$\chi^2$
0
1
2
3
4
5
Period, years
Total depth
Data file from March,26 1999

30
25
20
15
10
5
$\chi^2$
0.2
0.3
0.4
0.5
0.6
Period, years
Total depth
Data file from March,26 1999


Step size, mHz
0
2
4
6
8
10
12
98.1
94.1
97.1
97.2
94.2
96.1
96.2
98.2
94.3
97.3
98.3
'an
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month


E0-Estep, eV
0
5
10
15
20
98.1
97.1
94.1
97.2
94.2
96.1
96.2
98.2
94.3
97.3
98.3
1
2
Jan
Feb
Mar
Apr
May
Jun
Jul - Aug
Sep
Oct
Nov
Dec
Month

# Features of the bump (step) effect.

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

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

Capture of the relic neutrino

$\nu + {}^3H \rightarrow {}^3He + e + Q \qquad \sigma = 0.77 \cdot 10^{-44} cm^2$

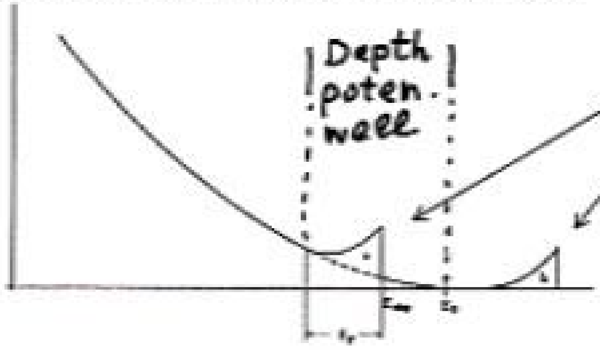
No energy threshold for ν-capture. But!

Branching ratio $10^{-10}$ corresponds to: $0.5 \cdot 10^{15}$ ν/cm$^3$

(average cosmological ~$10^2$ ν/cm$^3$). $\quad N = \frac{8\pi p_F^3}{3h^3}$

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

Differential spectrum of electrons:



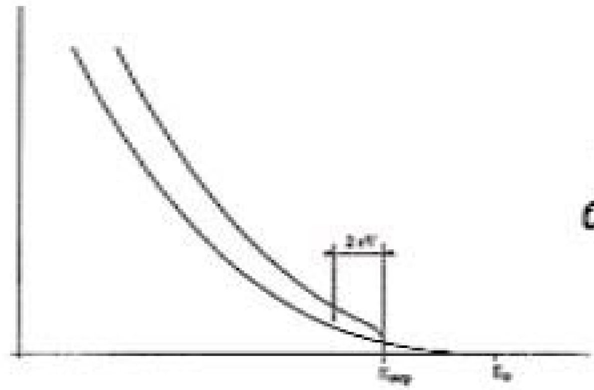

a. $E_0 - E_{st} > 0$ (bound ν)

b. $E_0 - E_{st} < 0$ (free ν)

$E_0 - E_{st} = V - E_F$

Modulation of $E_0 - E_{st}$ may arise from variation of $V$ or $E_F$ or both,

Integral Spectrum:



Modulation period 0.5 year imply the size of ν-cloud ~1÷3 A.U. and couple ν-cloud to Sun. Clustering avoid contradiction with average ν-density.

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

Common sense interpretation ν - are in potential well.

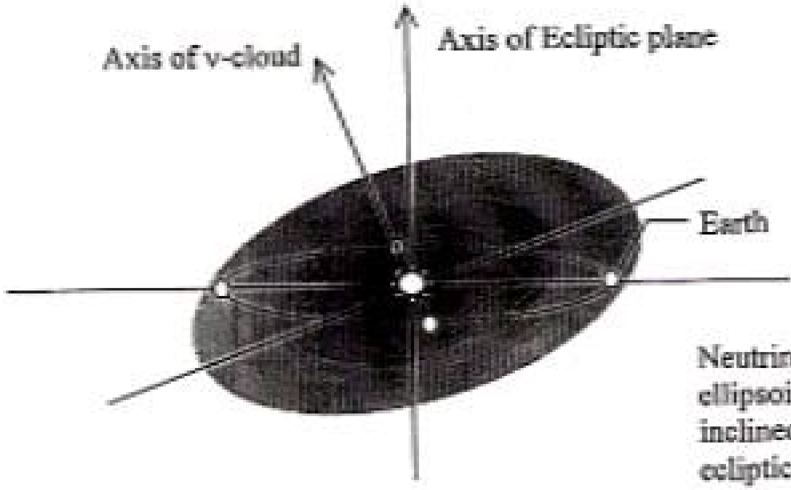
Well depth $E_0 - E_{step} + E_F \approx 20$ eV. ÷ 10 eV

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




Neutrino cloud is a flattered ellipsoid with symmetry axis inclined with respect to ecliptic plane.

Maxima of $E_0 - E_{step}$ 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 $E_\nu$ possible?
- What interaction provides trapping?
- Massless (or small mass) ν?

Theor. attemp Viollier, Marx, Stephenson .... Mc.Kellar Goldman

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

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

| $(E_0 - E_{step}) < 0$ |
|---|

Again contradicts to experiment.

# Shape of β-spectrum near end-point.

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

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

$m_\nu << \varepsilon << E_0$; $\boxed{N(\varepsilon) \sim \varepsilon^2 - m_\nu^2/2;}$

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

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

$m_\nu << \varepsilon << E_0$; $\boxed{N(\varepsilon) \sim \varepsilon^3 - 3\varepsilon m_\nu^2;}$

Maximum sensitivity:

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

# The possible systematic biases for $m_\nu^2$.

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 $E_e$-$E_{Spectr}$.

5. Background energy dependence.
   No dependence in the range 18,600 – 19,600 V within ± 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
   $2 \cdot 10^{-9} \cdot 3 \cdot 10^{2} \cdot 10^{3} \approx 10^{-4}$:

   No effect up to $10^{-1}$ ... $5 \cdot 10^{-2}$ relative abundance.

# The $m_\nu$ problem.

Shape of the β-specrum near end-point.

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

Integral spectrum near end-point

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

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

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

- Efficiency correction

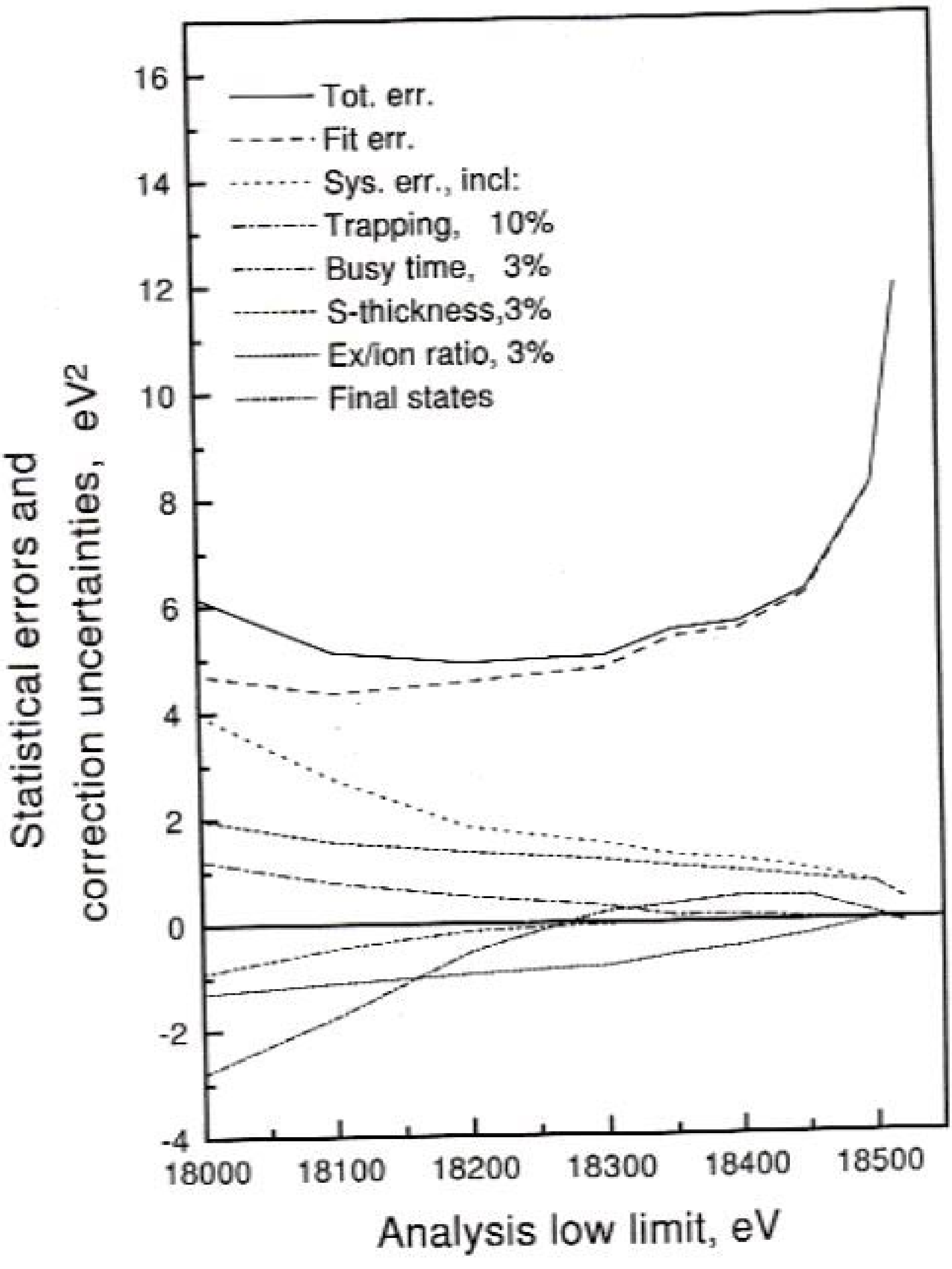
  $A\varepsilon^3(1 + \alpha\varepsilon + \beta\varepsilon^2)$
- Backward scattering

  $A\varepsilon^3(1 + k_b\varepsilon)$
- Trapping effect

  $A\varepsilon^3(1 + k_g\varepsilon)$
- Dead time correction

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

} Dependence of $m_\nu^2$ on $E_{LOW}$



Tot. err.
Fit err.
Sys. err., incl:
Trapping, 10%
Busy time, 3%
S-thickness,3%
Ex/ion ratio, 3%
Final states
Statistical errors and correction uncertainties, eV2
Analysis low limit, eV
16
14
12
10
8
6
4
2
0
-2
-4
18000
18100
18200
18300
18400
18500

# Neutrino mass results.

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

# Conclusion.

- "Troitsk ν-mass" set-up measured end-part of the tritium beta-spectrum during 4.5 years with resolution 3.5÷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÷15 eV with period 0.5 year.
- Main feature of the effect may be <u>phenomenologically</u> 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 $m_\nu < 2.5\ eV/c^2$.
- New facility is needed.

# 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 exited final states. $E_{ex} = 28 \div 35$ eV.
   - Practically possible with differential spectrometer.

4. Shape of the bump:
   - Needs new device.

5. Improvement of $m_\nu$:
   $< 1.5$ 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.