SNO-STR-94-005

Determination of Uranium and Thorium Contamination in the D_2O from the NPMT Spectrum Above 1.4 MeV

W. Frati

February 17, 1994

1 Introduction

The extraction of the U and Th content (actually the ^{208}Tl and and ^{214}Bi content) in the D_2O is discussed for several cases.

1) Only ^{208}Tl and ^{214}Bi are present.

2) The presence of K in the NaCl at the ppb level, with the analysis performed without the assumption of the presence of ^{40}K .

3) The presence of K in the NaCl at the ppm level and including ^{40}K in the analysis.

4) ^{208}Tl , ^{214}Bi and ^{234}Pa .

5) ^{208}Tl , ^{214}Bi , ^{234}Pa and ^{40}K .

The later two analyses are performed to address the disequilibrium question

The presence of signals from the PMT and acrylic are ignored. This will hopefully be the case by taking events in the central 3 meter radius of the D_2O and a using a better fitter to eliminate the PMT $\beta\gamma$ events that reconstruct in the D_2O .

2 Decay Rates

2.1 ^{208}Tl

The ^{232}Th contamination in the D_2O is taken to be:

$$1.0 \times 10^{-15}\text{gm/gm} \rightarrow 1\mu\text{gm}\ ^{232}\text{Th}$$

$$\text{Number }^{232}\text{Th Atoms} = \frac{6\times 10^{23}}{232}\times 10^{-6} = 2.59\times 10^{15}$$

The decay rate is

$$\frac{2.59\times 10^{15}}{\frac{1.4\times 10^{10}}{.693}\times 365} = 351 \text{ decays/day}$$

Only 36% of the ^{232}Th decays proceed to ^{208}Tl , resulting in

$$\boxed{126\ ^{208}\text{Tl}\ \beta\gamma \text{ events/day per } 10^{-15} \text{ gm/gm contamination}}$$

2.2 ^{214}Bi

The ^{238}U contamination in the D_2O is taken to be:

$$2.0\times 10^{-15}\text{gm/gm} \rightarrow 2\mu\text{gm }^{238}\text{U}$$

$$\text{Number }^{238}\text{U Atoms} = 2\times\frac{6\times 10^{23}}{238}\times 10^{-6} = 5.04\times 10^{15}$$

The decay rate is

$$\frac{5.04\times 10^{15}}{\frac{4.5\times 10^{9}}{.693}\times 365} = 2126 \text{ decays/day}$$

Assume only 77% of the ^{214}Bi decays produce enough Cernekov light to be observed (White Book pg 62), then one gets

$$\boxed{1637\ ^{214}\text{Bi}\ \beta\gamma \text{ events/day per } 2\times 10^{-15} \text{ gm/gm contamination}}$$

2.3 ^{40}K

The total K contamination in the 2.5 tonnes of NaCl is taken to be 1 ppb yielding 2.5×10^{-3}gms of K, of which 1.2×10^{-4} is $^{40}\text{K} \rightarrow 3\times 10^{-7}$ gms ^{40}K .

$$\text{Number }^{40}\text{K Atoms} = \frac{6\times 10^{23}}{40}\times (3\times 10^{-7}) = 4.5\times 10^{15}$$

The decay rate is

$$\frac{4.5\times 10^{15}}{\frac{1.4\times 10^{9}}{.693}\times 365} = 6103 \text{ decays/day}$$

$$\boxed{6103\ ^{40}\text{K decays/day per ppb total K contamination in NaCl}}$$

3 Event Rates after Cuts

Two cuts are now applied:

1. Events reconstruct within the central 3 Meter radius of the detector, reducing the event rate for all the decays by a factor of 8.

   ^{208}Tl) 15.8/day = 479/month

   ^{214}Bi) 205/day = 6224/month

   ^{40}K) 763/day = 23204/month

2. Require 14 or more PMT's to fire in a 100 ns window. This reduces the event rate by

   ^{208}Tl) .75 → 356/month

   ^{214}Bi) .287 → 1786/month

   ^{40}K) 3.0×10^{-3} → 71/month

4 Extraction of U and Th Assuming No K

Assuming the shapes of the ^{208}Tl and ^{214}Bi NPMT spectra are known from calibrations a least squares fit is made to one month of data (N_i) with 14 or more PMT's firing.

$$\chi^2 = \sum \frac{[N_i - (\alpha * F + \beta * G)]^2}{N_i}$$

where F and G are the known shapes of the ^{208}Tl and ^{214}Bi spectra and α and β are the extracted number of events. Table I summarizes the results with the data and best fits shown in Fig 1. All the figures use the number of PMT's in a 100 ns window (Nh100) for the energy scale (10 PMT/ 1 MeV).

5 Extraction of U and Th in Presence of K

The analysis of the previous section is repeated, except now the 71 ^{40}K events are included in the data, but not in the analysis. The results are shown in the third column of Table I and the best fits shown in Fig 2. The large systematic shift in the extracted ^{214}Bi and ^{208}Tl signals when the presence of ^{40}K is ignored states that K levels of less than 1 ppb are required if ^{40}K is to be ignored in the analysis. This also points out the systematic sensitivity of this analysis.

TABLE I

U and Th Extraction

	Input	Extracted No K Evts	Extracted With 71 K Evts
^{208}Tl	356	329(69)	267(69)
^{214}Bi	1786	1832(80)	1966(81)
χ^2 /DOF		17.9/24	17.0/24

6 Extraction of U Th and ^{40}K

The previous sections demonstrate the need for ppb levels of K in the NaCl in order to extract the U and Th signals without large systematic errors due to the unknown presence of ^{40}K . This ppb purity level is apparently three orders of magnitude beyond what has been achieved in NaCl purification and only the ppm levels are feasible. This being the case the above analyses are repeated except now the ^{40}K signal in included in the analysis, ie a three parameter extraction is performed with the three parameters being the levels of ^{208}Tl , ^{214}Bi and ^{40}K . ^{208}Tl and^{214}Bi events are generated under the same conditions as the previous sections and the ^{40}K is generated with K at the 0.1 ppm level. Again the analysis is performed for one month of running. It should be pointed out that this is identical to 3 days of running at White Book levels of U and Th and 1.0 ppm of K. The results are presented in TABLE II, and shown in Fig3. The statistical accuracy is much improved by starting the analysis at 18 PMT, running for the 30 days and using equal amounts of Uranium and Thorium as shown in TABLE III.

TABLE II

U Th and 40K Extraction

	Input	Extracted	Ratio Extracted/Input
^{208}Tl	356	281(111)	$0.79 \pm .31$
^{214}Bi	1786	1948(213)	$1.09 \pm .12$
^{40}K	7258	7243(141)	$1.00 \pm .02$
χ^2 /DOF		20.5/23	

7 The Disequilibrium Question

This analysis of the wall shape is critically dependent upon knowing the NPMT shape for the U and Th chains. However in addition to ^{214}Bi and ^{208}Tl in the Uranium and Thorium chains resp, there are ^{234}Pa and ^{228}Ac as well. This would be of no concern if the Uranium and Thorium chains in the D_2O are in equilibrium, since calibrations with a ^{232}Th and ^{238}U source would give the integrated spectrum of all the elements which is all the analysis requires. However due to things like the sticking ability of Thorium and the leaking in and out of Radon, the Uranium and Thorium chains can easily get out of equilibrium, resulting in an unknown ratio of ^{234}Pa and ^{214}Bi in the Uranium chain and an unknown ratio of ^{228}Ac and ^{208}Tl in the Thorium chain. This requires a four parameter analysis, which is an impossibility on an exponential shape and is further exacerbated by the not too different shapes of the ^{234}Pa and ^{214}Bi spectra as shown in Fig 4.

To illustrate this sensitivity, two further analyses were made.

1) Assuming only ^{208}Tl , ^{214}Bi and ^{234}Pa are present.

2) Assuming ^{208}Tl , ^{214}Bi , ^{234}Pa and ^{40}K are present.

To present these analyses in the most favorable light, the input was changed to equal parts of Uranium and Thorium at the 1.0×10^{-14}gm/gm level, 30 days of running and starting the analyses at 18 PMT. The ^{40}K level is 1 ppm grams total K to NaCl. The results are summarized in TABLE IV, with TABLE III showing the reruns of ^{214}Bi , ^{208}Tl and ^{214}Bi , ^{208}Tl and ^{40}K with the new input. Note the deterioration of the statistical accuracy in going from a ^{208}Tl and ^{214}Bi scenario to a ^{208}Tl , ^{214}Bi and ^{234}Pa scenario due to the similarity in the ^{234}Pa and ^{214}Bi spectra. Adding ^{40}K to the input and analysis totally destroys the ability to extract any information since the statistical errors are now comparable to the extracted signal.

TABLE III

U Th 1.0×10^{-14}

1 ppm K/NaCl

30 Day Run

Analysis Starting at 18 NPMT

U and Th Extraction

	Input	Extracted	Ratio Extracted/Input
^{214}Bi	3626	3694(178)	$1.02 \pm .05$
^{208}Tl	2421	2359(174)	$0.97 \pm .07$
χ^2 /DOF		26.5/23	

U Th and K Extraction

	Input	Extracted	Ratio Extracted/Input
^{214}Bi	3626	3862(406)	$1.07 \pm .11$
^{208}Tl	2421	2268(279)	$0.94 \pm .12$
^{40}K	3957	4193(171)	$1.06 \pm .04$
χ^2 /DOF		22.7/23	

TABLE IV

U Th 1.0×10^{-14}
1 ppm K/NaCl
30 Day Run
Analysis Starting at 18 NPMT

U Th and Pa Extraction

	Input	Extracted	Ratio Extracted/Input
^{214}Bi	3626	5139(1510)	1.41 ± .42
^{208}Tl	2421	1708(683)	0.71 ± .28
^{234}Pa	1119	340(836)	0.30 ± .75
χ^2 /DOF		22.7/23	

U Th Pa and K Extraction

	Input	Extracted	Ratio Extracted/Input
^{214}Bi	3626	6497(2302)	1.79 ± .63
^{208}Tl	2421	1185(948)	0.49 ± .39
^{234}Pa	1142	-665(1585)	−.58 ± 1.75
^{40}K	3957	4482(304)	1.13 ± .08
χ^2 /DOF		21.5/22	

8 Conclusion

Extraction of the ^{208}Tl and ^{214}Bi levels in the D_2O by analyzing the shape of the NPMT spectrum in the 1 - 4 MeV region is confronted with three problems.

1) RECONSTRUCTION

At present, using a χ^2 timing fitter, the number of PMT $\beta\gamma$ events that misreconstruct within the central 3 Meters of the detector exceeds the number of events from the U and Th in the D_2O . This hopefully will be taken care of by new fitters under development and was not considered in this report.

2) POTASSIUM

If the level of all K per gm of NaCl exceeds 1 ppm then the wall is dominated by ^{40}K events and extraction of the ^{214}Bi and ^{208}Tl components becomes impossible.
It is possible that other isotopes can have the same effect. ^{36}Cl is being looked into, but if its level is no worse than ^{40}K it should not be a problem.

3) DISEQUILIBRIUM

The presence of ^{234}Pa in an unknown proportion relative to ^{214}Bi destroys the ability to extract meaningful amplitudes. Two possible scenarios can circumvent this problem.
a) The Uranium and Thorium level in the D_2O per se is at the 10^{-15} level and the primary contribution to the ^{208}Tl and ^{214}Bi is from Radon leaking into the D_2O circulation system. This eliminates ^{234}Pa and ^{228}Ac from the chains reducing the analysis to the extraction of ^{214}Bi , ^{208}Tl and ^{40}K .
b) Again a 10^{-15} level of U and Th in the D_2O per se but the primary contribution coming from Thorium sticking to whatever. This would cause the Thorium chain via ^{238}Th to dominate over the Uranium chain (^{230}Th is stopped by the long lived ^{226}Ra) and the structure of the ^{208}Tl would manifest itself, making it simpler to extract.

Figure

93/10/19 1

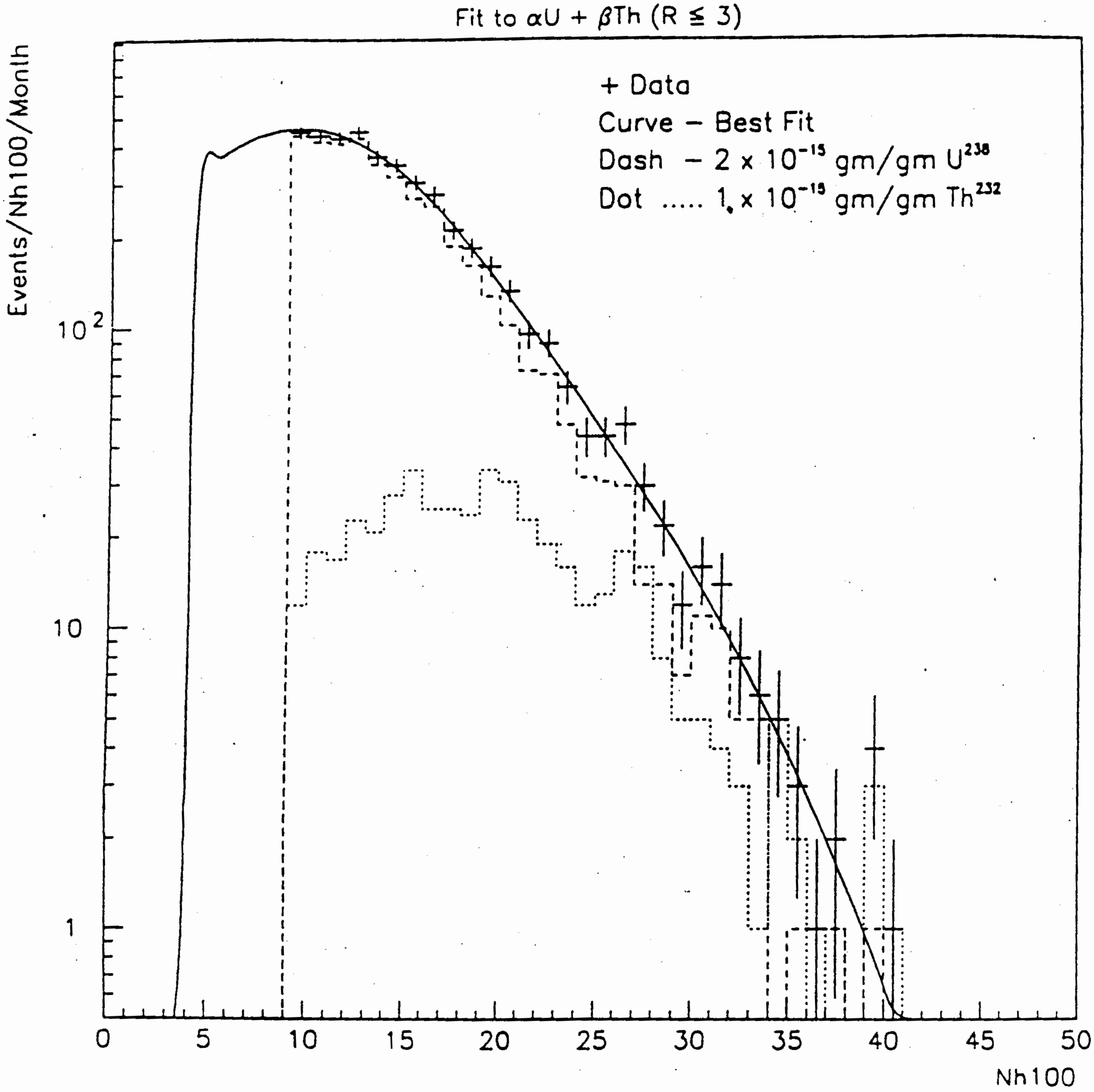

Fig 1

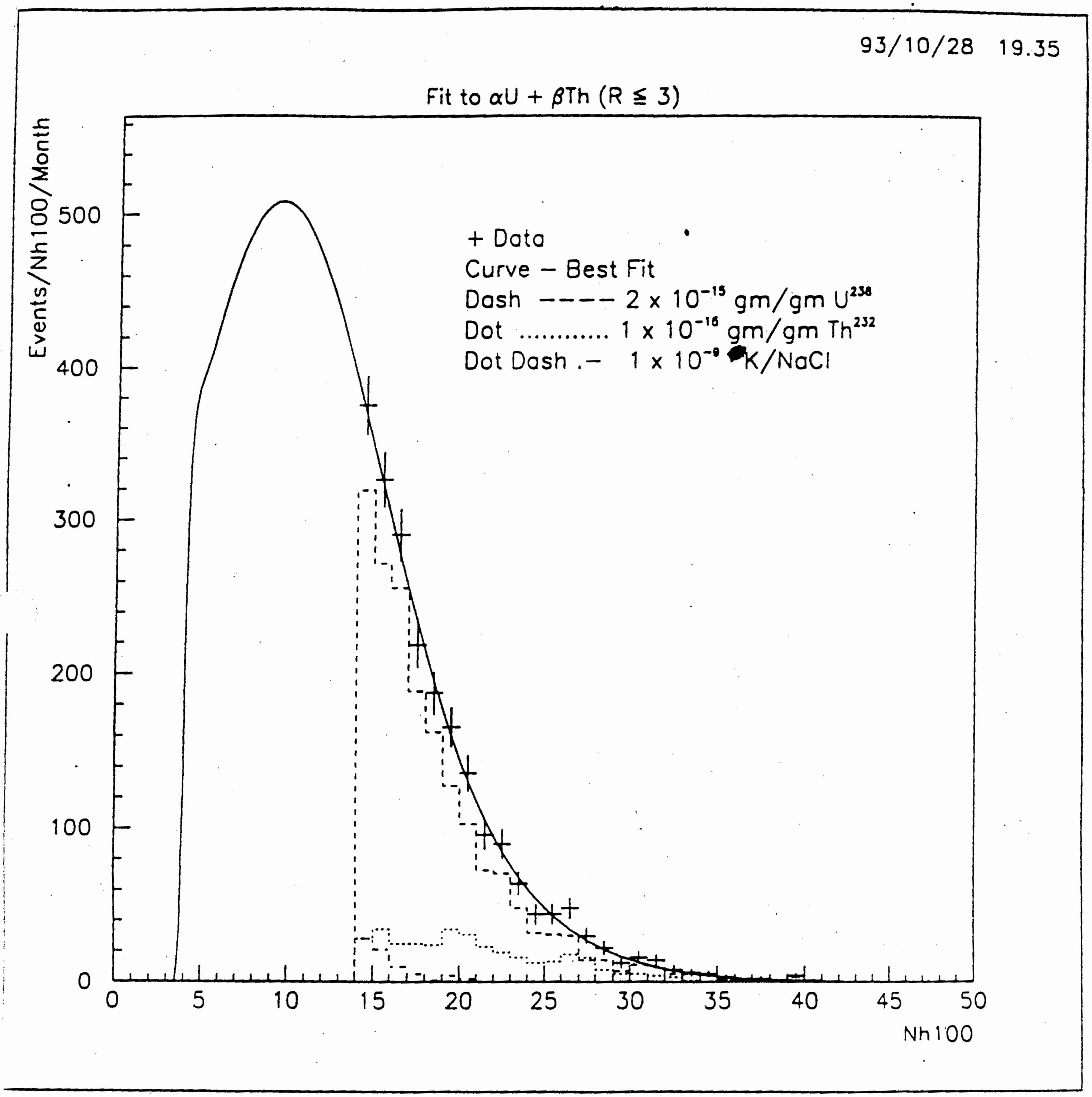
93/10/28 19.35
Fit to αU + βTh (R ≦ 3)
Events/Nh100/Month
0
100
200
300
400
500
0
5
10
15
20
25
30
35
40
45
50
Nh100
+ Data
Curve – Best Fit
Dash ---- 2 x 10⁻¹⁵ gm/gm U²³⁸
Dot .... 1 x 10⁻¹⁶ gm/gm Th²³²
Dot Dash .– 1 x 10⁻⁹ K/NaCl

Fig 2
(Linear)

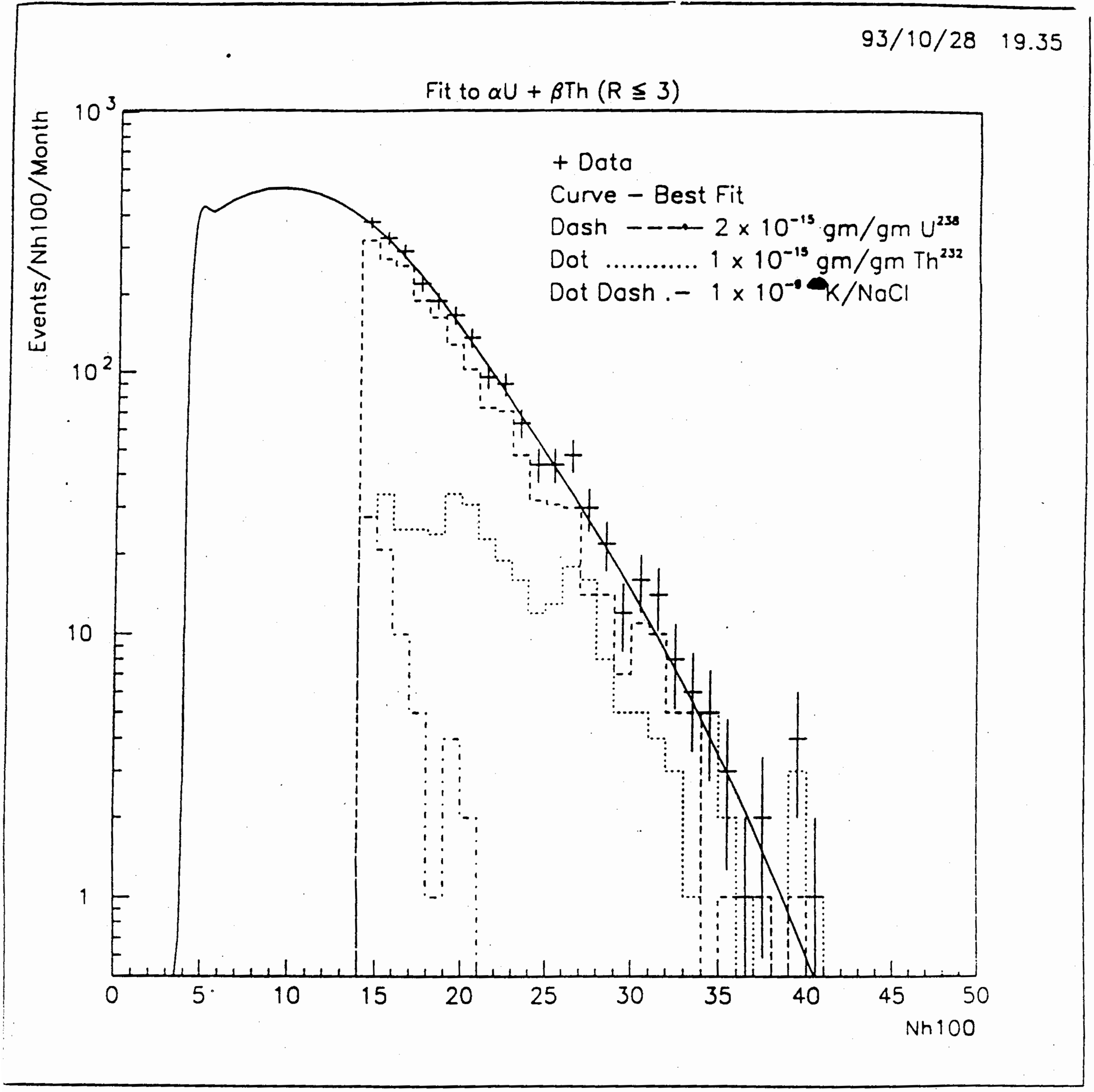
93/10/28 19.35
Fit to αU + βTh (R ≦ 3)
Events/Nh100/Month
10^3
10^2
10
1
+ Data
Curve – Best Fit
Dash ———— 2 x 10^{-15} gm/gm U^{238}
Dot .... 1 x 10^{-15} gm/gm Th^{232}
Dot Dash .– 1 x 10^{-9} K/NaCl
0
5
10
15
20
25
30
35
40
45
50
Nh100

Fig 2
(Log)

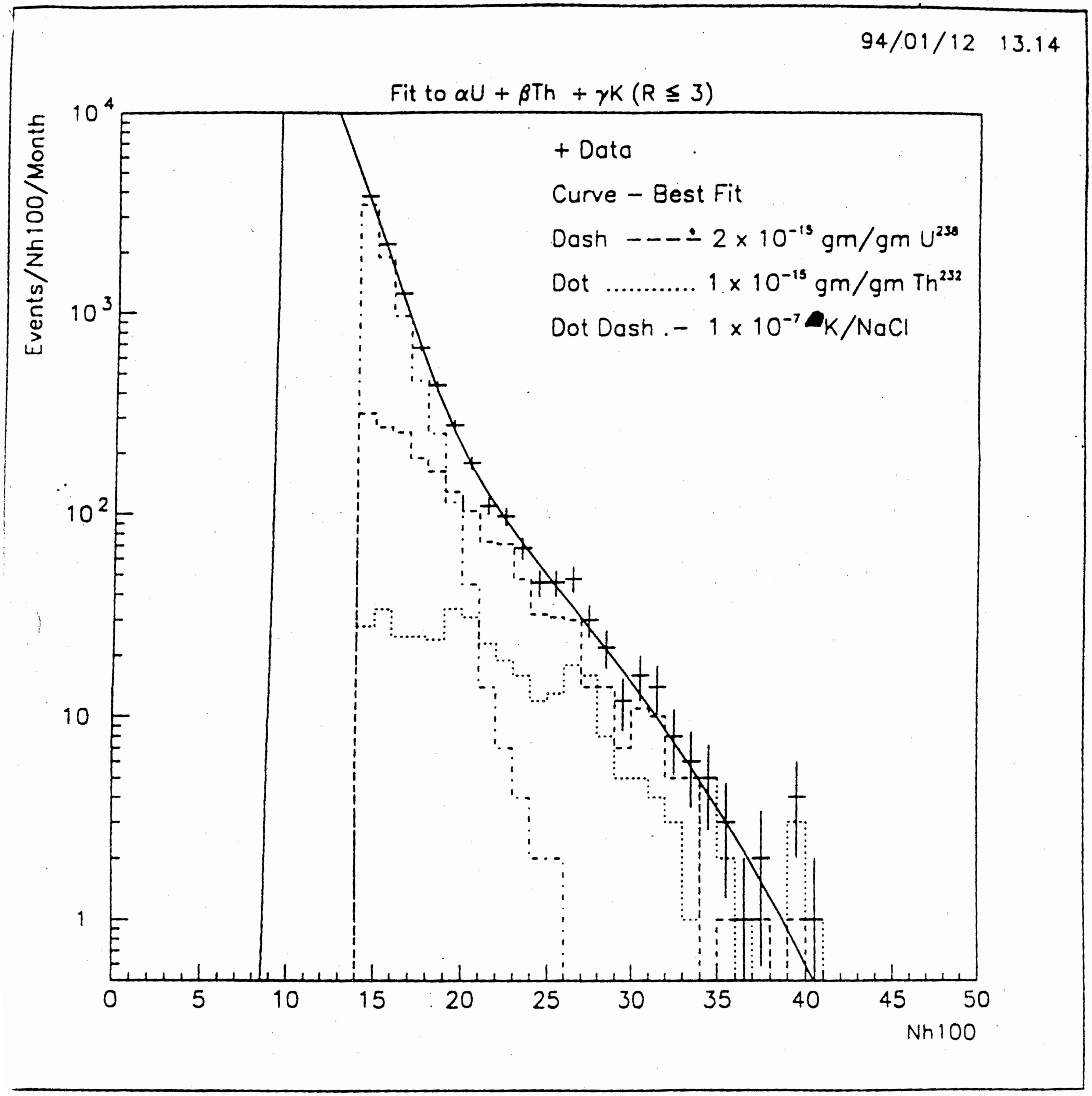
94/01/12 13.14
Fit to αU + βTh + γK (R ≦ 3)
Events/Nh100/Month
10^4
10^3
10^2
10
1
+ Data
Curve – Best Fit
Dash ---- 2 x 10^-15 gm/gm U^238
Dot .... 1 x 10^-15 gm/gm Th^232
Dot Dash .– 1 x 10^-7 K/NaCl
0
5
10
15
20
25
30
35
40
45
50
Nh100

Fig 3
(Log)

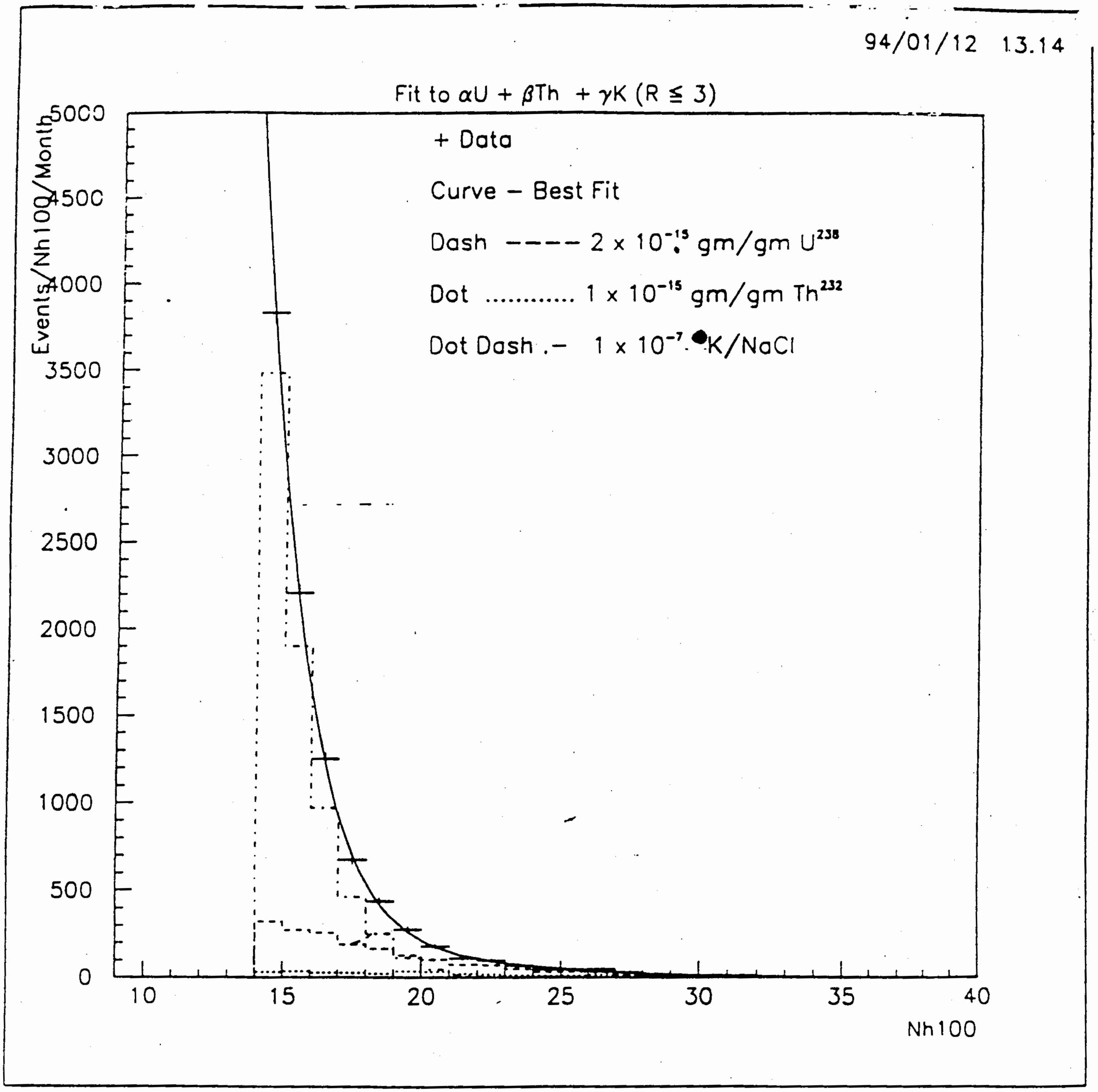
94/01/12 13.14
Fit to αU + βTh + γK (R ≤ 3)
+ Data
Curve – Best Fit
Dash ---- 2 x 10^-15 gm/gm U^238
Dot .... 1 x 10^-15 gm/gm Th^232
Dot Dash .– 1 x 10^-7 K/NaCl
Events/Nh100/Month
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
10
15
20
25
30
35
40
Nh100

Fig 3

(Linear)

94/02/09 10.24

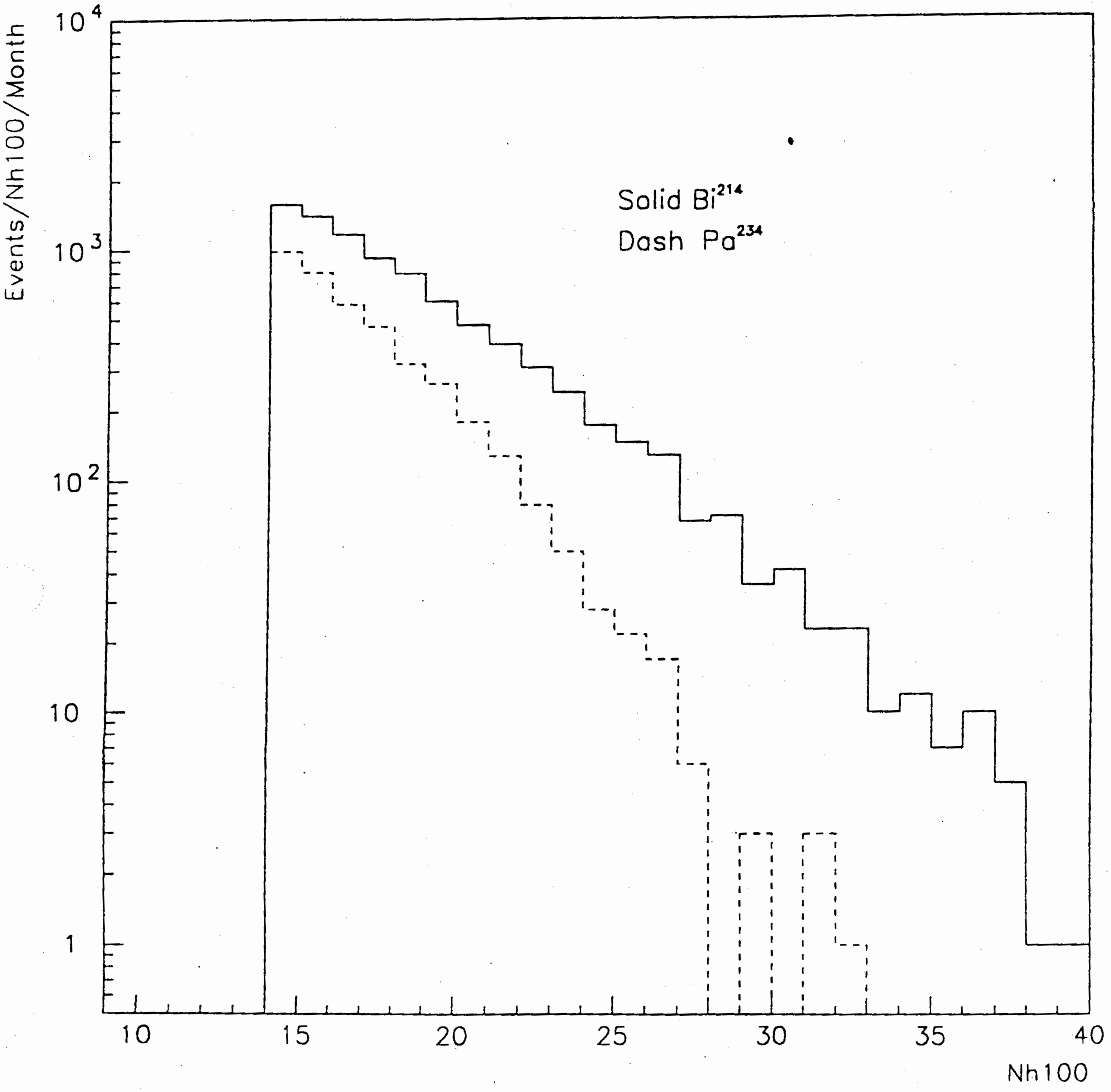

Fig 4 (Log)

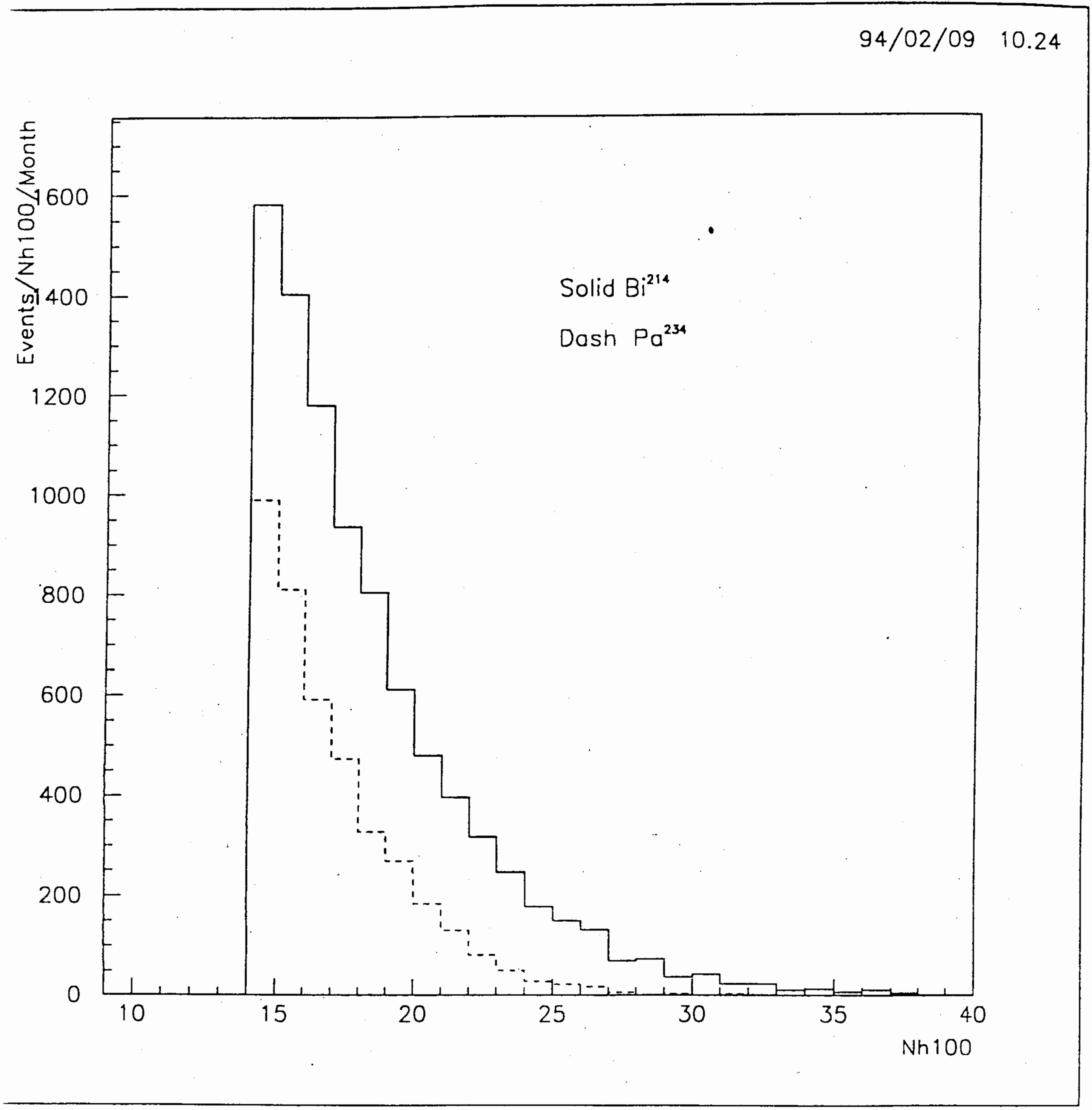
94/02/09 10.24
Events/Nh100/Month
0
200
400
600
800
1000
1200
1400
1600
10
15
20
25
30
35
40
Nh100
Solid Bi^{214}
Dash Pa^{234}

Fig 4 (Linear)