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NEUTRON FREE GAMMA RAY CALIBRATION SOURCES

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Recent tests addressing the feasiblity of using ^{16}N and ^{24}Na for γ ray calibration sources are presented. Two other possibilities using ^{3}H(p,γ)^{4}He and ^{7}Li(α,γ)^{11}B reactions are briefly discussed.

1 ^{16}N

^{16}N has a 7.13 sec half life, with two principal decay modes
a) 68% β^-(4.27 MeV) + γ(6.13 MeV)
b) 29% β^-(10.4 MeV)
Because of its long half life, the ^{16}N can be produced with a neutron source irradiating a liquid target that is far removed ($\approx$ 50 meters) and well shielded from the SNO detector and then pumped to the detector with sufficient velocity to reach the detector within a few ^{16}N half lives. This procedure has been tested with two reactions, ^{16}O(n,p)^{16}N and ^{19}F(n,α)^{16}N .

1.1 ^{16}O(n,p)^{16}N

Fig 1 shows the cross section for the ^{16}O(n,p)^{16}N reaction as a function of neutron energy. The reaction has a threshold of 10.5 MeV from which the cross section rises rapidly to 80 mb just below 12 MeV. A 12 MeV neutron flux of 5×10^5/sec was produced at the Queens University Van de Graaff with a 3 MeV ^{3}He beam striking a boron target. The neutrons irradiated a 2" thick water target, producing about 1000 ^{16}N /sec. The water was pumped via a 75 foot, 1/2" diameter hose to an annular NaI crystal (12" Diameter, 3" hole, 12" long) at the rate of 1.9 Gallons/minute. The transit time from neutron target to NaI crystal was 25 seconds. Figure 2 overlays the observed energy spectrum with the pump on and off. The counting rate in the peak is about 5/sec which agrees well with the calculated value.

To initiate the ^{16}O(n,p)^{16}N reaction in the mine one can use either a commercial

DT generator such as used by oil companies for exploration of oil deposits or a ^{252}Cf source. A DT generator generates 14 MeV neutrons and is easily capable of fluxes up to 10^7 neutrons/sec. MP Physics Corporation has quoted a price of $60,000 for such a generator. A ^{252}Cf source costs about $1000.

For purposes of comparing the various methods of generating ^{16}N in the mine, the following assumptions are made. Turbulent flow through a 1" diameter hoses over a distance D between the neutron source and detector. 1" diameter plastic pipe extending down 17 meters (5 meter neck plus 12 meters to the bottom of the of the acrylic vessel) into the detector plus another 17 meters back and a 2" diameter return hose to the neutron source. Table I lists some pumping parameters and 6.13 MeV γ counting rates, for various neutron source to D_2O distances, pumping rates and production cross sections, assuming a neutron source of 10^5/sec embedded in an 11 cm thick target. This is the optimum thickness for a target assuming the total neutron cross section is 1.5 barns. Making the target any thicker only dilutes the density of ^{16}N atoms. The 40 mb cross section used in TABLE I is assuming a DT generator. The .040 mb is for a ^{252}Cf source which has the thermal neutron energy spectrum shown in Fig 1. Also displayed in this figure are the $^{16}O(n,p)^{16}N$ cross section and the integrated product of the ^{252}Cf yield and the ^{16}O cross section which levels out to 0.040 mb.

TABLE I shows that with a DT generator, the γ rate is 30/sec at the low neutron flux of 10^5/sec and a separation of 50 meters. The pumping rates and pressure drops are all quite reasonable and easily achieved. To use a ^{252}Cf source and achieve a counting rate approaching 1/sec, one would have to increase the source strength by an order of magnitude (10^6 neutrons/sec = 0.23 mCi) and move the source to within 25 meters of the center of the detector. A 0.23 mCi ^{252}Cf source is about the upper limit for easy and inexpensive shipping and handling.

1.2 $^{19}F(n,\alpha)^{16}N$

The compound initially proposed for the ^{19}F target is perflouro-dimethylcyclohexane (C8F16), a non corrosive fluid that costs $450/liter in 0.10 liter quantities. It has a 1.3000 index of refraction and a density of 1.8. Inquiries were made to Aldrich Chemical about the availability and properties of this compound. The largest quantity

they would commit themselves to is 15 liters which would be delivered over a one year period. The limits this quantity and price imposes are discussed below. Also they did not know the coefficient of viscosity, but conveyed the information that it pours like water and is not viscous.

To initiate a quick and cheap test, NaF dissolved in water (4 gms/liter) was substituted for the C8F16, and an available Pu-Be neutron source (10^6 neutrons/sec) was used to initiate the reaction. The integrated product of yield times cross section is 70 mb, which is of course diluted by the 4% concentration of NaF. A pumping system similar to the one used for the $^{16}O(n,p)^{16}N$ Van de Graaff run was set up at Penn. Here the NaF solution was pumped through 50 feet of 1/4" hose at the rate of 0.3 Gallons/minute to an annular NaI crystal (9.5" diameter, 2.5" hole, 10" long). Fig 3 overlays the results with the pump on and off. Fig 4 displays the subtraction of the two. A clear signal is observed around 6 MeV at a rate of 0.25 counts/second, in reasonable agreement with what is predicted. The $^{19}F(n,\alpha)^{16}N$ cross section as a function of neutron energy is shown in Fig 5 along with the integrated product of the cross section times the ^{252}Cf neutron yield which levels out at 16 mb. For this reaction a DT generator offers no advantage over a ^{252}Cf source since the cross section for a 14 MeV neutron increases to only 24 mb from the 16 mb for the ^{252}Cf source.

The total volume of fluid used for the ^{16}N configuration is 150 liters of which 100 is in the return hose. The 15 liter limit on the availability of C8F16 (as well as its $7000 price tag) dictates that the source-D_2O distance, hose and pipe sizes be reduced to 30 meters, 0.5" and 0.5" resp. With this configuration the counting rate would be 10/sec using a 10^5 neutrons/sec ^{252}Cf source. The parameters are listed in TABLE I.

1.3 MC Studies

The option exists to make the piping in the D_2O opaque to eliminate the Cerenkov radiation from the electrons with the resulting signal coming only from the monoenergetic 6.13 MeV γ or to make it transparent resulting in a higher energy calibration but one that is more complex and hence requiring a MC to unscramble the three types (3γ, 3 and γ) of events. The opaque option has the further advantage that reconstruction algorithms can be tested since the Cerenkov radiation is known to originate from a

single γ of a known energy.

Fig 6 presents a MC simulation of the energy spectrum (in PMT units. 10 PMT/MeV) of the 6.13 MeV γ and the 4.27 MeV β along with their convolution. Should the piping be transparent then the calibration runs would yield the weighted sum of the $\beta\gamma$ convolution and the pure 10.4 MeV β with no separation possible on an event by event basis. Fig 7 shows the energy spectrum of weighted sum of the convoluted $\beta\gamma$ and the 10.4 MeV electron.

1.4 Possible Installations

Three methods of placing the ^{16}N source into the D_2O have been suggested.
1) Lowering a 20 cm diameter ball into the center of the detector using flexible tubing, and placing sonic position monitors on the ball.
2) Same as above but instead of flexible tubing use a helical tube to feed the ball, which would be stretched like a "slinky" to be lowered into the tank.
3) Install 1" plastic tubing down to the bottom of the acrylic vessel and back and leave it there until removal is required when the neutron detectors are installed. So as not to take up valuable real estate at the center of the neck, the piping could be attached off center to the neck itself. This has several nice features.

- (a) No need for mechanical insertion and removal at every calibration run. A run is initiated by simply turning on a pump and a high voltage supply should we use a DT generator.
- (b) No sonic sensors required to determine the position of the source. The position is surveyed in once and for all.
- (c) The calibration as a function of position in the tank comes out automatically in one run without having to move the source.
- (d) This calibration can be performed simultaneously with the laser ball.

Of course if the ^{19}F compound is used with the permanent installation then its radioactive purity has to be determined.

2 ^{24}Na

2.1 Test Run

^{24}Na has a 15 hour half life and simultaneously emits two gamma rays with energies of 1.37 and 2.74 MeV. Thus it can serve a purpose in addition to an energy calibration, namely a fair simulation of the $\beta\gamma$ background, (with the Compton electron from the 1.37 MeV γ mimicking the betas) offering the opportunity to make an empirical study of such events.

^{24}Na is easily produced via an $^{23}Na(n,\gamma)$ reaction with a cross section of 0.2 mb for all neutron energies above 1 MeV. At lower neutron energies down to .007 MeV the cross section gets as high as 1 mb (Fig 8).

A cylinder of table salt (1" diameter, 10" long) was placed next to a Pu-Be source (10^6 neutrons/sec) for a 24 hour period. The salt was then placed the annular NaI crystal used for the ^{19}F tests described above. Fig 9 displays the energy spectra of 5 minute runs before and after the salt was placed in the crystal. (The peaks at 2.64 and 3.2 MeV before the salt was inserted in the NaI is from Thorium contamination in the crystal) Fig 10 shows the background subtracted result. The peak in channel 125 at 4.1 MeV represents the detection of both gamma rays. The peak in channel 85 at 2.74 MeV is where the 1.37 MeV gamma ray escapes the crystal. The counting rate including the 2.74 MeV peak is about 100/second. Thus a weak neutron source of 10^4 neutrons/sec embedded in a 10 cm diameter ball of salt will easily yield an event rate of tens/second.

2.2 Monte Carlo Studies

Since the 4.1 MeV is distributed between two γ rays, the number of Cerenkov photons generated will be considerably less than that of a 4.1 MeV electron. Fig 11 shows the PMT distribution for 1.37, 2.75 MeV γ rays and the convolution of the two. The peak occurs at 22 PMT's corresponding to a 2.0 MeV electron. (A 4.1 MeV electron peaks at 46 PMT's firing in a 100 ns window) Further, to ensure full trigger efficiency at 12 PMT's one will have to set the trigger threshold at 10 PMT's. At this PMT level, the system will trigger on PMT noise and (PMT + acrylic + internal) $\beta\gamma$.

Should the PMT noise rate be at the advertised level of 1000 Hz then the trigger rate just from 10 random firings within the 100 ns triggering window is $\approx$ 10/sec. and drops rapidly with increasing PMT's as shown in Fig 12. This is marginal at best and should the noise rate be 1500 Hz, the trigger rate will increase to the unacceptable level of over 100/sec. To avoid this problem (as well as the PMT $\beta\gamma$ discussed below) the source will have to centered in the detector an the trigger window narrowed. Fig 13 shows the random trigger rate as a function of PMT number for a trigger window of 20 ns, something that can easily be done in hardware or software. Now even if the PMT singles rate is as high as 3000 Hz the trigger rate will be less than 1/sec at the 10 PMT level.

The internal and acrylic $\beta\gamma$ present no problem. The Uranium decay rate from a 10^{-14} gm/gm contamination in a 9 meter radius of light and heavy water is 0.5/sec. The decay rate from a 4×10^{-12} gm/gm contamination in 40 tons of acrylic is 2/sec. Thus the PMT $\beta\gamma$ are the only competitive reaction. 100μg of U per PMT of which 1/2 the decays occur in front of the PMT's, results in 6000 U decays/sec from the 0.5 gms of Uranium in 10,000 PMT's. Thus a four order of magnitude decrease is required to bring the trigger rate down to the 1/sec level.

Here it is proposed to take advantage of the ^{24}Na source being in the center of the detector and requiring the PMT's to fire within a 20 ns window in *real* time and further require that the ratio of the number of PMT's in a 20 ns window to that in a 100 ns window be greater than 0.8. Fig 14 shows the *raw* trigger timing of the PMT's for Thorium $\beta\gamma$ from the PMT's and a Th source (aka ^{24}Na) at the center. (Even though it is the Uranium that contributes chiefly to the counting rate, it is the Thorium $\beta\gamma$ that are used to present a worst case scenario, since its energy is greater than that of U.) A $\pm$ 5 ns wobble is inserted in the raw timing to allow for variations in the cable length. Fig 14 shows that the PMT timing from PMT $\beta\gamma$'s is spread out considerably more than that from a source at the center of the detector. Fig 15 shows the event distribution as a function of PMT number for both cases (PMT and central source) when a 20 ns window is applied for 10000 Th $\beta\gamma$ events. Requiring 10 or more PMT's results in 9529 (165) triggers for the central source (PMT's). Fig 16(17) displays the ratio of the number of PMT's in the 20 ns window relative the the number in a 100 ns window for a central (PMT) Th $\beta\gamma$. Requiring this ratio to be greater than 0.8 results

in 7682 (1) triggers surviving out of the original 10.000. Thus a trigger requiring 10 PMT's in a 20 ns window coupled with the requirement that the 20ns/100ns ratio be greater than 0.8 reduces the trigger rate from the PMT $\beta\gamma$ to the order of 1/sec while still retaining a 75% trigger efficiency for a source at the center of the detector. Keep in mind this is without any reconstruction being applied, but only two conditions that can easily be applied in the hardware or software part of the trigger.

Applying the 20 ns window and 20ns/100ns ratio requirements to a uniform distribution of $\beta\gamma$ over a 3 meter radius reduces the 75% efficiency to 50% as shown in Fig 18.

3 ^{3}H(p,γ)^{4}He

Once the use of a DT generator to produce ^{16}N is admitted to, then the possibility arises of replacing the deuterium with hydrogen and using a ^{3}H(p,γ)^{4}He reaction to generate a 20 MeV γ . MP Physics is investigating to what extent the two generators can be combined. While the DT generator runs at 100 keV the PT generator would probably operate at a lower voltage since it has to be lowered into the detector. We could run as low as 20 keV, where the ^{3}H(p,γ)^{4}He cross section is 63 nb. A 10 μamp beam would result in 1.6 γ /sec. If we can run at higher voltages, so much the better since the cross section increases with voltage. The technical problems to be investigated are:

1) Keeping the deuterium content of the hydrogen down to prevent neutron production.
2) Inserting the source ($\approx$1 foot long and 1" diameter) and the cable supplying the 20 keV accelerator voltage into the D_2O .

4 $^{7}\mathbf{Li}(\alpha,\gamma)^{11}\mathbf{B}$

The $^{7}Li(\alpha,\gamma)^{11}B$ reaction would take advantage of a strong capture resonance at an α energy of 2.6 MeV to produce a 10.6 MeV γ . The γ rate is 120/sec per Curie of α activity. This scheme needs the most study of the ones presented here.

- The levels of low atomic number nuclei are to be less than 10^{-3} because of their copious neutron production.
- The energy of the α must be less than 4.2 MeV to be below neutron production threshhold. This requires the use of ^{148}Gd which emits a 3.0 MeV α. Unfortunately the worlds supply is only a few hundred μCi. Degrading the α's from a higher energy α emitter is a possibility.

TABLE I

^{16}N

D Src→D_2O meters	Tgt	$Y\sigma$ mb	Time Src→D_2O sec	Pump Rate Gal/min	Event Rate 1/sec	Pressure Hose+D_2O psi
50	^{16}O	40.0	25	17.5	30	14+10
75	^{16}O	40.0	48	13.1	3	13+6
25	^{16}O	.040	13	18.5	0.10	7+10
30*	^{19}F	16	22.7	2.6	10	8+9+8 †

* All hoses and pipes reduced to 0.5 inch

$$Y\sigma = \int \sigma(E)\frac{dN}{dE}_{Source} dE$$

Neutron Flux: 10^5 neutrons/sec

Pressure: The two numbers show the pressure drop in the Source to D_2O hose and D_2O pipe separately.

†Assuming viscosity of water. The third number is the pressure drop in the return hose

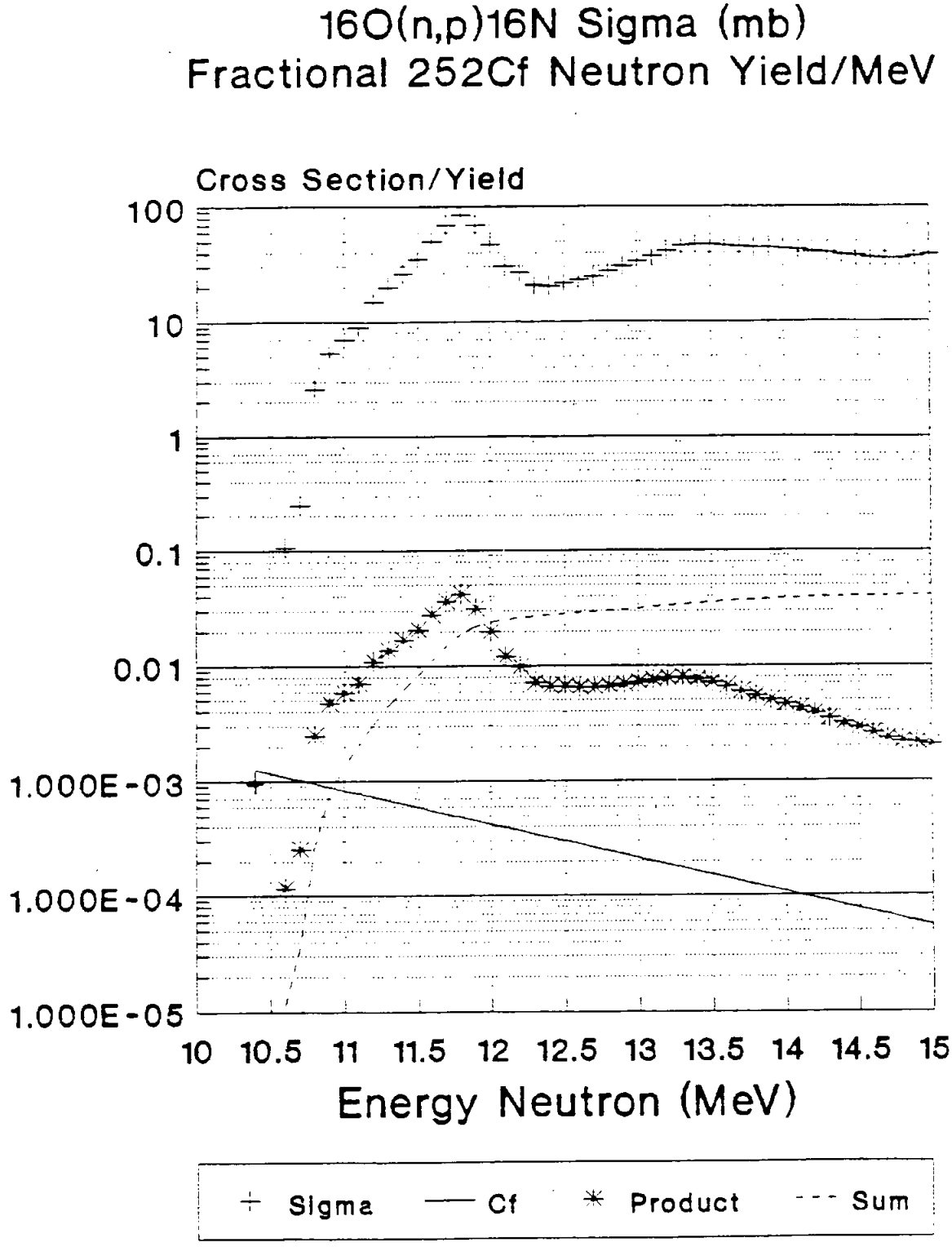
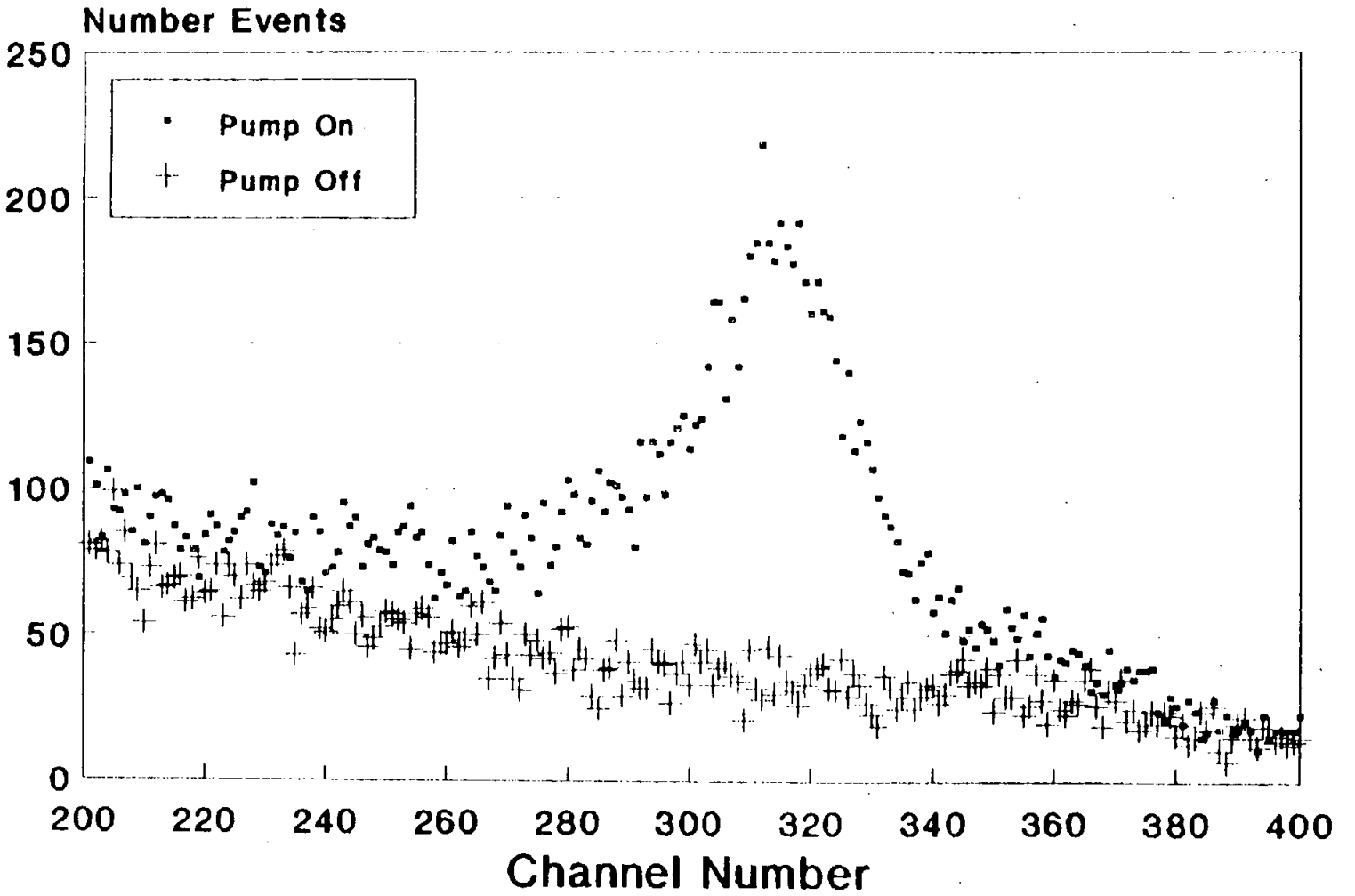

16O(n,p)16N Sigma (mb)
Fractional 252Cf Neutron Yield/MeV
Cross Section/Yield
100
10
1
0.1
0.01
1.000E-03
1.000E-04
1.000E-05
10
10.5
11
11.5
12
12.5
13
13.5
14
14.5
15
Energy Neutron (MeV)
Sigma
Cf
Product
Sum

Fig. 1

16O(n,p)16N


Number Events
250
200
150
100
50
0
Pump On
Pump Off
200
220
240
260
280
300
320
340
360
380
400
Channel Number

Fi

NaF Run 1

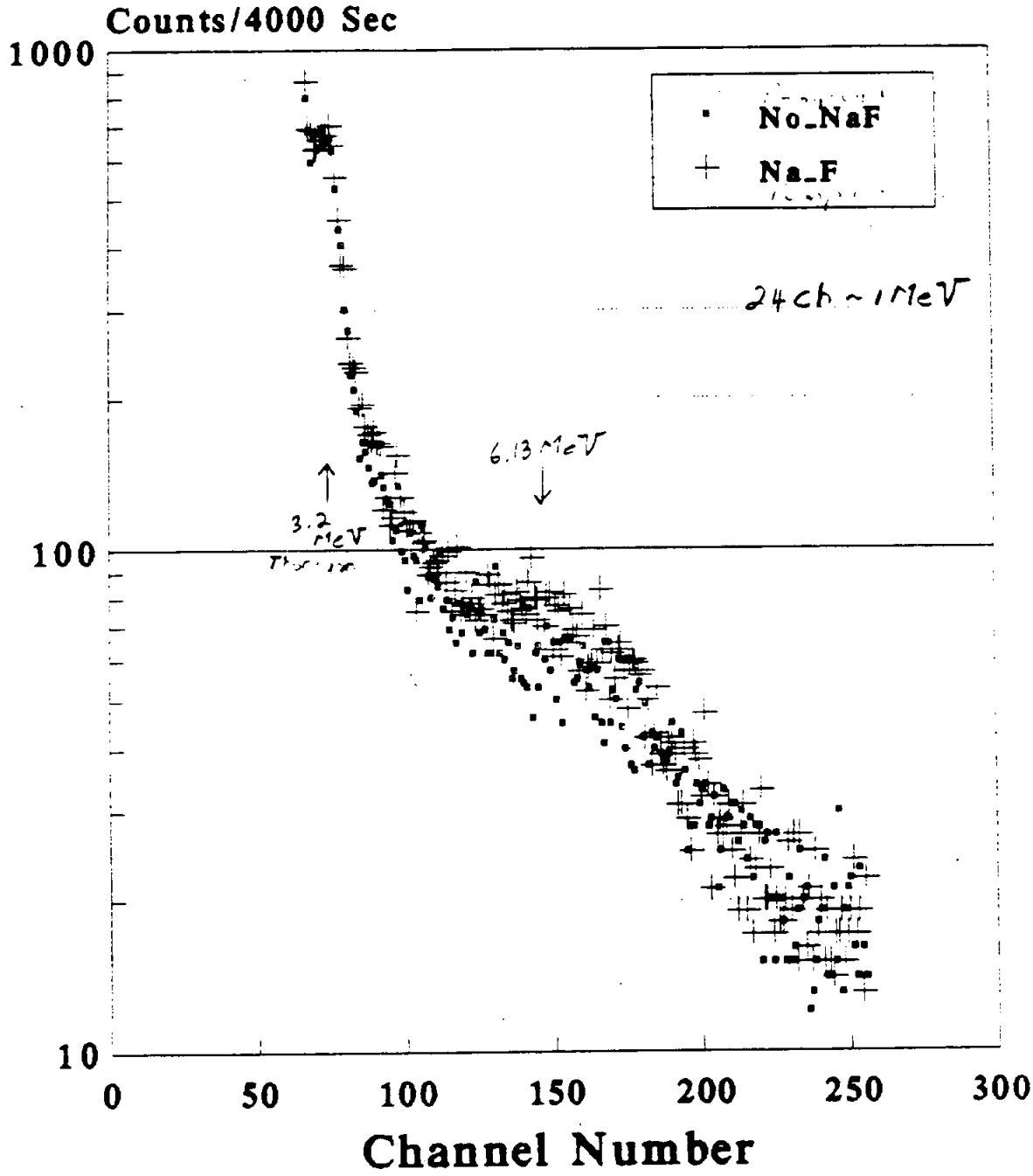


Fig. 3

NaF Set 1

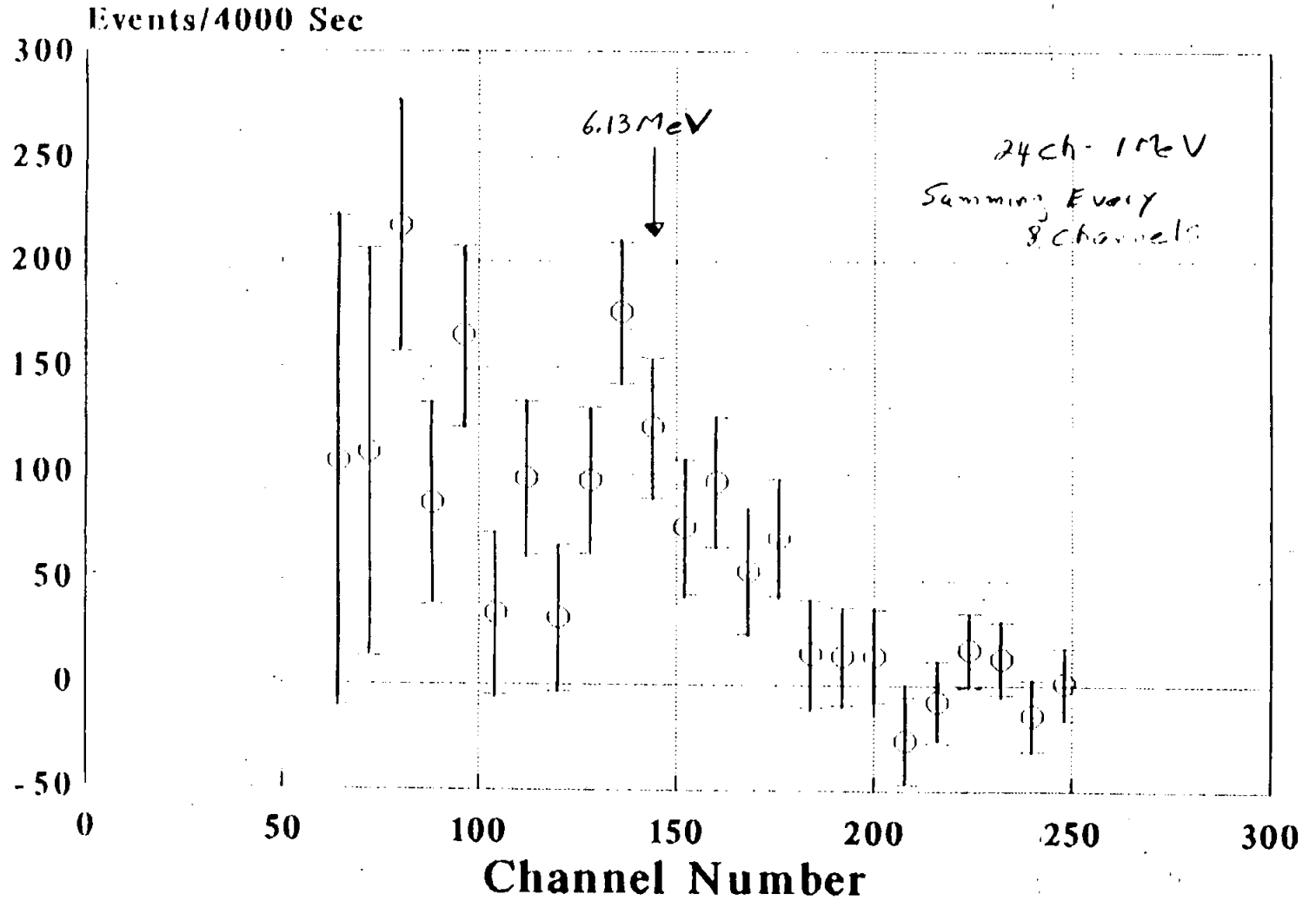


Fig. 4

19F(n,alpha)16N

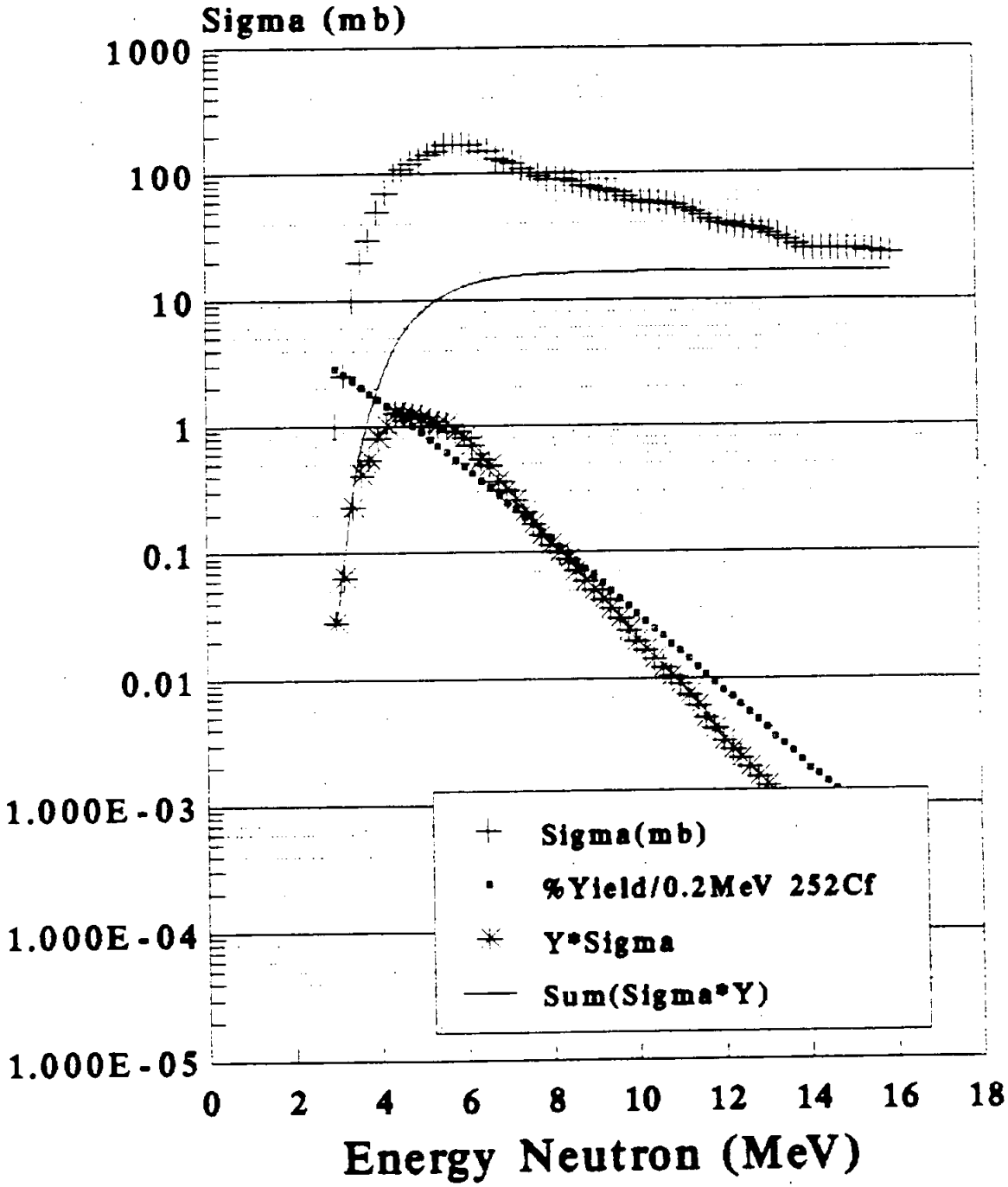


Fig. 5

92/04/28 15.40

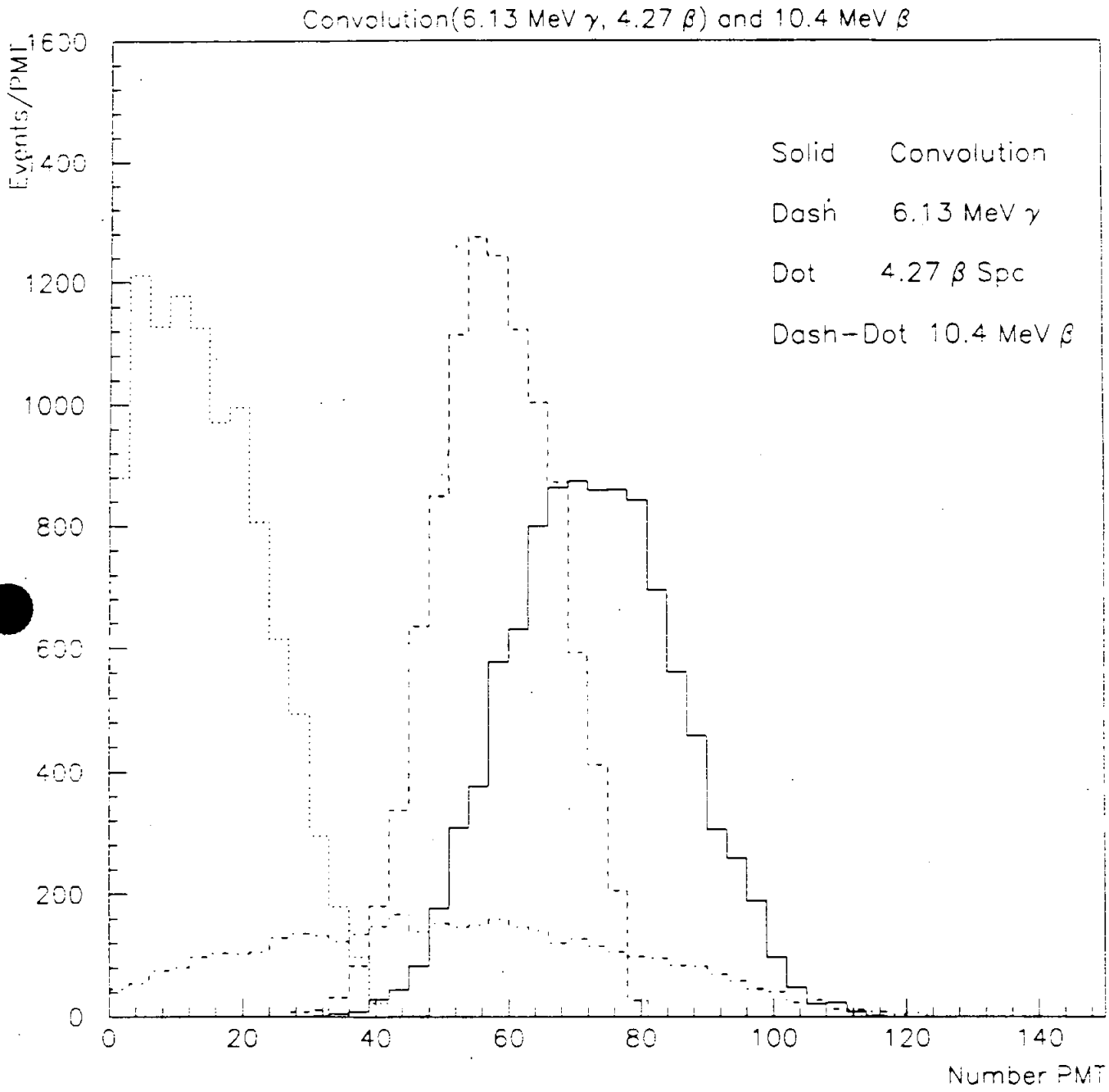


Fig. 6

92/04/28 15.40

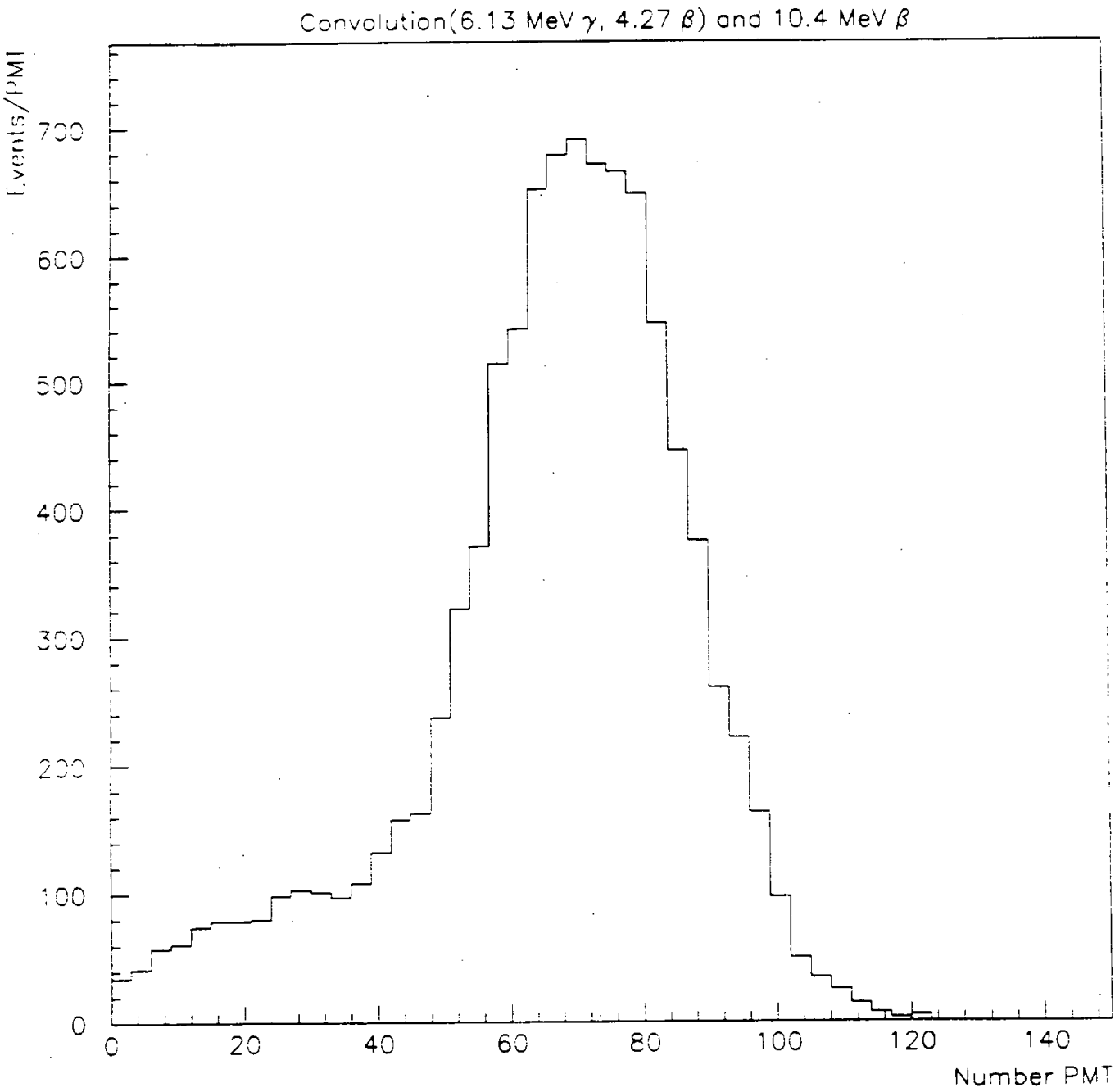


Fig. 7

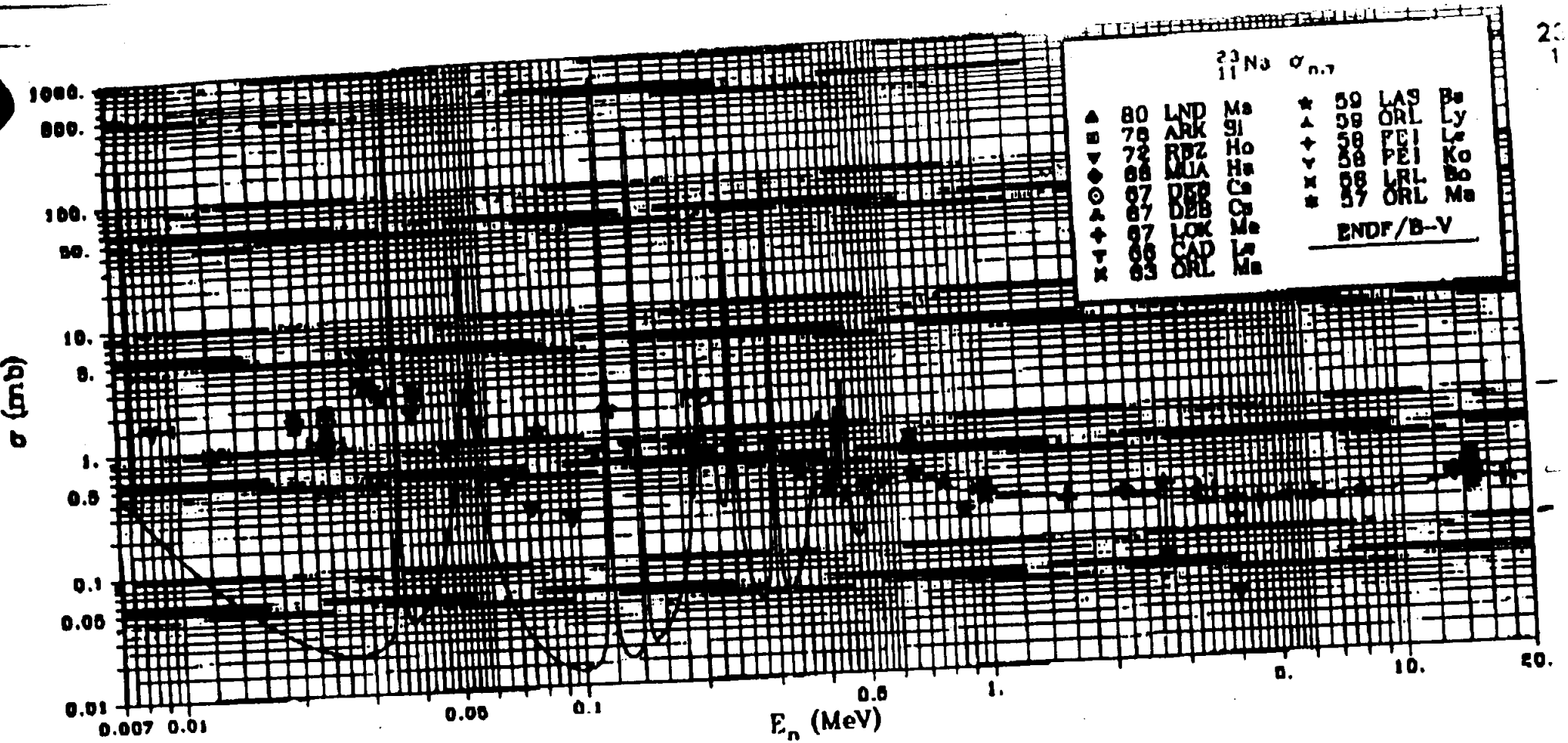
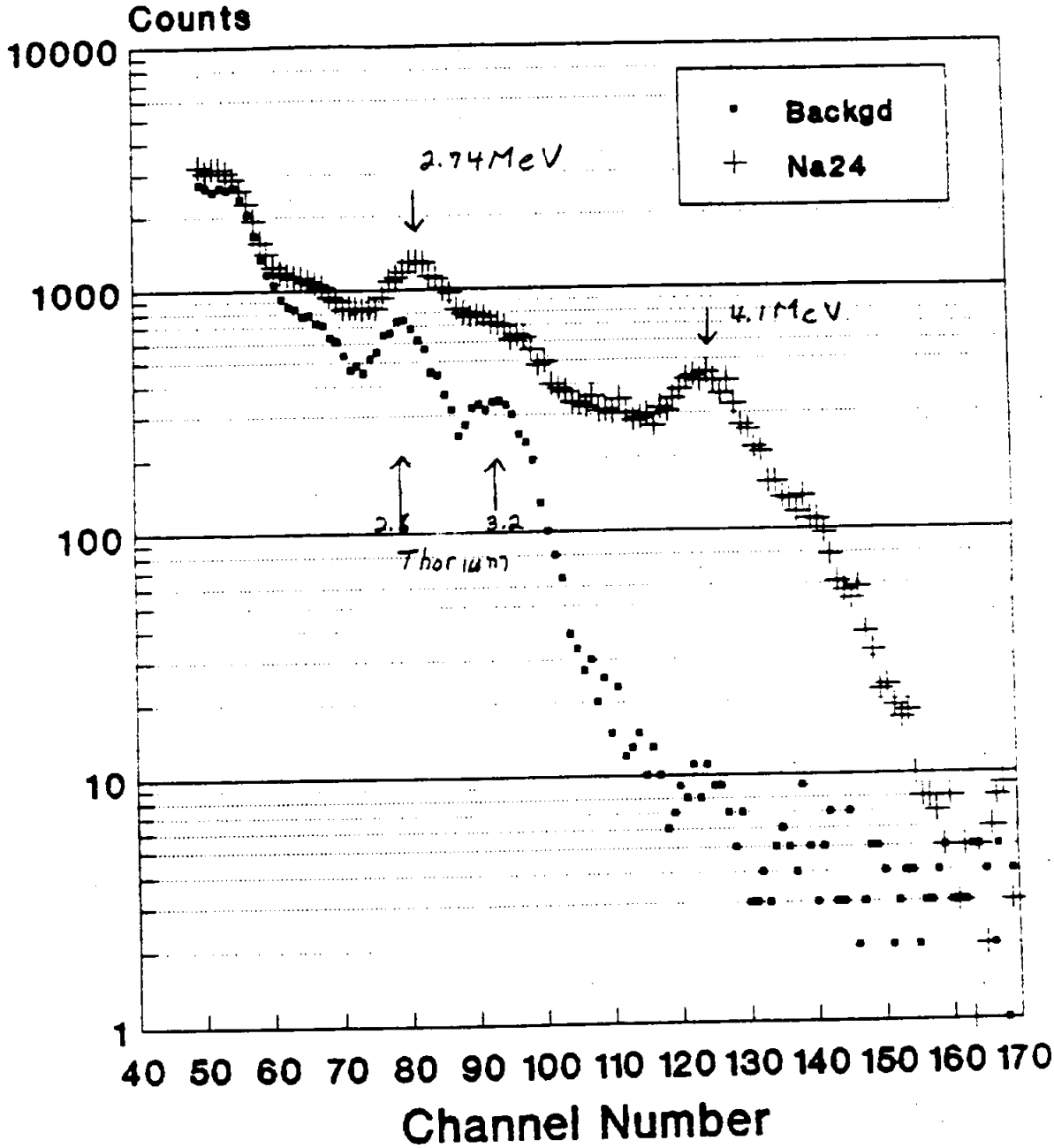

$^{23}_{11}Na\ \sigma_{n,\gamma}$
80 LND Ma
78 ARK Si
72 RPI Ho
68 MUA He
67 DEB Ca
67 DBB Ch
67 LOK Ma
66 CAD La
63 ORL Ma
59 LAS Ba
58 ORL Ly
58 PEI Le
58 PEI Ko
58 LRL Bo
57 ORL Ma
ENDF/B-V
σ (mb)
1000.
800.
100.
50.
10.
8.
1.
0.5
0.1
0.05
0.01
0.007
0.01
0.05
0.1
0.5
1.
0.
10.
20.
E_n (MeV)

Fig. 8

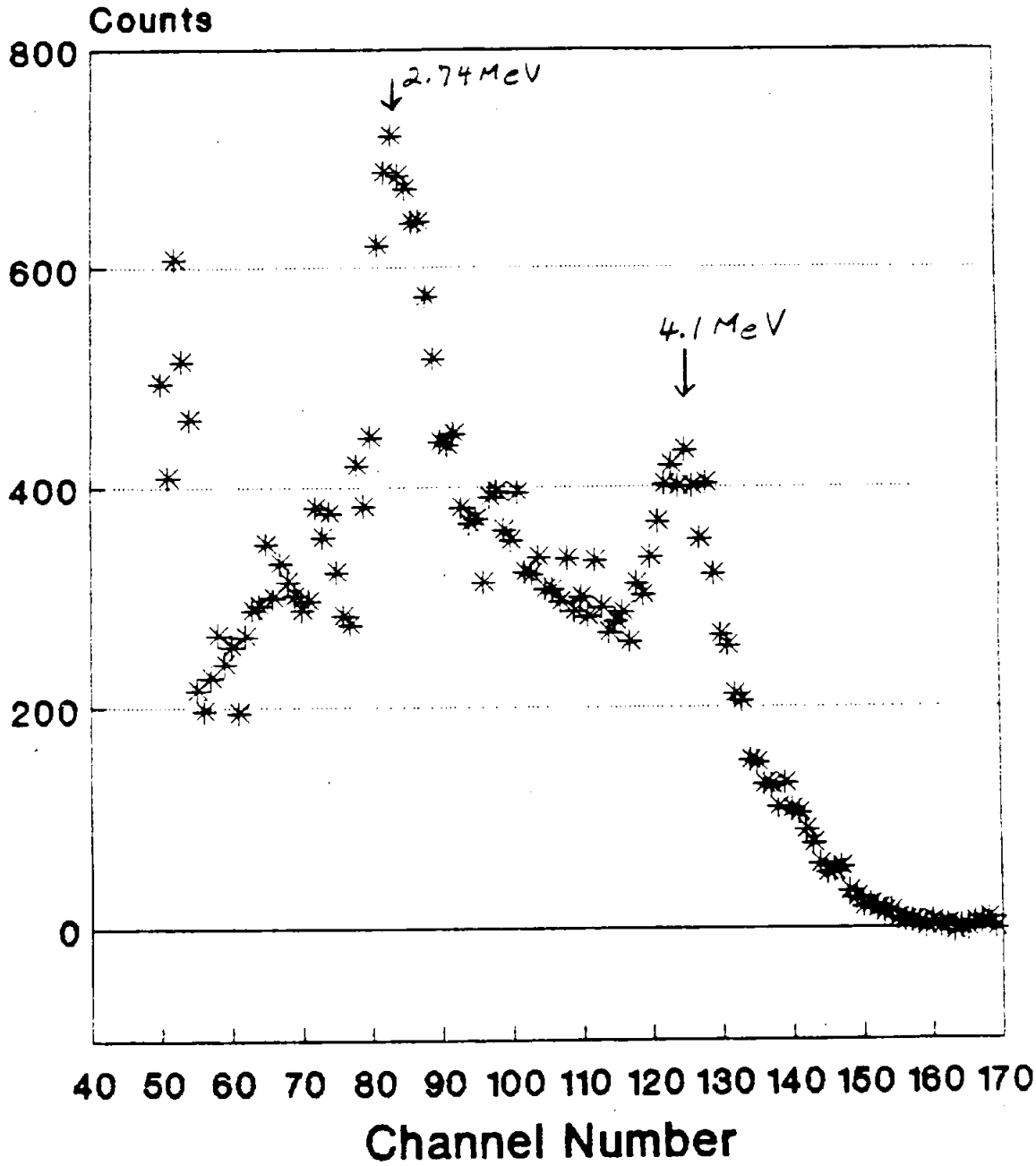
Na24 and Background
All 6 PMT's - 5 Minute Run



March 5 1992

Fig. 9

Na24 - Background
All 6 PMT's - 5 Minute Run



March 5 1992

Fig. 10

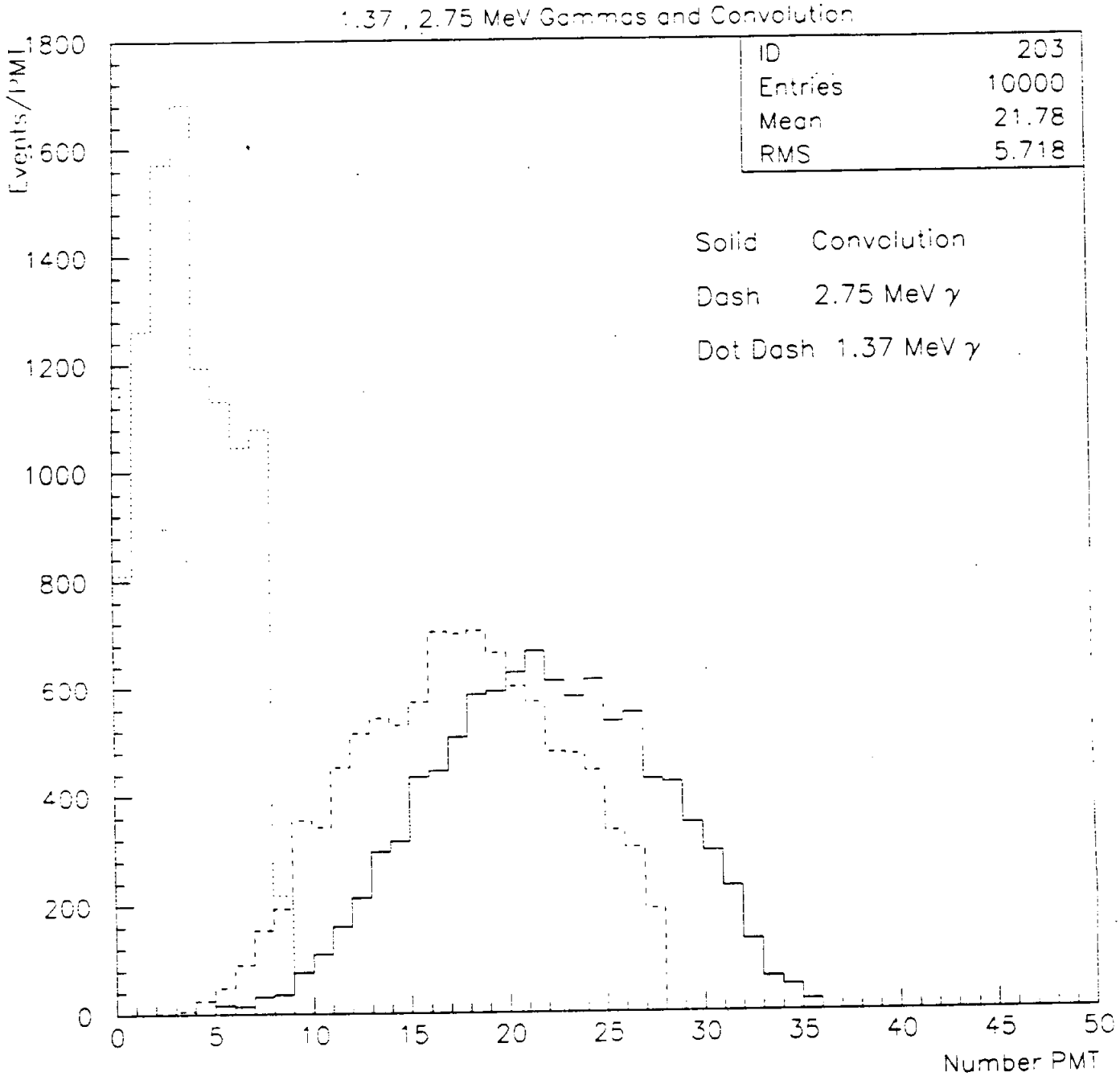

1.37 , 2.75 MeV Gammas and Convolution
ID 203
Entries 10000
Mean 21.78
RMS 5.718
Solid Convolution
Dash 2.75 MeV γ
Dot Dash 1.37 MeV γ
Events/PMT
Number PMT
0
200
400
600
800
1000
1200
1400
1600
1800
0
5
10
15
20
25
30
35
40
45
50

Fig. 11

NOISE
100 ns Window

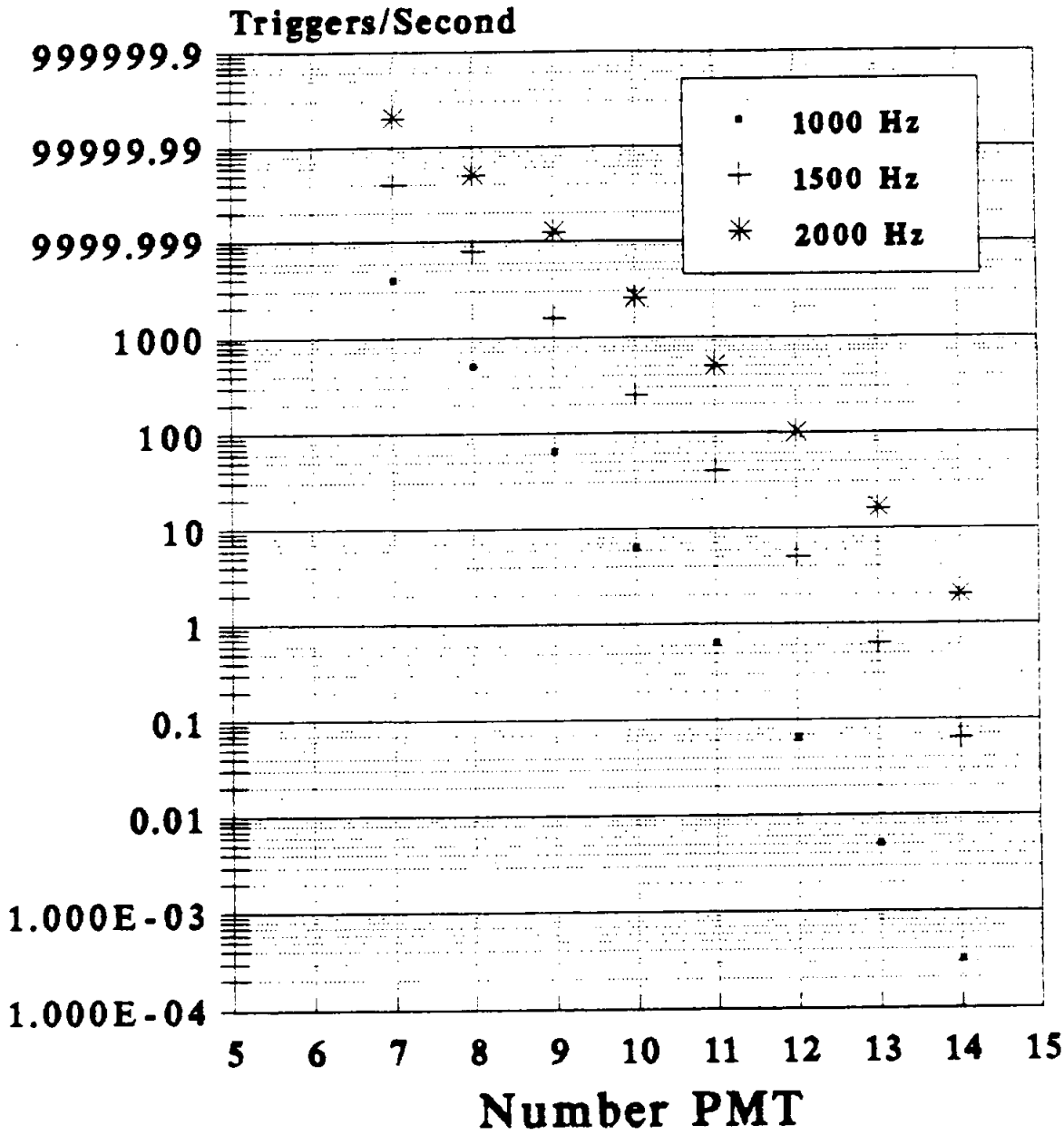


Fig. 12

NOISE
20 ns Window

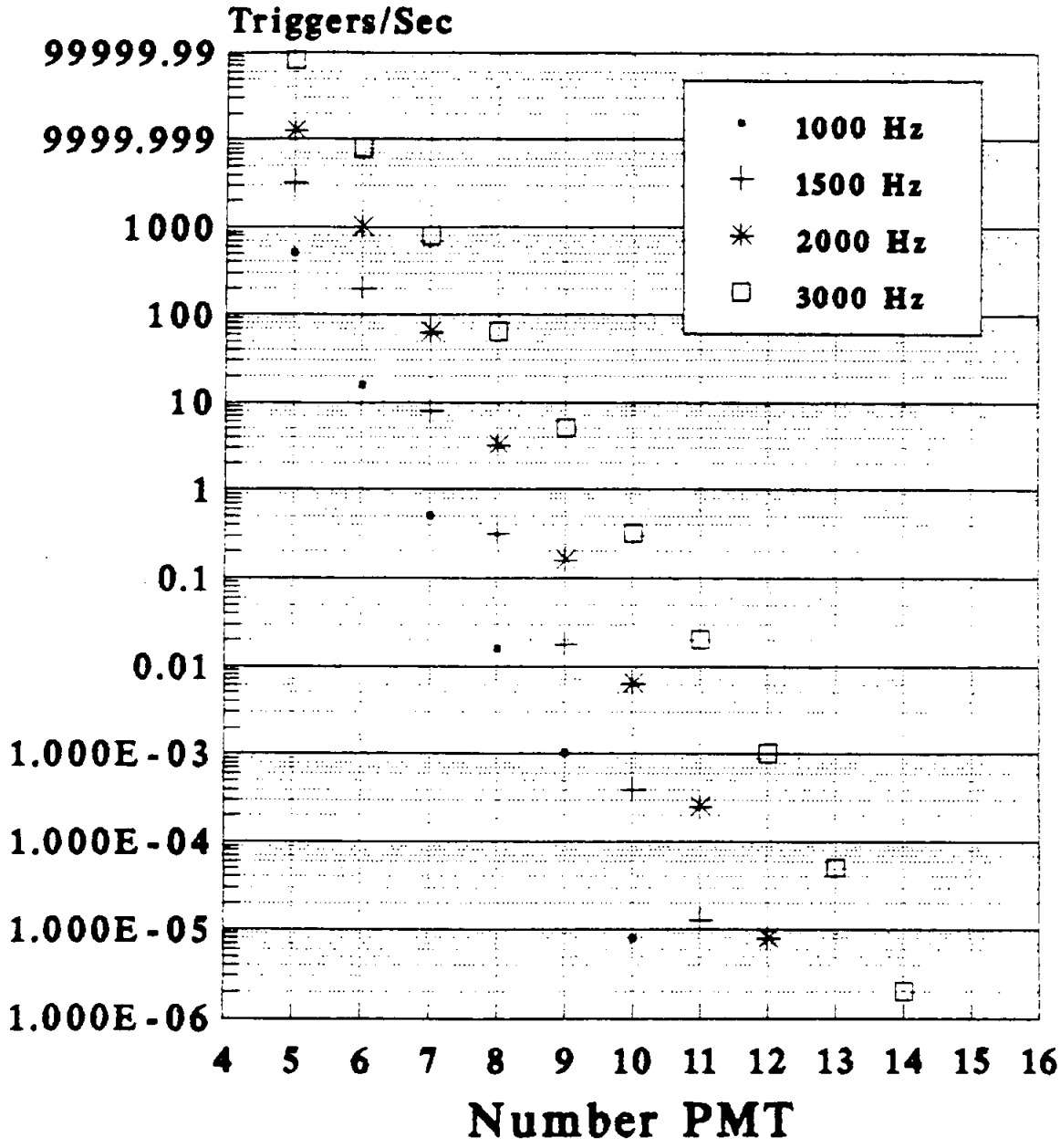


Fig. 13

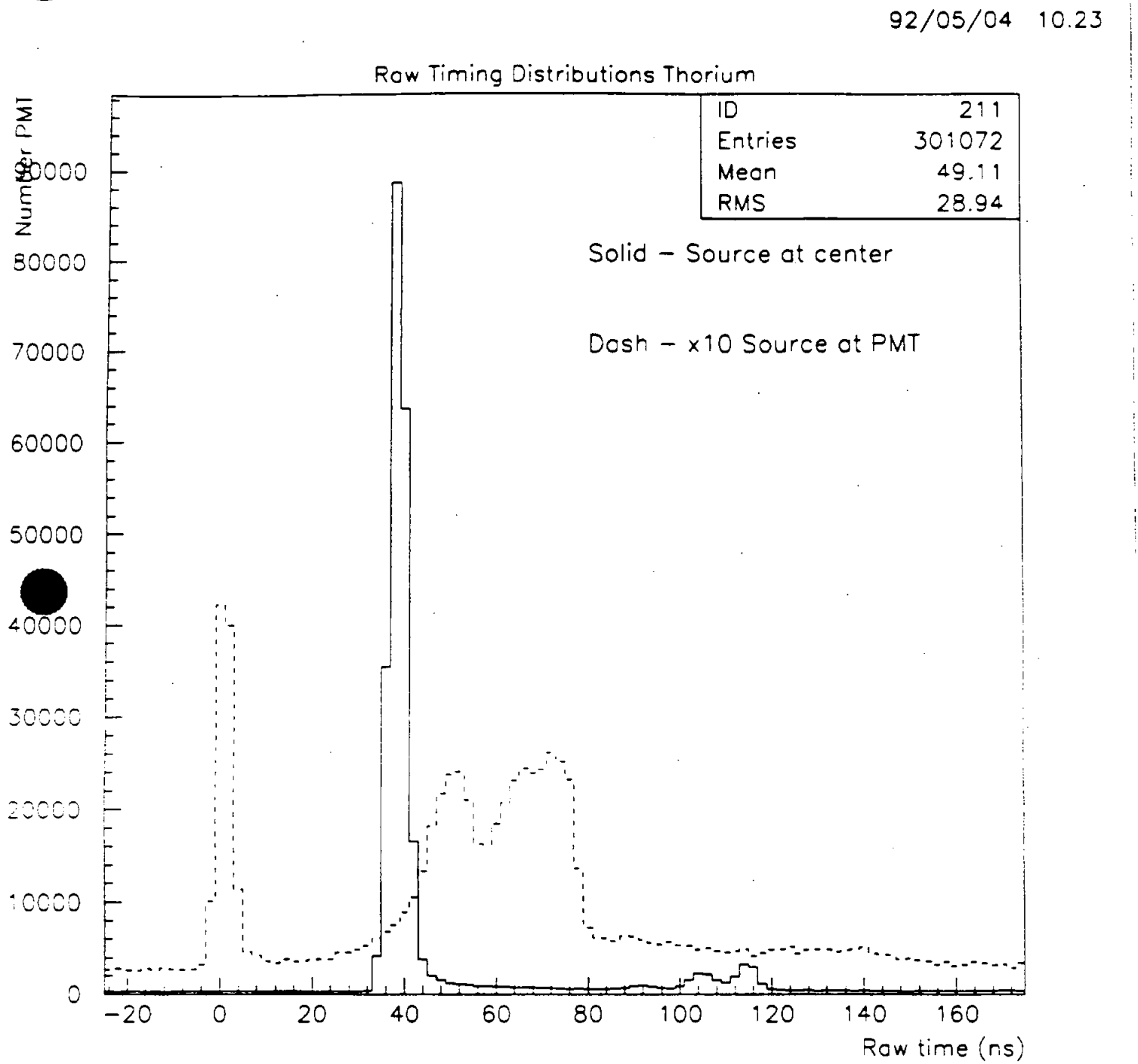

92/05/04 10.23
Raw Timing Distributions Thorium
ID 211
Entries 301072
Mean 49.11
RMS 28.94
Solid – Source at center
Dash – x10 Source at PMT
Number per PMT
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
−20
0
20
40
60
80
100
120
140
160
Raw time (ns)

Fig. 14

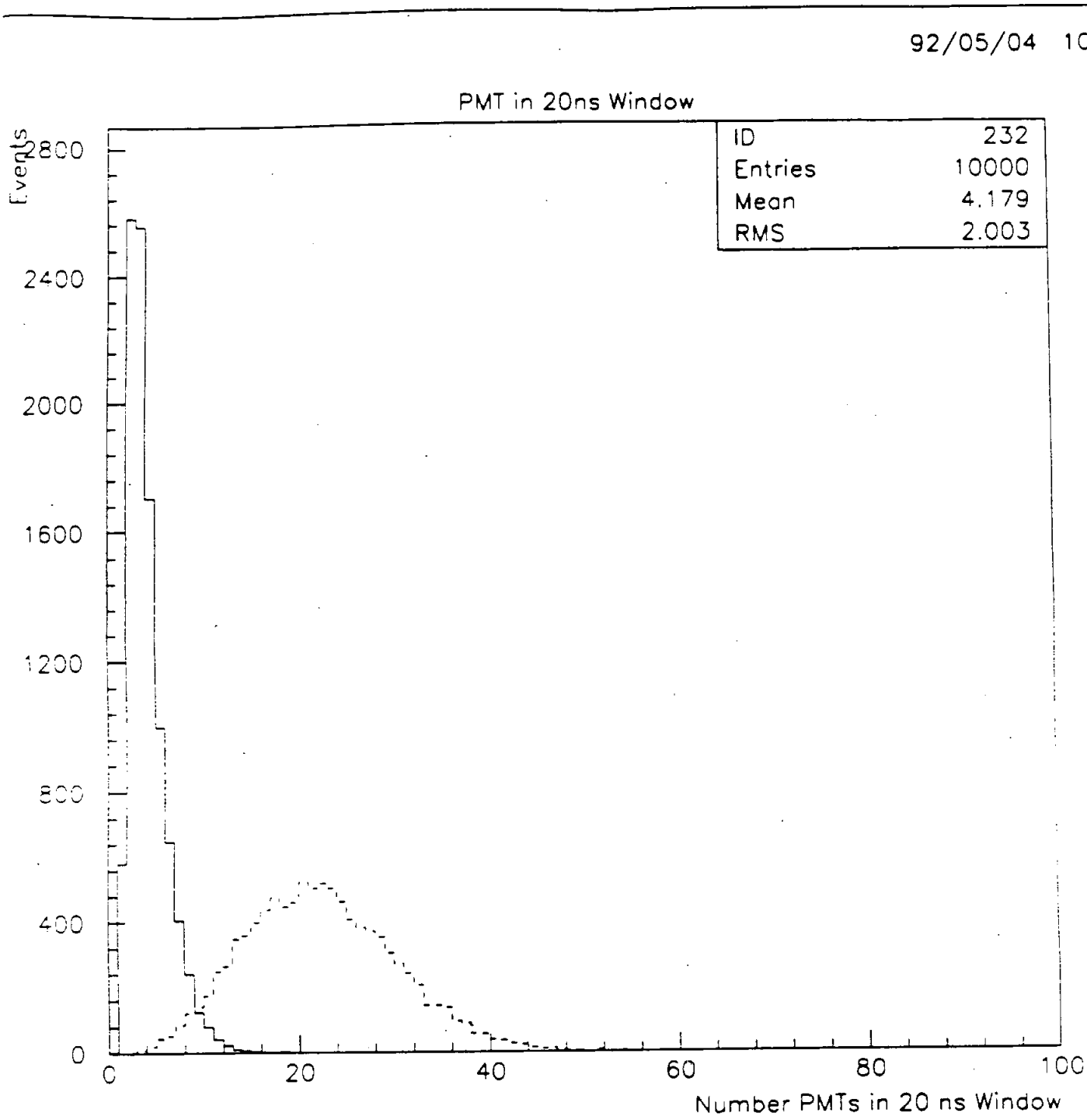

92/05/04 10.23
PMT in 20ns Window
ID 232
Entries 10000
Mean 4.179
RMS 2.003
Events
2800
2400
2000
1600
1200
800
400
0
0
20
40
60
80
100
Number PMTs in 20 ns Window

Fig. 15

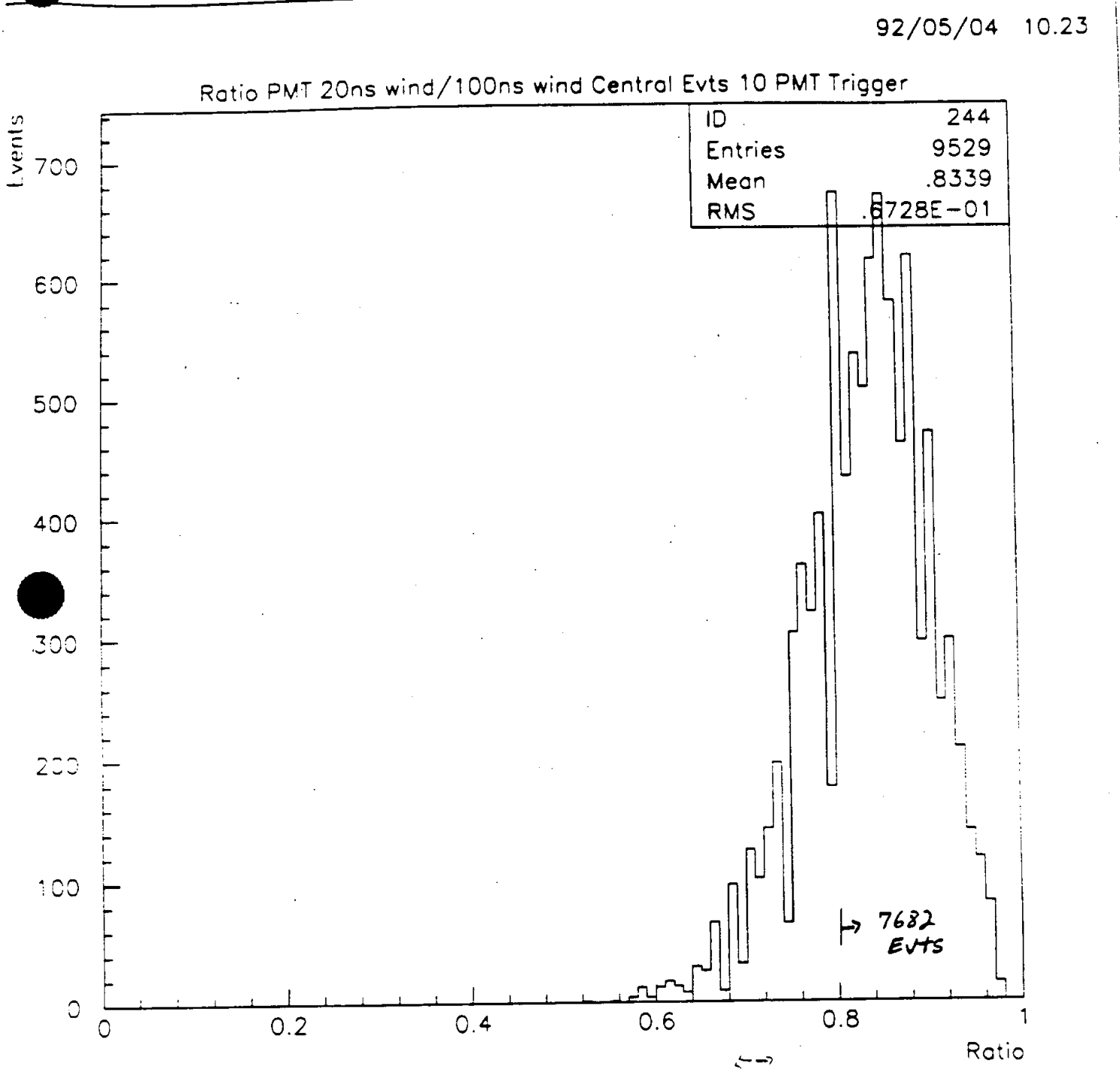

92/05/04 10.23
Ratio PMT 20ns wind/100ns wind Central Evts 10 PMT Trigger
ID 244
Entries 9529
Mean .8339
RMS .6728E-01
Events
700
600
500
400
300
200
100
0
0
0.2
0.4
0.6
0.8
1
Ratio
7682 EVTS

Fig. 16

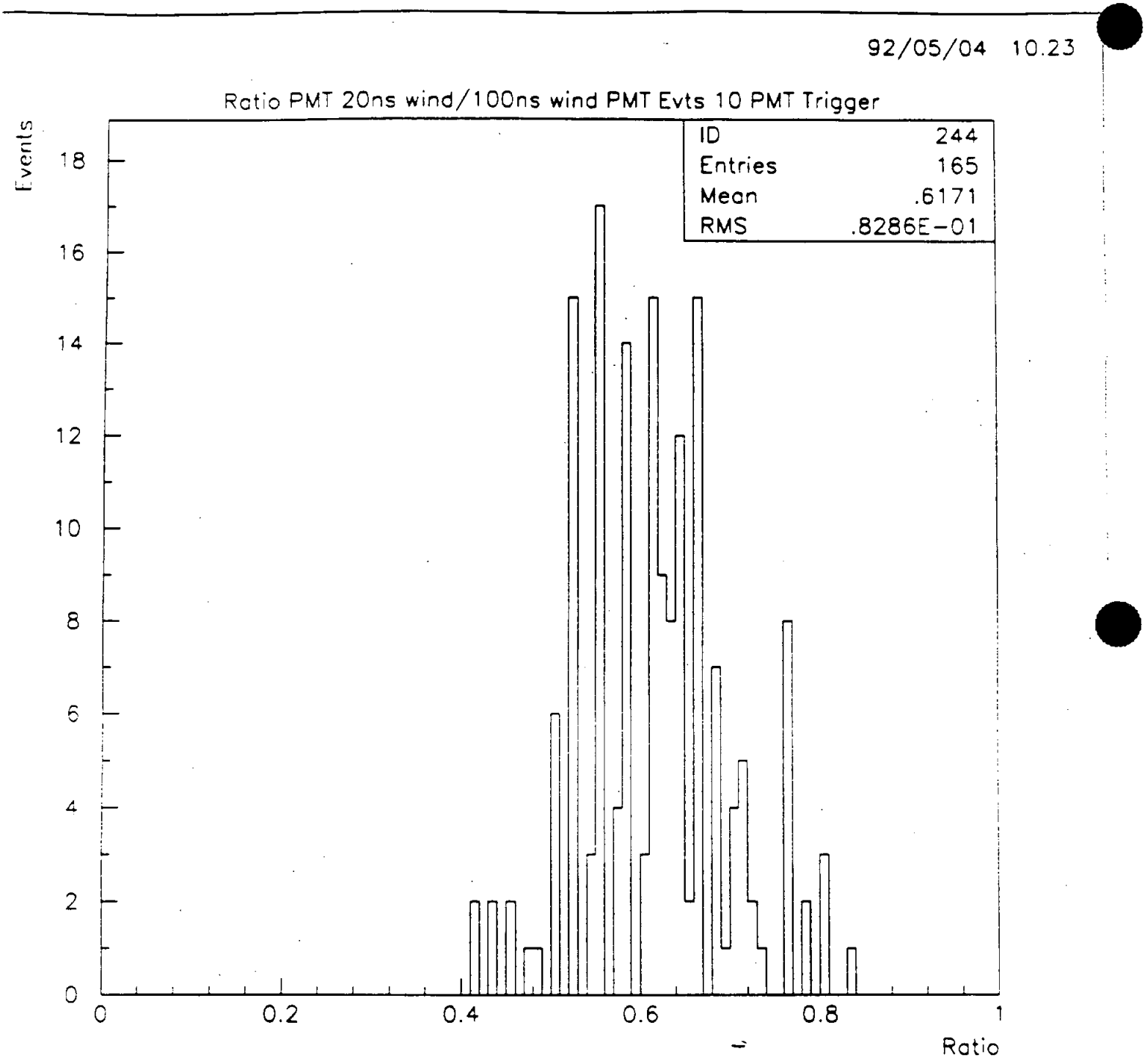

92/05/04 10.23
Ratio PMT 20ns wind/100ns wind PMT Evts 10 PMT Trigger
ID 244
Entries 165
Mean .6171
RMS .8286E-01
Events
Ratio
0
2
4
6
8
10
12
14
16
18
0
0.2
0.4
0.6
0.8
1

Fig. 17

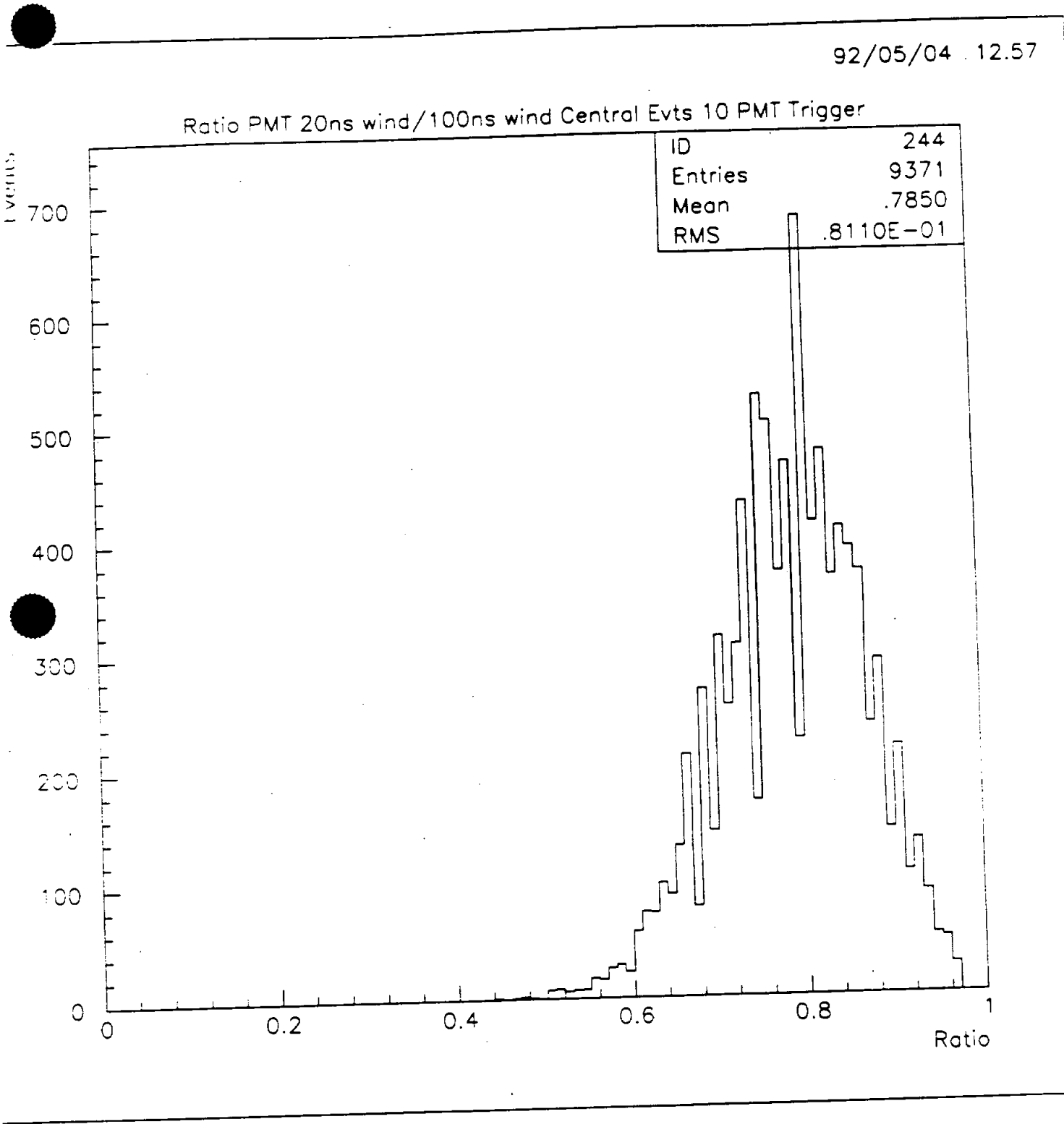

92/05/04 . 12.57
Ratio PMT 20ns wind/100ns wind Central Evts 10 PMT Trigger
ID 244
Entries 9371
Mean .7850
RMS .8110E-01
Events
700
600
500
400
300
200
100
0
0
0.2
0.4
0.6
0.8
1
Ratio

Fig. 13