Use of Gd in Gas Counters as a Neutral Current Detector in SNO

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INTRODUCTION

Gadolinium has a number of properties which make it an interesting element for use in SNO as a neutral current detector. These properties are:

- * The isotopes 155Gd and 157Gd have large cross sections for capture of thermal neutrons.
- * The de-excitation of the nuclei after neutron capture goes through their first excited states with high probablility.
- * These states have high conversion electron coefficients, thus producing electrons with energies up to 90 keV with high efficiency on neutron capture.
- * The high energy neutron capture gamma rays are easily detected by the SNO photomultipliers.

These properties combine in the following way to make Gd useful in detecting the neutral current neutron in SNO. The high neutron capture cross section makes it possible to capture a large fraction of the neutrons produced in SNO with a small amount of material. The high conversion electron coefficient of the first excited state combined with the large fraction of neutron captures going through this state makes it possible to detect a large fraction of the neutron captures in relatively simple detectors. The coincidence between the counters and the SNO photomultipliers makes it possible to eliminate the backgrounds from noise in the counters and radioactivity in the materials of the counters, none of which have high energy gamma rays easily detectable in SNO. The small amount of materials required in the counters make it possible to reduce to reasonable levels the neutron production in the D2O from disintegration of the deuteron by gamma rays above 2.2 MeV from the counter material.

The detailed properties of Gd are given in Table I.

Table I

Properties of Gadolinium

Property	155Gd*	157Gd+	Natural Gd
Density			7.902
Atomic number			64.
K Binding energy (keV)			50.239
L Binding energy (keV)			8.376, 7.931, 7.243
M Binding energy (keV)			~1.5
Abundance (%)	14.8	15.7	
Cross section (barns)	64,000	255,000	49,122
Neutron binding energy (MeV)	8.4	7.9	
E 1st excited state (keV)	88.97	79.49	
E 2nd-1st excited state (keV)	199.21	181.97	

1->0 transitions/n-capt	.976	.66	0.74
2->1 transitions/n-capt	.348	.239	0.266
1->0 e's/n-capt	.778	.587	
2->1 e's/n-capt	.064	.056	
Total e's/n-capt	.79	.61	0.66
Total/K conversion	2.63	2.94	
Ee (K conversion) (keV)	40.	30.	
Ee (L conversion) (keV)	70.	80.	
dE/dx(Gd) 30.0 keV (keV/micron)			3.3
70.0 keV (keV/micron)			2.2

* Reference 2
+ reference 3

This use of Gd was initiated by discussions with Victor Perez-Mendes and Ali Mireshghi of LBL about the use of amorphous silicon hydride counters (a-Si:H) with Gd neutron converters as a possible neutron detector in SNO. As a result of our discussions, they made us a a-Si:H detector which I have tested. The results of this test are described in a separate paper.

In this paper we describe a method of using Gd in SNO as a neutral current detector. In the first section, we calculate the amount of Gd required to detect the neutrons with reasonable efficiency. In the second section, we discuss the conversion electron detection efficiency. The third section describes the coincidence capability. Section 4 discusses the efficiency for detection of the neutron capture gamma rays in SNO. In the fifth section, we describe and discuss the proportional wire chamber design. Section 6 discusses the overall neutron detection efficiency. Section 7 describes the measurements with a test counter and a Gd foil. In section 8, we give a general discussion of the technique and in Section 9 we give the conclusions. Appendix I expands on the distribution of the counters in the D2O with particular application to the 3He counters.

1. NEUTRON CAPTURE EFFICIENCY IN SNO USING GD STRIPS

i) Introduction

It is essential to know the amount of Gd one will need to capture a significant number of neutrons in SNO. A Monte Carlo program (ref 1) has been written to calculate the neutron capture efficiency for a variety of capture agent geometries. This program has been used to simulate various arrangements of Gd in the volume of SNO. An initial efficiency calculation was made for Gd dissolved in the D2O of SNO. This calculation gives the maximum achievable efficiency for a given mass. All the other efficiency calculations described in this section have been done for 1 micron thick strips of 157Gd as a function of total Gd mass. These calculations may be translated to natural Gd by taking into account the cross sections and relative abundances of 155Gd and 157Gd. The result requires increasing the thickness of the strip by the ratio of the neutron capture cross section of 157Gd and natural Gd, a factor of 5.20.

For the strip geometry, two different calculations have been made. In the first calculation, the strips were uniformly distributed through the full volume of SNO. In the second calculation, an attempt was made to optimize the capture efficiency for a fixed mass of Gd by varying the inner and outer radii of the strips keeping the distribution of the strips uniform between these two radii. The results of the Monte Carlo program have been compared with other similar programs in the SNO collaboration and found to give comparable numbers.

ii) Neutron Capture Efficiency in SNO for Gadolinium

The results of these neutron capture efficiency calculations for Gadolinium distributed in SNO are plotted against mass of 157Gd and are shown in Fig. 1 and Fig. 2. The upper curve is for Gd dissolved in the D2O. This represents the maximum possible efficiency for neutron capture. The lower curves display the results of the calculations for strips with widths of 0.5, 1.0, 5.0, 10.0, and 15.0 cm on lattices of 50, 75, and 100 cm. Lines of constant lattice spacing are drawn with solid lines while lines of constant strip width are drawn with dotted lines. Once the lattice spacing is fixed the length of the foil is determined and since the width and thickness of the foil are known, the total volume of Gd is determined and hence its mass. One can draw a number of conclusions from these calculations.

1. The neutron capture efficiency increases initially rapidly with mass and then slows and eventually saturates.

2. Arranging the Gd in strips reduces the efficiency for neutron capture significantly relative to the uniform distribution. Over most of the interesting region the loss is about a factor of two.

3. In order to get reasonable capture efficiency we require 400 gms or more of 157Gd. Since this is distributed in a 1 micron layer, 500 gms requires an area of 63 square meters. This latter point is critical since it determines the final volume of counters required.

The 157Gd can be formed by rolling or vacuum deposition into self-supporting 1 micron thick foils which are then placed in gas counters (5.2 micron thick foils of natural Gd would give the same result). The mean free path of neutron absorption of the 157Gd is about 1.3 microns. The area of the Gd is 1.266xE5 (cm2/100gm).

iii) Optimization of the Gd Foil Distribution in SNO

In addition to the investigations above, Fig.1 and 2, we conducted detailed investigations of the distributions of Gd foil proportional tubes in SNO. In these simulations the outer boundary of the tubes was reduced in steps from that of the SNO vessel outer boundary keeping the mass of the Gd fixed. These investigations showed that the efficiency could be improved, particularly for low mass cases, by up to 15%. The optimum outer boundary for the tubes seemed to occur at about 550 cm. This effect is demonstrated in Fig. 3, in which the efficiency as a function of outer radius for a fixed mass is plotted. We also varied the inner boundary but found that this always reduced the efficiency so that all the calculations discussed here are for the inner boundary set to zero. The importance of this result is that this is equivalent to reducing the number of counters by about 20%. (A distinct difference between the proposed 3He detectors and the Gd foil detectors which we investigated is the fact that the low mass Gd foil counters were not neutron black and therefore neutron capture efficiency could be improved in some cases by moving the Gd inwards.)

iv) Discussion

The calculations as shown in Fig. 1 and Fig 2 indicate that we can obtain, with reasonable geometries, a neutron capture efficiency of up to 50%. The higher the required neutron capture efficiency, the greater the photon losses and the greater the critical radius. A reasonable compromise which we will use for the rest of this note is 45% neutron capture efficiency. On a 100 cm lattice, 900 g of 157Gd will achieve 45% neutron capture efficiency with approximately 16% loss of light signals due to obstruction.

2. CONVERSION ELECTRON EFFICIENCY IN GADOLINIUM

One is required to know the probability of observing a conversion electron after a neutron capture. Gd has been carefully studied and one can extract these numbers from the literature. The cross sections for neutron capture in the two main isotopes can be found in Table I. The fraction of captures which go through the first excited state and other relevant transitions for the two main isotopes may also be found in that table.

There is considerable K and L conversion in the first excited state and some contribution from higher states. We have extracted the fraction of conversion electrons as 61% for 157Gd and 79% for 155Gd. The efficiency for natural Gd is a combination of these two numbers and adds up to about 66%.

In order to convert these numbers into useful efficiencies, one has to work out the probability for a conversion electron getting out of the Gd foil and making a measurable signal in a detector. This will depend on the thickness of the foil and the energy spectrum of the electrons. The energy of the K conversion electrons is between 30 and 40 keV while the L electrons have between 70 and 80 keV depending on the isotope. The estimated energy loss of electrons in Gd is 3.8 keV/micron at 30 keV and 2.2 keV/micron at 70 keV. Thus the efficiency for detecting the L electrons in foils of a few microns of Gd will be high while that of the K electrons will be lower. However the alpha(total)/alpha(K) is 2.63 for 156Gd and 2.94 for 158Gd. Therefore most of the electrons will have the higher energies and we can expect the efficiencies of the counters to be very high. We intend to measure this and also to calculate it using the EGS code.

For the purposes of this paper, we estimate the efficiency for natural gadolinium conversion electrons is 65%. There are two options open which would allow one to get to higher overall efficiencies. These are to use the pure isotopes. The isotope 157Gd would allow one to increase the capture efficiency while 155Gd gives a higher conversion electron efficiency.

3. THE COINCIDENCE OPTION

A major feature of this technique is the use of coincidences between the Gd conversion electrons in a counter and the Cherenkov light produced in SNO by the associated neutron capture gamma rays. This coincidence measurement makes it possible to operate counters in SNO with a singles rate which one can reasonably expect in normal counters.

For instance for the proposed counters a simple calculations shows:

R(chance) = R(SNO)*N*R*RT 1.

Here R(chance) = the chance rate between SNO and the counter system.
R(SNO) = singles rates in SNO
N = the number of proportional counters
R = the noise rate per counter
RT = the resolving time of the counters

Putting the following reasonable numbers for a proportional counter system into equation 1:

R(chance) = 2.3xE-5 Hz (2.0/day)
R(SNO, E>4 MeV) = 4.8E-4 Hz (15,000 counts per year)
R(SNO, E>3 MeV) = 6.3E-3 Hz (200,000 counts per year)
RT = 1.0xE-7 Sec.

gives
N*R = 500,000 Hz (4 MeV threshold)
N*R = 36,000 Hz (3 MeV threshold)

A reasonable value for N is 1,000. Therefore, the rates for the two cases may be divied by 1,000 if one assumes that the counters are summed for measurement purposes. However if one assumes that the resolution of SNO is good enough so that one can resolve indiviual counters, then N = 1 and these rates then apply to the indivual counters. One can expect that reasonable numbers for the singles rates in the counters in the SNO environment would be lower than 36 if careful attention is paid to materials and activity levels. It is further obvious that one would be easily able to work with reasonable variations in the rates from things like counter breakdown and electronic noise.

4. EFFICIENCY FOR GADOLINIUM NEUTRON CAPTURE GAMMA RAYS IN SNO

The energy spectrum of the capture gamma rays from Gd in SNO is calculated as a function of energy in the White Book and the expected background rates in SNO were calculated for the report to the NSERC review committee, see Fig 4a and

Fig. 4b respectively. The efficiency for observing the gamma rays will depend on the lowest energy at which we can observe coincidences between the counter system and SNO without being swamped by chance coincidences. This number will depend on the spectrum of background pulses and the singles rates in SNO. To calculate this number we have used fairly conservative numbers from Fig 4 as shown in Fig 5. That figure is a graph of efficiency and count rate in SNO as a function of the threshold energy for gamma ray detection in SNO. If we choose 4 MeV as a reasonable threshold then the efficiency for detecting the gamma rays is about 70%. If the rates in the counters are lower than the 100 Hz and one makes use of the spatial resolution of SNO, one can easily go much lower. At 3.0 MeV one would have an efficiency of 90%. In what follows we will use 70%.

One factor which has to be taken into account is the effect of the proportional counters on the energy spectrum of the gamma rays. It is possible that the number of photons could be reduced by as much as 20%, in which case we should lower the efficiency correspondingly.

Another factor which has to be evaluated is the background from real electron-gamma ray coincidences due to background radioactivity in the counters. This will depend on the amount of the various radionuclides in the materials of the counters which has not been determined yet.

5. THE PROPORTIONAL COUNTER DESIGN

The proposed design would use a multi-layer Gd foil proportional wire sandwich. Fig. 6 is a drawing of such a counter. For a given cross section of counter, one can put a number of foils in the counter and thus achieve a foil area which is considerably larger than the width of the counter itself. The amount of Gd in such a counter can be adjusted to be whatever is needed.

The parameters of this design are determined by the neutron detection efficiency. The process of arriving at the parameters follows the following steps (see Figures 1 & 2).

1. Pick the Efficiency which you require (Fig 1 or 2 vertical axis).
2. Use this number to determine the required mass (Fig. 1 or 2 Horizontal Axis) of capture agent (Gd) for the lattice of interest (the length of the counters is determined by the lattice).
3. This determines the width of foil required and therefore the size of containment tube required.
4. For the Lattice spacing and the foil width work out the photon loss fraction. These losses are shown in the bottom half of Figures 1 & 2.

We have determined these numbers for lattices of 50, 75 and 100 cm and an efficiency of 45, 50 and 40%. The results of these determinations are given in Table II.

Table II

Parameters of a Gd Counter Design

Eff neu cap	Latt	Rad. Out	Mass	Foil Width	Tube Diam.	# of foils	Len. ctrs	Photon losses
%	cm	cm	grams	cm	cm		m	
45	100	550	900	16.2	5.4	4.	705	.16
	100	600	920	13.0	4.7	4	893	.18
	75	550	670	6.8	4.5	2	1249	.19
	75	600	680	5.4	3.8	2	1588	.20
	50	550	470	2.1	2.3	2	2781	.29
	50	600	480	1.7	2.2	2	3585	.29
50	100	550	1150	20.7	6.5	4	705	.19
	100	600	1220	17.3	5.7	4	893	.19
40	100	550	700	12.6	4.6	4	705	.14
	100	600	705	10.0	4.1	4	893	.14

There are a number of conclusions which can be drawn from this table:

1. The neutron capture efficiency of the system can be made usefully high.
2. The photon losses can be kept to a reasonable level
3. The mass of Gadolinium is not unreasonably large.
4. The number of counters required is not unreasonable large.
5. There are a number of parameters available to optimize the system.

The counter of Fig. 6 would be operated at atmospheric pressure or adjusted in such a way that the average pressure in the tube balances the water pressure. At this low pressure the voltage on the counters would be in the region of 1500 V which is quite low and easily handled. One would also use a standard counting gas like P10 thus guaranteeing ease of operation and low cost. The signals would be reasonable,in the region of 1000 electrons before gain. This would require gains of the order of 1000 on the wires of the counters which is very low. It is possible that one could make the counters operate without any preamps in the tubes which would simplify the electronics and increase the reliability of the system.

The amount of material in the system could be quite small since the gas pressure can be made to roughly balance the hydrostatic pressure. For this reason one can anticipate that problems with Thorium and Uranium gamma rays, which cause the disintegration of the deuteron, can be kept to a negligible level.

All the proportional wires would be connected in parallel and only one signal would have to be taken out per counter. These signals could be taken out on the high voltage cables so that only one cable would be required per counter. The signals and cables from a number of counters could be ganged together to reduce the number of cables to whatever is required or practical.

6. OVERALL EFFICIENCY

The overall efficiency of such a system can be calculated from the above numbers.

Table III
Overall Efficiency

	Optimistic	Conservative
Neutron capture	.5	.45
Conversion electron	.8	.65
Capture gamma rays in SNO	.9	.70
Total efficiency	.36	.20

We use the number .2 in this document. Certainly the Optimistic number is too high. It seems likely that one can achieve 30% without too much trouble.

7. GADOLINIUM TEST COUNTER

The test counter constructed for the Li counter has been used with a thin Gd foil in coincidence with a NaI(Tl) scintillation counter to measure the response of the system to thermal neutrons. The neutrons were produced by an Am-Be neutron source with a rate of 10E5 neutrons per sec. The source and the PWC were placed inside a parowax castle with the PWC shielded from the source by 5" of Pb. A 6"x5" NaI crystal was placed at right angles to the line between the source and the PWC counter at a distance of 5" from the centre of the PWC counter. The pulse heights of the NaI and the PWC for all coincident events were digitized and stored in an IBM compatible computer.

Three Gd foils were prepared for us by Peter Dymtrenko of CRNL. They were 1 cm wide by 10 cm long and had thicknesses of 1.1, 1.2 and 2.0 microns. All the tests reported in this document were carried out using the 1.1 micron foil.

As described earlier, see Table I, a large fraction of the neutron captures go through the first excited state. In natural Gd, 80% of the captures occur on 157Gd and 20% on 155Gd. There is a large amount of both K and L internal conversion with L conversion being about 3 times the K conversion, see Table I. Hence one would expect to see electrons with an energy between 30 and 40 keV for K conversion and between 70 and 80 keV for L conversion. Also since there is a considerable amount of energy loss by the electrons in getting out of the foil and because the range for the higher energy electrons is close to the size of the counter, one would not expect great resolution in measuring the energy of these electrons.

A typical background and neutron PWC spectra along with the background subtracted neutron spectrum are shown in Fig. 7. One can see that the background is smooth while the neutron source spectrum has a double peak which is roughly consistent with the spectrum expected for the K and L conversion energies. Further there is a high energy continuum which is consistent with some high energy electrons being produced by higher transitions.

The coincidence spectra between the NaI scintillator and the PWC for both the NaI and the PWC are shown in Fig. 8. The PWC spectrum has the same double humped structure and no significant background. The NaI spectrum isalso shown in Fig. 8 for the energy range up to 2.5 MeV. There is no high energy structure but there are a number of low energy lines which may be identified with prominent lines in the Gd capture gamma ray spectrum.

The two NaI spectra in coincidence with each of the K and L lines are shown in the top and bottom spectra respectively of Fig 9. One can see that the spectra have the same general shape but the peak structure is quite different. This suggests that the two peaks in the PWC spectrum are associated with different cascades. This will require further investigation.

The spectrum from the PWC with 10 b gas pressure is shown in Fig. 10. One can see that the intensity ratio of the two peaks has changed and that the upper peak is much more intense. This is presumably because much more of the energy of the conversion electrons is absorbed in the gas.

These measurements are very preliminary and there are a number of important measurements which still have to be made. These are:

1. The fraction of neutron captures which go through the first excited state of Gd and the resultant number of electrons produced.
2. The efficiency of detection of these electrons in a typical counter with a typical foil thickness.

In addition there are a number of technical problems which have to be addressed.

1. How does one make the foils?
2. What are typical singles rates in a counter?
3. How does one get the signals out of the counters?

8. DISCUSSION

It is necessary to show that this system has some advantage over currently proposed systems to make it an acceptable alternative to the SNO collaboration. I will attempt to list the pros and cons of this system, not necessarily in order of importance, and evaluate it as a SNO neutral current detector.

i) Pros

1. The coincidence capability is the biggest advantage. This allows one to insure that the event in both counters is a neutron capture event. It allows one to measure the Gd capture gamma ray spectrum and use this to correct for the Gd captures which are missed by the detectors due to detector inefficiency. It makes the neutron detection insensitive to the singles rates in the detectors.

2. The counter construction is relatively simple since they can be operated at atmospheric pressure with relatively low voltage and standard counter gas.
3. A relatively small number of counters is required.
4. The amount of material in the counters can be kept small.
5. The photon losses due to insertion of the counters can be kept under 20%.
6. The amount of neutron capture material can be kept small.
7. The electronics can be simple requiring only a preamplifier and one or two levels of discrimination. It is quite possible that these components could be installed on the deck thereby improving the reliability of the system.

ii) Cons

1. The discriminators thresholds for the signal will have to be kept low, in the region of a few keV, making the system sensitive to background radiations and noise.
2. The construction of the foils will have to be such as to keep the Gd thin and uniform in order to keep the efficiency for the conversion electrons high.
3. The construction of the foil system inside the tubes is somewhat complex. It is not forbidding, in comparison with the complex proportional wire systems which are standard in particle physics and which have been constructed in Ottawa.
4. The Th content of the Gd is known to be between .1-.3 ppm Ref.5. This is too high and requires work on achieving a purity which is around two orders of magnitude greater.

iii) Proposed program

There are a number of steps which must be followed in order to develop these counters. A list of these steps is:

1. Measure the fraction of neutron captures which go through the first excited state.
2. Measure the conversion electron detection efficiency for the electrons emitted from a foil into a PWC.
3. Study the radioactivity in the Gd, in particular Th.
4. Develop a prototype counter.
5. Investigate low background materials.
6. Measure the background rate in a PWC in a low background environment.
7. Study the e-gamma coincidence background in SNO for real materials.

There may well be other projects which have to be developed along the way and this program will be updated as we progress.

9. CONCLUSIONS

The use of Gd as a neutron converter in a proportional counter system for SNO has been shown to be an interesting technique for a neutral current detector for SNO. It has the following properties:

1. High overall neutron capture efficiency
2. Capability of using a coincidence technique between the counters and SNO.

3. Reasonably high efficiency for coincidence detection of neutrons, 20-30%.
4. Relatively small amount of Gd.
5. Relatively simple construction
6. Relatively simple electronics.
7. Low levels of background neutron activity in SNO

These points lead to the conclusion that an active program should be instituted to develop this technique and search for possible problems.

References

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Figures

1. Efficiency vs Mass, uniform distribution, outer radius of 6 m.
2. Efficiency vs Mass, uniform distribution, outer radius 5.5 m.
3. Efficiency vs outer radius of Gd.
4. SNO capture gamma ray efficiency for Gd vs Threshold energy
5. (a) Gd neutron capture gamma ray energy spectrum in SNO.
   (b) Gd neutron capture gamma ray efficiency plotted as a funcion of the threshold energy in SNO.
6. Cross sectional view of a typical counter
7. Background and neutron energy spectra in the test counter.
8. NaI-PWC coincidence spectra
9. The NaI spectra in coincidence with the K and L lines respectively
10. High pressure PWC conversion electron spectrum.

A1. Histogram of Neutron Deaths as a Function of Birth Radius.

APPENDIX I

NC DETECTOR LOCATING

Simulations have been conducted to investigate the effects of various deployment options for nc detectors in SNO. These options involve variations in the radial extent of the nc detectors, as measured from the centre of the SNO vessel. The purpose of the investigations was to seek the optimum placement of such nc detectors, under the restriction that a fixed mass of neutron absorbing material was being incorporated into detectors for use in SNO. The effect of these investigations was to explore the neutron free path to the various available mortality channels, as a function of the neutrons radial position in SNO.

In order to find the most efficient distribution of nc counters, we must consider the neutron mean free path as a function of neutron production radius, mfp(r). In the SNO vessel without nc detectors or additives to the D2O, it is apparent that neutrons nearer the centre of the vessel have a long mfp with a high probability of being captured on deuterons or 1H or oxygen, and a lower probability of escaping the D2O. The opposite is true for those neutrons born near the outer surface. A Monte Carlo simulation of the neutron deaths as a function of birth radius is shown in Fig.

A1. In this figure the dotted histogram refers to those neutrons which are captured in the volume of the D2O and the solid histogram refers to those which escape. This curve graphically displays that the neutrons born in the outer part of the vessel mainly escape while those born in the inner part of the vessel are largely captured in the 1H and 2H etc. Another way of looking at this is to say that the mfp of neutrons born in the outer part of the detector is short while those in the inner part approach the theoretical maximum. Clearly, the nc capture probability relative to the other possible neutron losses will depend directly on the relative values of the mfp's of the various processes. The implication of this for neutral current detectors in SNO is obvious. Unless the neutron capture mfp for the nc detectors is short compared with the competing processes the efficiency of the nc counters will be small. That is, the effectiveness of the nc counters in capturing neutrons in the outer part of SNO will be very poor unless one puts a very large number of detectorsin that region. In other words, there is an optimum outer radius for nc counters which depends on the lattice constant and the absorption probability of the neutrons in the counters.

It is apparent that, where the number of nc detectors is limited, or the mass of neutron absorber is limited, they would be most effectively deployed where they can compete with the long mean free path to absorption, rather than where they will have to compete with the short escape free path. Then one can envision that a neutron capture efficiency of up to say 50% can be optimally achieved simply by loading SNO with sufficient neutron detectors out to a particular critical radius, as determined from the mfp(r) profile near the D2O surface. This outer critical radius was investigated through numerous Monte Carlo simulations. These investigations have pointed out the potential for achieving good efficiency with a considerably reduced number of counters.

i) Optimized 3He Detector Deployment

To illustrate our point, we have calculated the optimum positioning of the proposed 3He nc detector proportional tubes. The reference design is an array of 109 strings of proportional tubes, of 2.54 cm outer radius, placed on a 100 cm square lattice (lattice points in the X-Y plane) The total length of the tubes is 900 m. The proposed 3He detectors (ref 4) have a wall thickness of 3 mm, and contain a gas mixture which is principally 3He for the dual purposes of capturing the neutrons, and detecting the charged products released upon capture. The 3He gas is proposed to be maintained at 3 Atm, for a total mass of 575g of 3He. The neutron capture efficiency for this arrangement is quoted as 37%, based on LASL simulations.

Our simulations of this design have produced a prediction of 41% neutron capture efficiency (1sigma = 1%), though neutron losses to the proportional tube materials and other components of the gas have not been accounted for. Our simulations also predicted 17% loss of light from events of all types due to the obstruction of such light in the SNO vessel upon insertion of the nc detectors. This prediction is in agreement with the LASL prediction of light loss.

From our simulations we have observed that mfp(r) falls off rapidly in the outer one metre shell of the SNO vessel. For neutron capture efficiencies below about 45%, the optimum radius is near 550 cm from the centre of the vessel. The density of neutron absorbing material within the outer boundary for the counters increases in the cases shown in Fig.3 as the outer boundary is reduced. However, for the 3He case, neutron blackness is already achieved by the tubes, so a reduction of the total length of the tubes with a corresponding reduction in the mass of 3He should not result in any appreciable loss in neutron efficiency, provided that this reduced radius is set at a radius where the detectors are ineffective relative to the high probability for neutrons to escape. An outer detector boundary of 550 cm would reduce the total length of the 3He tubes from 897 m to 705 m. This case was simulated in the Monte Carlo and the results are shown in Table I. It is seen from this table that the neutron capture efficiency dropped from 41% by only 3%, despite the removal of 21% of the detectors. Light losses for this case were 16%.

TABLE I

Outer Bndy. cm	Lattice Constant cm	Total detector length(m)	% Capture Efficiency for Neutrons	Light Loss on Insertion %
600	100.0	897	41	17
550	100.0	705	38	16

We conclude that reducing the outer boundary of the nc counters relative to the radius of the acrylic vessel can lead to a substantial reduction of the number of detectors required to achieve a given neutron capture efficiency. This reduction can then lead to a reduction of the background radioactivity requirements in the counters or equivalently a reduction in the background in SNO. Also it will lead to some reduction in the cost of the nc detector scheme through matters of scale in the construction of the counters, their deployment and attachment, and of the readout electronics.

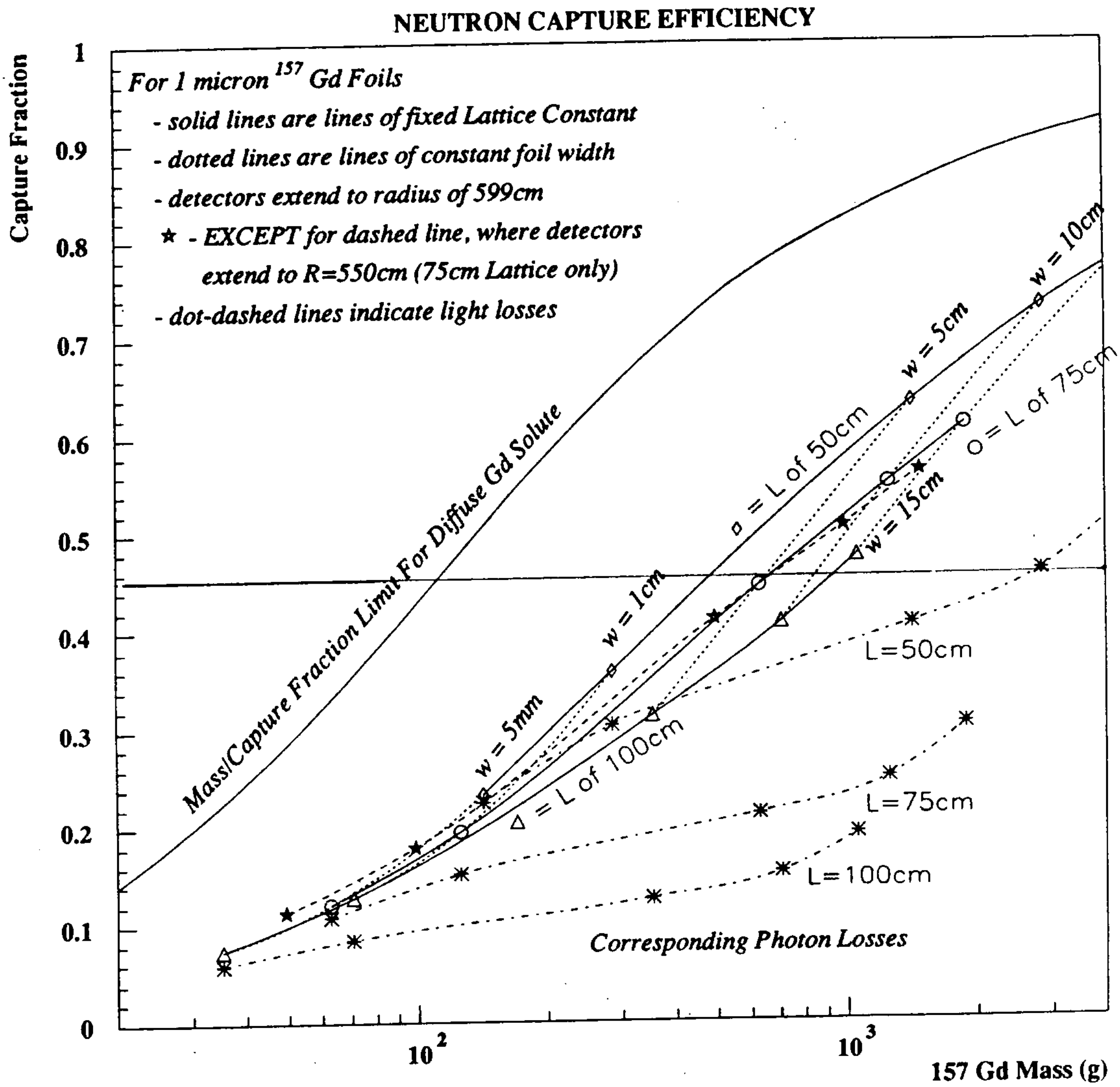

NEUTRON CAPTURE EFFICIENCY
Capture Fraction
157 Gd Mass (g)
For 1 micron ^{157} Gd Foils
- solid lines are lines of fixed Lattice Constant
- dotted lines are lines of constant foil width
- detectors extend to radius of 599cm
★ - EXCEPT for dashed line, where detectors extend to R=550cm (75cm Lattice only)
- dot-dashed lines indicate light losses
Mass/Capture Fraction Limit For Diffuse Gd Solute
w = 5mm
w = 1cm
w = 5cm
w = 10cm
w = 15cm
◇ = L of 50cm
○ = L of 75cm
△ = L of 100cm
L=50cm
L=75cm
L=100cm
Corresponding Photon Losses
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
10^2
10^3

Fig 1

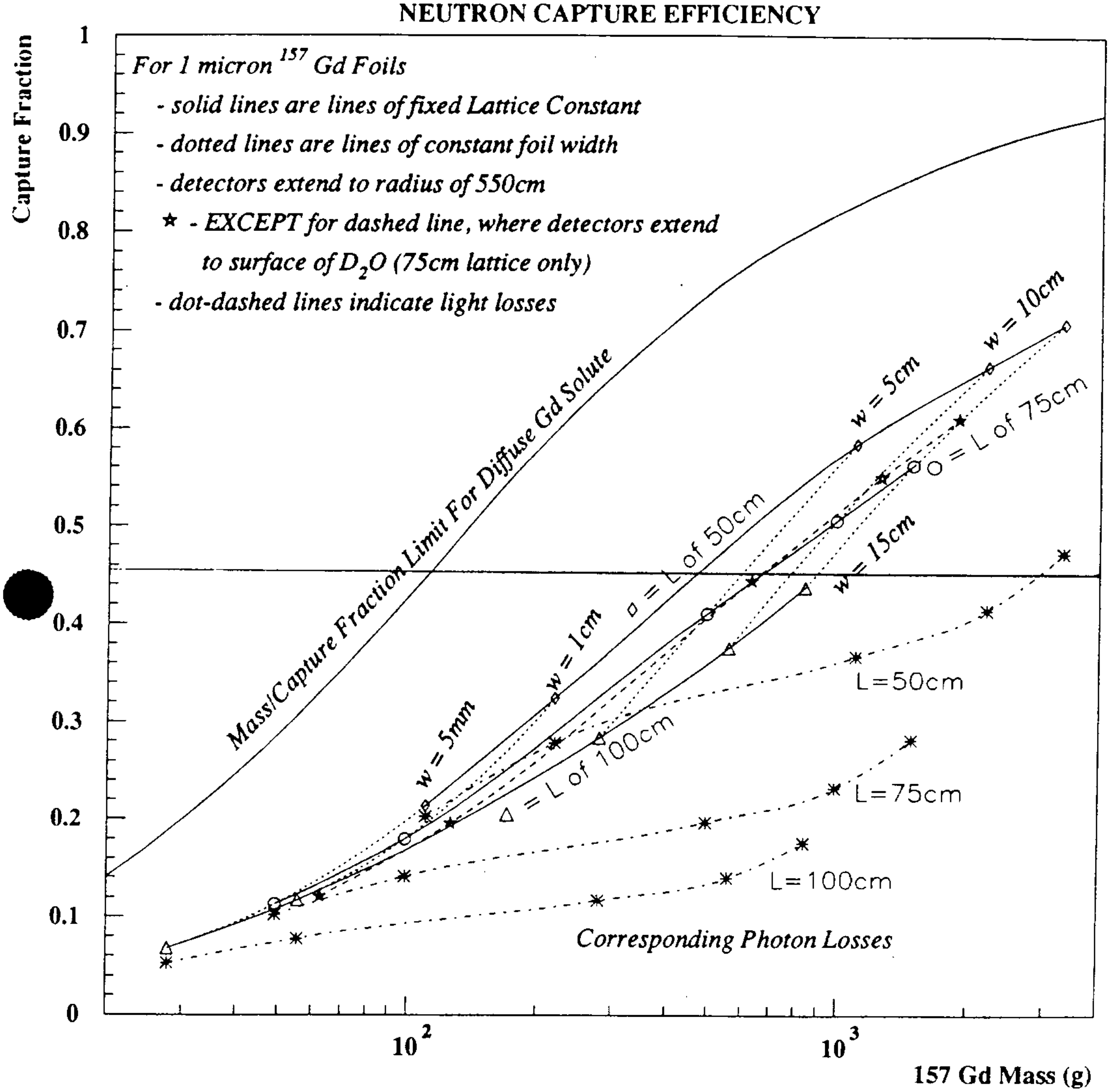

NEUTRON CAPTURE EFFICIENCY
Capture Fraction
157 Gd Mass (g)
For 1 micron ^{157}Gd Foils
- solid lines are lines of fixed Lattice Constant
- dotted lines are lines of constant foil width
- detectors extend to radius of 550cm
★ - EXCEPT for dashed line, where detectors extend to surface of D_2O (75cm lattice only)
- dot-dashed lines indicate light losses
Mass/Capture Fraction Limit For Diffuse Gd Solute
w = 5mm
w = 1cm
w = 5cm
w = 10cm
w = 15cm
◇ = L of 50cm
○ = L of 75cm
△ = L of 100cm
L=50cm
L=75cm
L=100cm
Corresponding Photon Losses
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
10^2
10^3

Fig 2

Efficiency vs Outer Radius of Neutral Current Counters

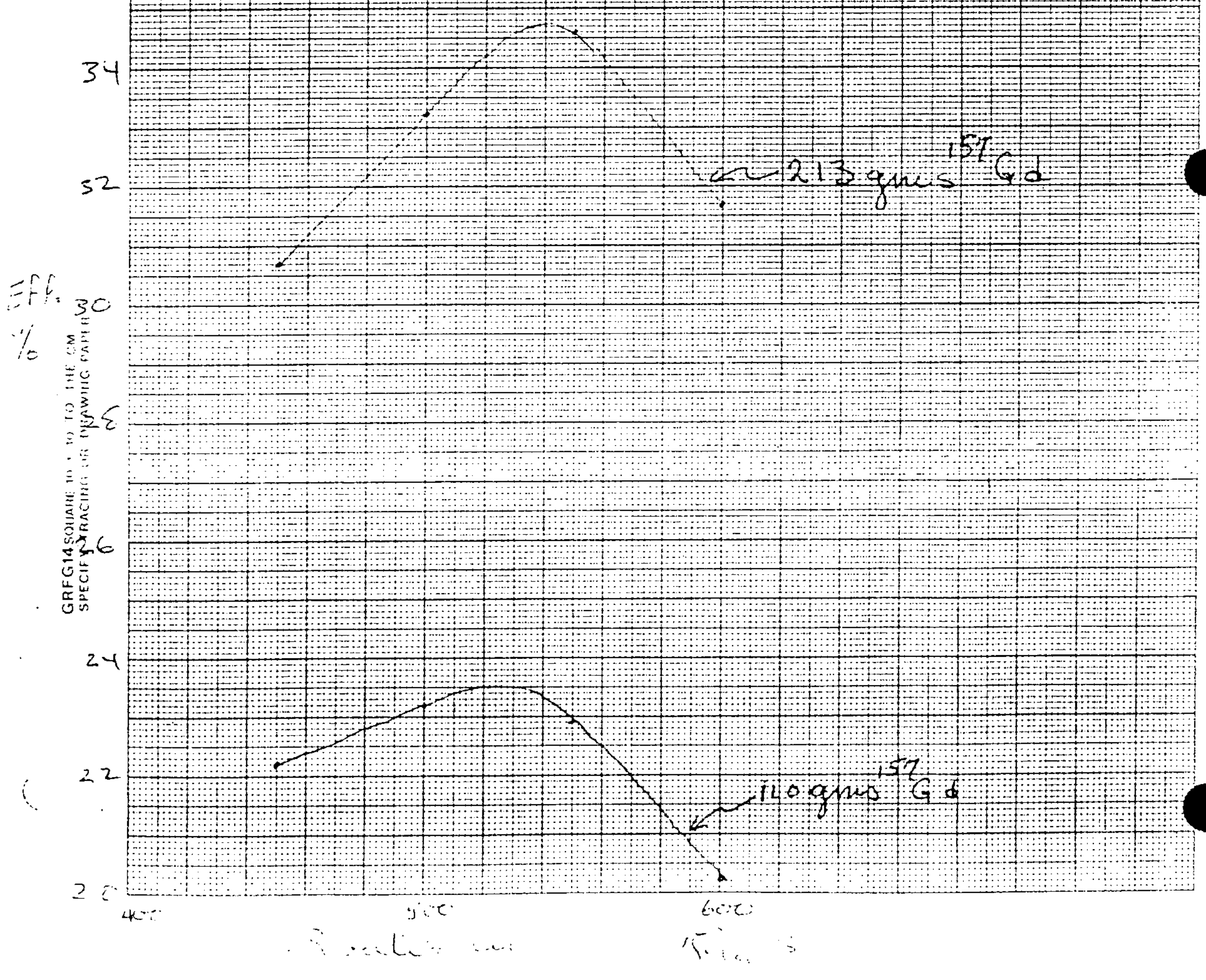


Fig. 5

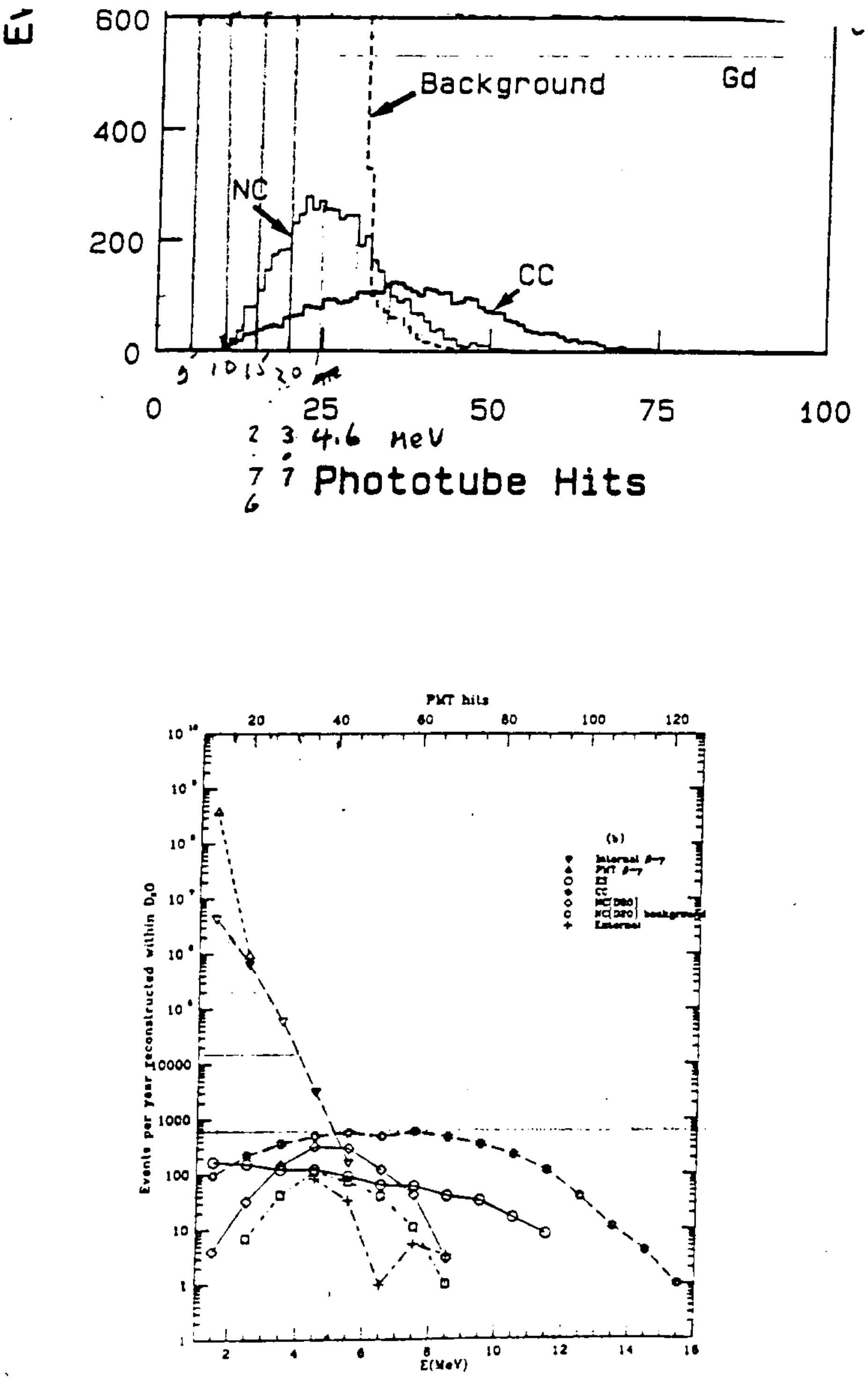

E
600
400
200
0
Background
Gd
NC
CC
5
10
15
20
25
0
25
50
75
100
2
3
4.6 MeV
7
7
6
Phototube Hits
PMT hits
20
40
60
80
100
120
10^{10}
10^9
10^8
10^7
10^6
10^5
10000
1000
100
10
1
1
Events per year reconstructed within D_2O
(b)
Internal β-γ
PMT β-γ
CC
NC[D2O]
NC[D2O] background
External
2
4
6
8
10
12
14
16
E(MeV)

Fig 4

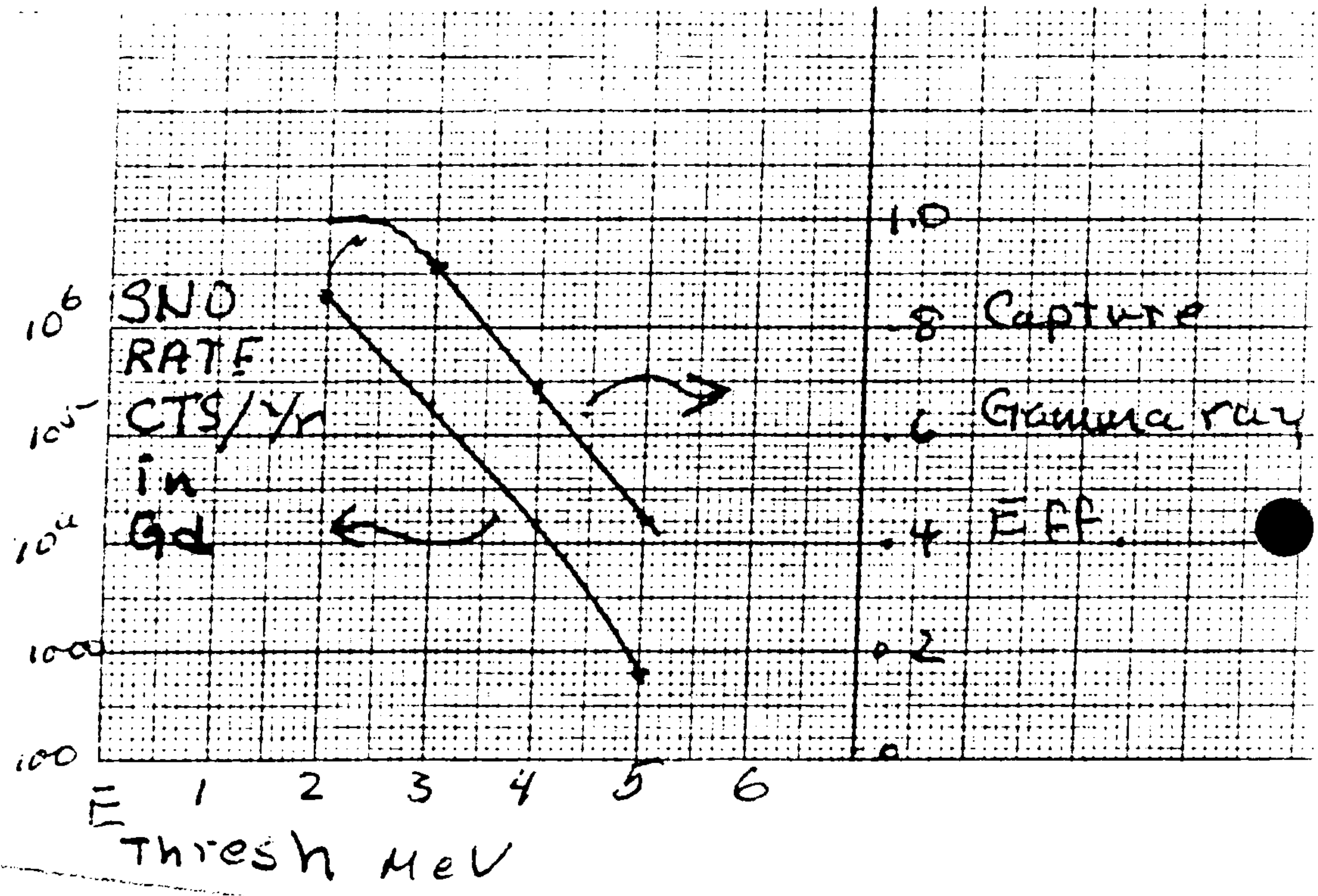

10⁶
10⁵
10⁴
1000
100
SNO
RATE
CTS/Yr
in
Gd
1.0
.8
.6
.4
.2
0
Capture
Gamma ray
Eff.
1
2
3
4
5
6
E Thresh MeV

Fig 5

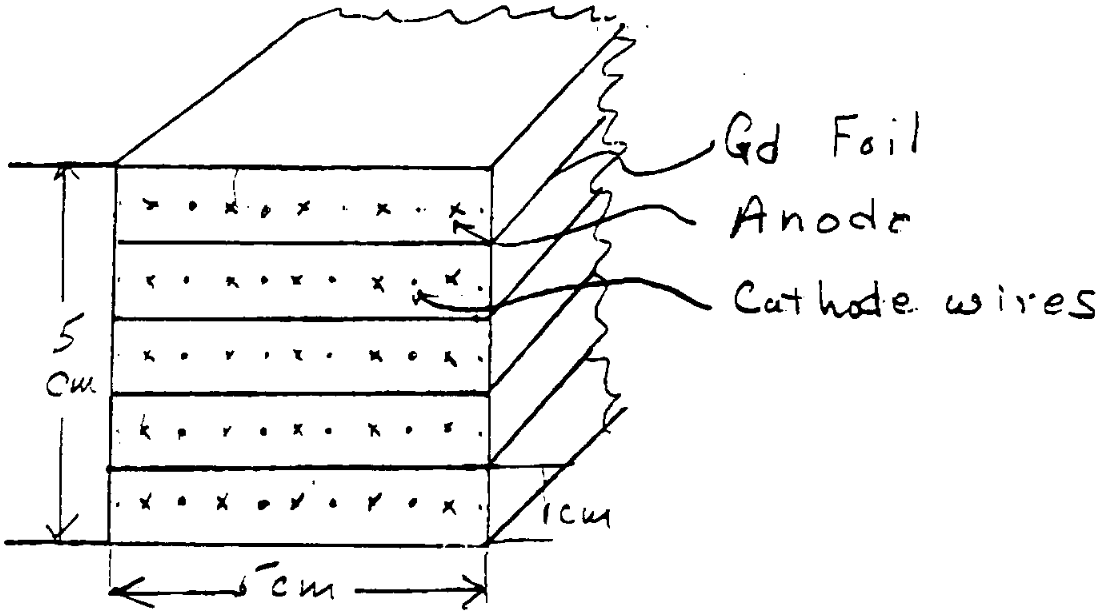
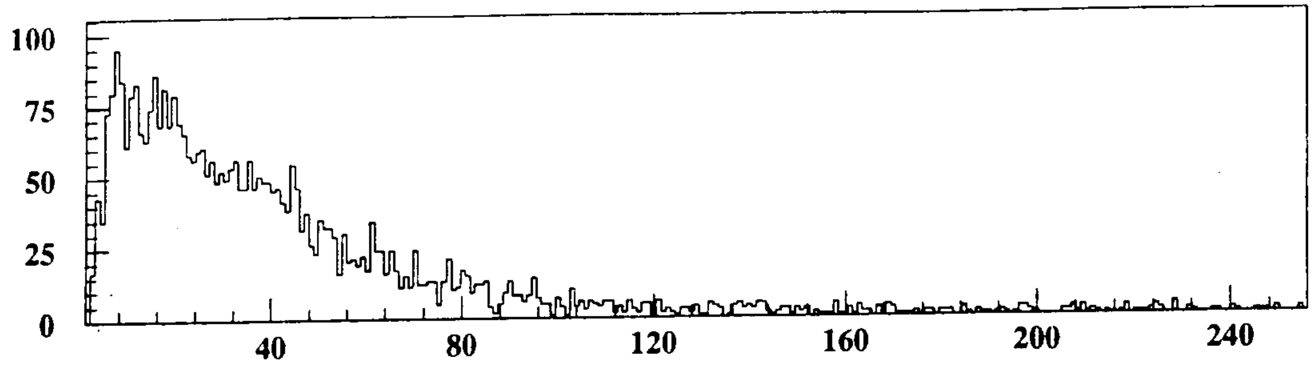
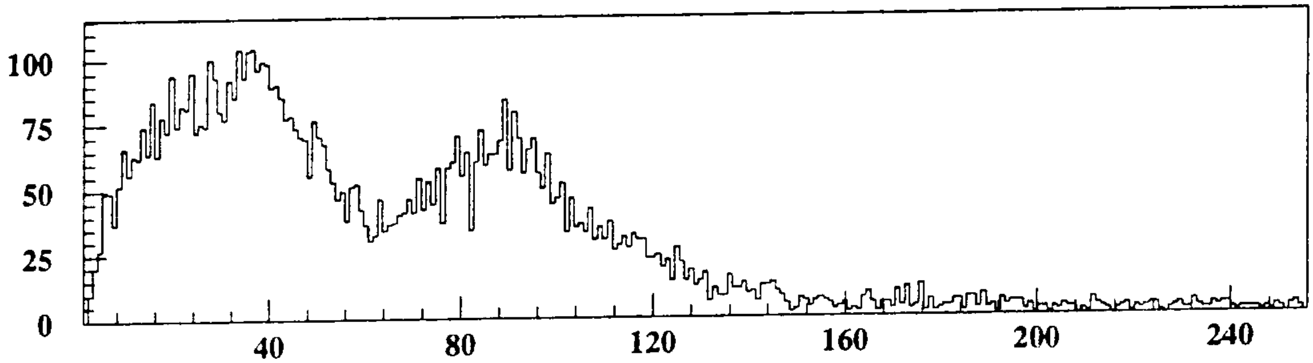


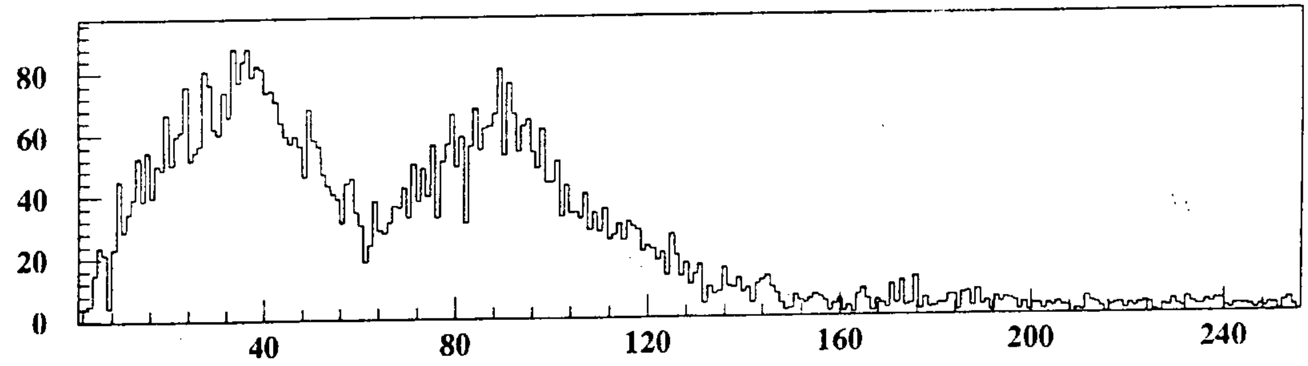
Figure 6



PWC Spectrum Background



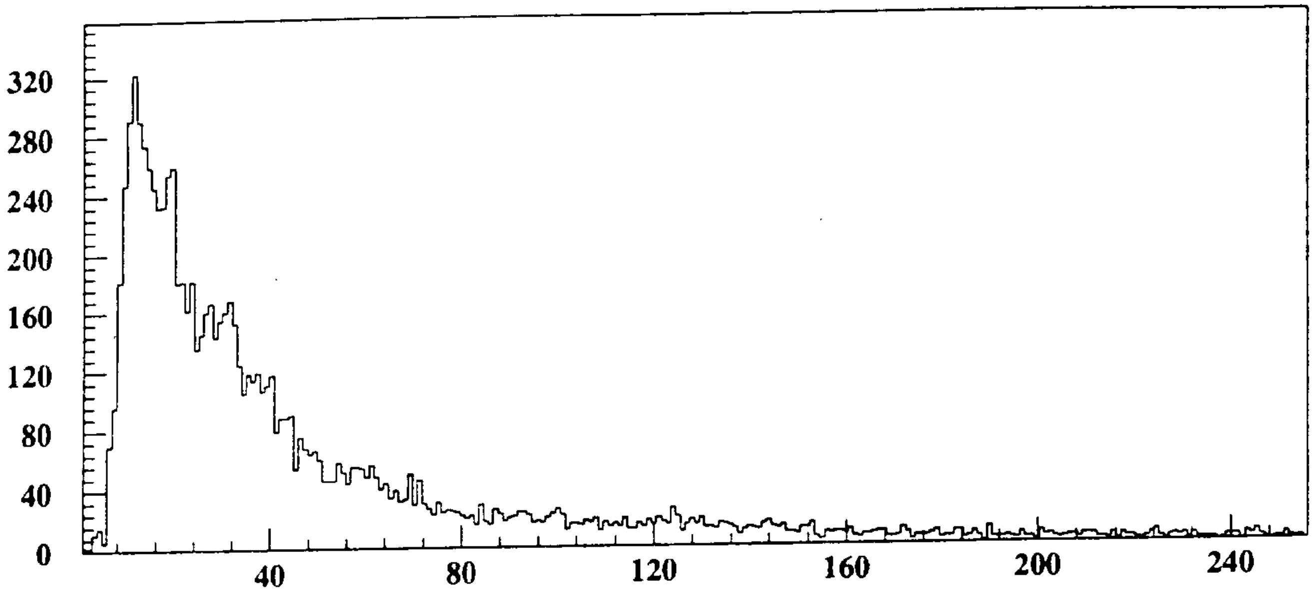
PWC Spectrum Neutrons



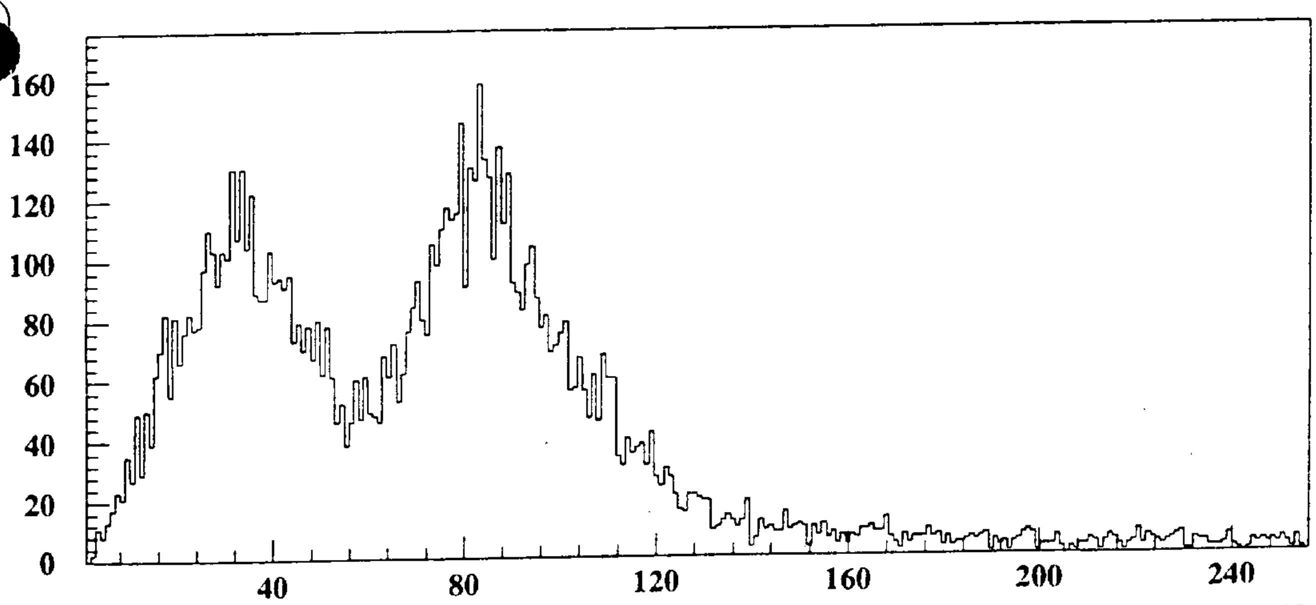
Runs jan0313 and jan314

PWC Spectrum Neutrons - Background

Fig 8



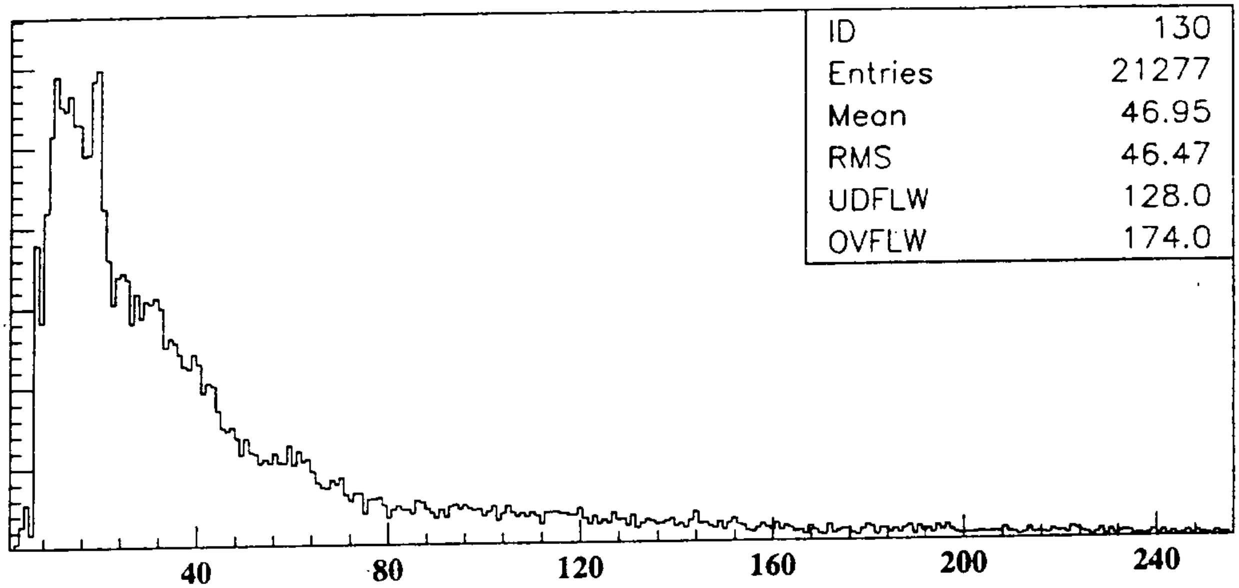
NAI Spectrum in Copinc. with PWC



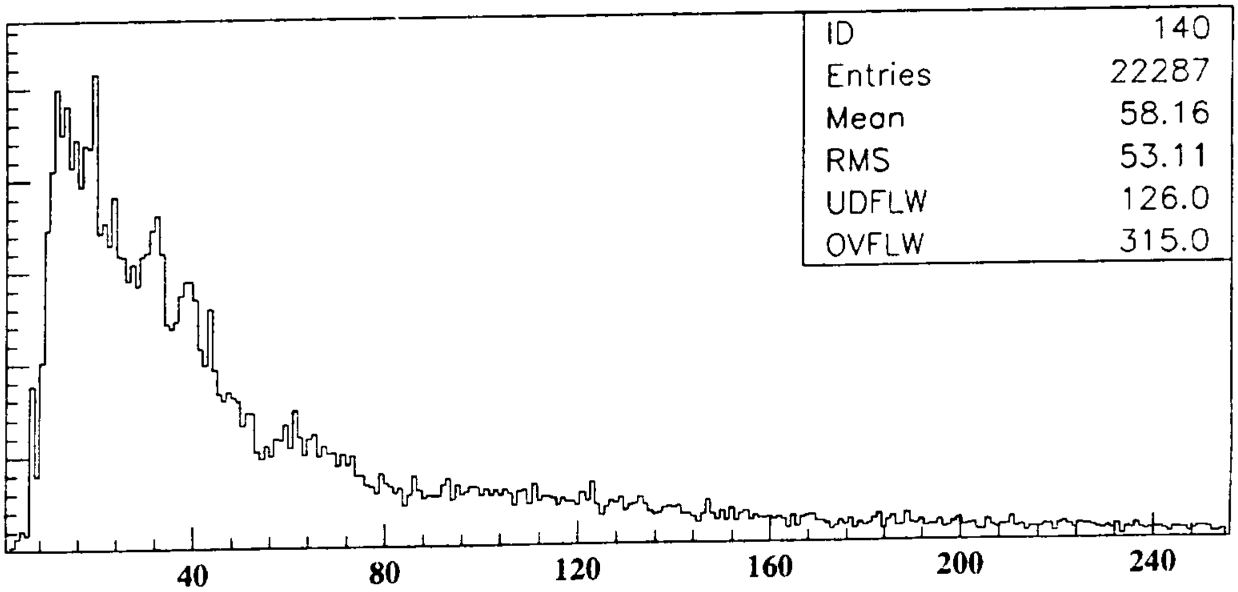
run jan0315.r80

PWC Spectrum in Coinc. with NAI

Fig. 9



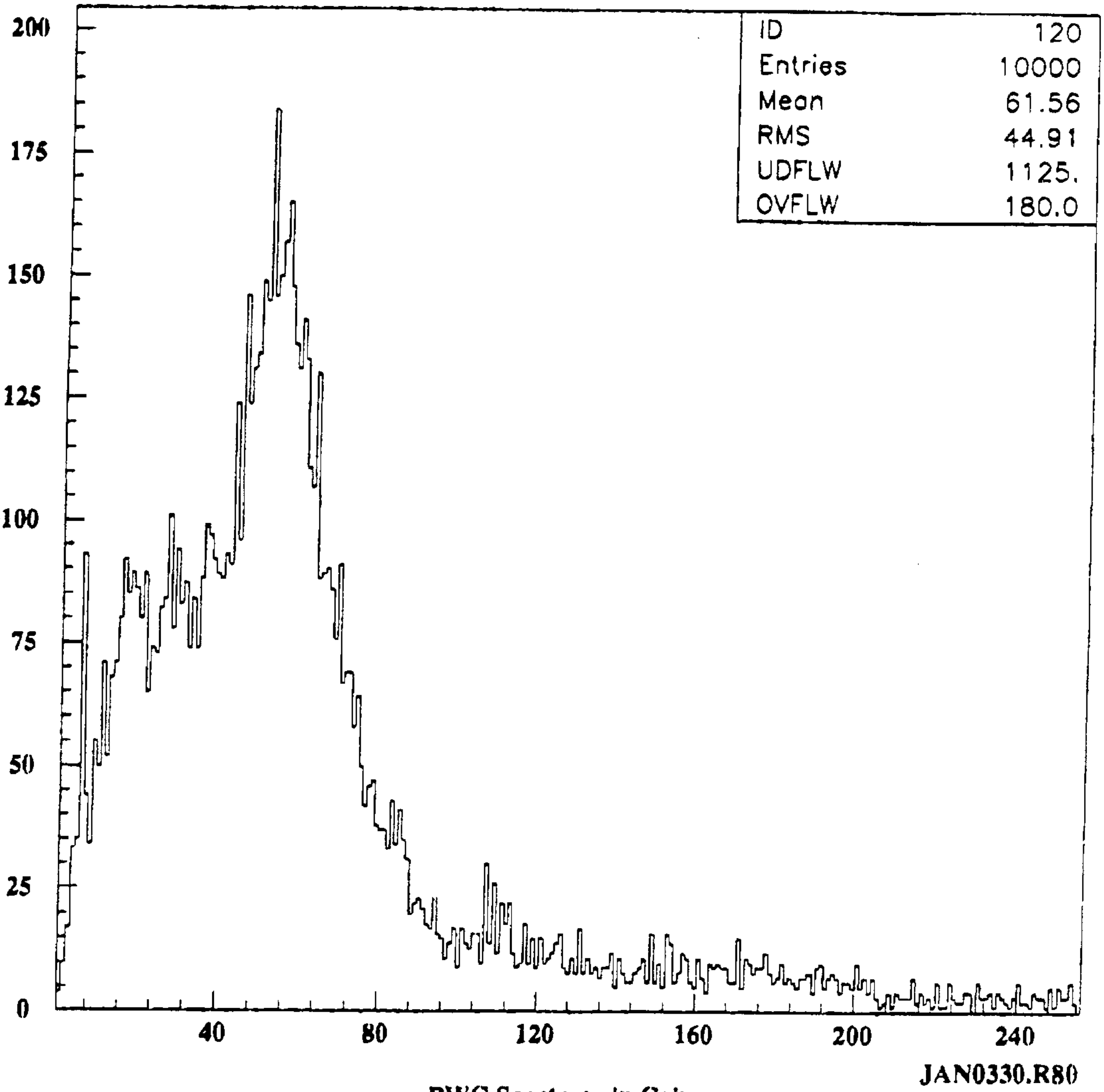
NAI Spectrum 0<PWC<60



run JAN0316.R80

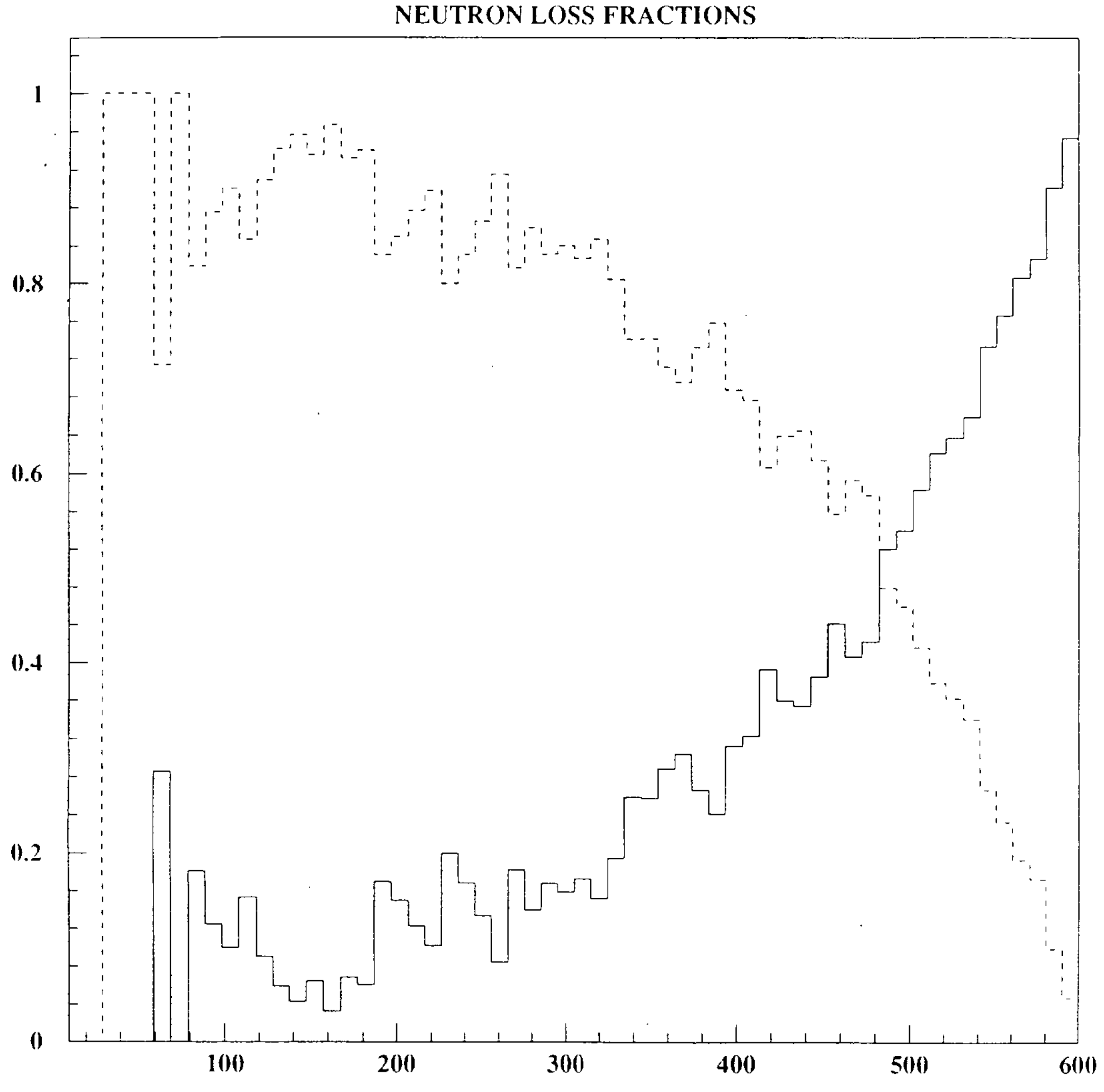
NAI Spectrum 60<PWC<120

Fig. ~~10~~ 9



PWC Spectrum in Coinc

Fig. 10



FRACTIONAL LOSS vs BIRTH RADIUS

Fig 11