ITR-15

SOUTHWESTERN RADIOLOGICAL HEALTH LABORATORY

INTRALABORATORY TECHNICAL REPORT

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PRELIMINARY REPORT ON THE PERFORMANCE OF A 10 X 10 INCH PLASTIC SCINTILLATOR IN THE WHOLE-BODY COUNTER

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SUMMARY

A 10 x 10 inch plastic scintillator was installed in the whole-body counting chamber at the Southwestern Radiological Health Laboratory (SWRHL) for the purpose of evaluating its spectral response in comparison with a 4 x 9 inch and 4 x 11.5 inch NaI(Tl) crystal detector. The investigation took place in one room (Whole-body counting chamber) of a pair of steel chambers located 20 feet below ground level in a large basement enclosure shielded by concrete and earth. Each crystal assembly was coupled with a 400 channel analyzer with integrator-resolver, magnetic and paper tape output and input, type-out, and x-y plotter accessories.

The sensitivity of the plastic scintillator, measured in photopeak efficiency over an energy band width from 0.66 MeV to 1.12 MeV, matched closely the gamma efficiency for the 4 x 11.5 inch NaI(Tl) detector.

The resolution of the plastic scintillator for an energy band of the same width was of a magnitude from five to seven times larger than observed with either the 4 x 9 inch or 4 x 11.5 inch detector. Other investigations included: total room background activity; rotation of the plastic scintillator on an axis to detect any drift of activity; and

fall-off rate of a point source moved on a directed line away from the 4 x 11 inch and plastic detector. Each of the detector systems and the method and results of the investigation are described in detail.

EXPERIMENTAL

The SWRHL Whole-body counting facility consists of a large underground room (20 ft. below surface level) which encloses a pair of steel chambers identical in physical dimensions (12'L x 8'W x 9'H). Each chamber is constructed of clean, pre-World War II, 6 inch thick plate steel and is lined with 1/8 inch each of lead and stainless steel. Both chambers weigh 160 tons and each room is entered through a single swing-type steel door. One chamber contains an Ohio-nuclear scanner consisting of a single overhead NaI crystal and four smaller crystals below bed level. The other room contains the whole-body detector, a 4 x 11.5 inch NaI(Tl) crystal (Figure 1), which is mounted on an overhead support, allowing three-dimensional movement for crystal placement.

The 4 x 11.5 inch NaI(Tl) crystal is used on a regular basis at the SWRHL facility for the whole-body counting of individuals who have been exposed to fission-yield products connected with operations at the Nevada Test Site.

The crystal is optically coupled to a 2 inch unactivated NaI light pipe, canned in stainless steel, and attached to seven matched venetian-blind dynode photomultipliers. A 4 x 9 inch NaI(Tl) crystal is also canned in stainless steel and is optically coupled to four photomultipliers. A plastic scintillator (Figure 2) is optically coupled to an unactivated (Vycor) light pipe, canned in aluminum and attached to a single 5 inch photomultiplier.

The spectral response from a plastic scintillator when even a mono-energetic source such as ^{137}Cs is counted, presents special problems not confronted in NaI crystal spectrometry. Figure 3 shows a typical spectrum obtained by counting the same source (^{137}Cs) in the same geometry under the 4 x 11.5 inch NaI and 10 x 10 inch plastic crystals. The extent of peak broadening from the plastic scintillator is greatly in excess of the NaI generated peak.

For a NaI crystal, the cross sections for Compton and photoelectric interaction vary according to gamma-energy. The ^{137}Cs peak is the result of total energy absorption either by single photoelectric collision or multiple Compton interaction. The contribution of Compton scattered photons resulting in partial energy loss is diminished due to the density and size of a large detector. This leads to a peak with minimal spectral broadening (the photopeak), since the contribution of the total energy loss, due mostly to the photoelectric effect, is maximal.

The pulse-amplitude spectrum from a plastic scintillator differs in that the total cross-section for absorption is dominated by the Compton interaction. Primarily due to the density of the plastic detector, the probability is high that an initial incoming photon or Compton-scattered gamma photon will escape the volume of the detector. Therefore, the pulse from this type of spectrum can best be described as a "Compton-peak" which results from Compton-scatter followed by photon absorption or escape.*

Another contribution to spectral broadening is the multiple interaction in the scintillator from back-scattered photons which increases the total energy deposited beyond the energy corresponding to the Compton edge. This event broadens the spectrum on the high-energy side.[1] Consequently, the delineation of a photopeak by Compton subtraction techniques suitable for NaI spectrometry magnifies to a problem of identifying a peak corresponding to some given pulse height from a Compton smear. This becomes a nearly impossible task for multipeak spectrums.

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* In this paper the terms photopeak and Compton-peak are used interchangeably.

A worthy illustration of the problem of applying NaI spectrometry techniques to a plastic scintillator is the variation of Compton-peak efficiency obtained with the latter: 0.249%; 0.090%; and 0.017%.**

Three different approaches to the difficulty of resolving a peak to obtain a "figure of merit" by which the plastic scintillator could be compared to the NaI detector, included as a basis:

a. The use of photopeak efficiency by selecting an energy band of sufficient width to correspond to either;

   1. One-half peak height, applicable to only those isotopes used which gave a peak/Compton trough ratio of two or more;

   2. Or two-thirds peak height. This grew out of the need to furnish as a basis of comparison the relative efficiency of the photopeak, which would eliminate many of the errors associated with the Compton continuum, and which would permit the application of a simple, accurate, and reliable technique.

b. The treatment of an energy band of varying width (channel width) as a window to obtain total efficiency.

** These values were obtained by integration and Compton subtraction of the ^{137}Cs photopeak channels: 40-95; 44-78; 40-78 respectively, and indicates initial attempts to resolve the photopeak by separation of channels which contribute to either a definite rise or fall of activity to either side of the peak channel(s).

RESULTS

From the calibrated standards available, only those were chosen which were suitable as monoenergetic sources and provided sufficient activity to reduce statistical error to a minimum.* Each standard was counted in a geometry identical for each crystal: .6 meter from the crystal center. The choice of .6 meter was necessitated by our use of this geometry in whole-body counting measurements of people at the station. Figures 1 and 2 show the final placement of the plastic and 4 x 11.5 inch NaI crystals respectively (although not shown the 4 x 9 inch NaI crystal placement is similar to Figure 2).

The spectral response of the plastic scintillator is essentially constant with any change in direction of the detector over a point source. By rotating the detector on an axis from zero to ninety degrees, the maximum efficiency detectable was in a position where the photocathode end in contact with the crystal window, faced the source. However, this exceeded any other position by no more than 5 percent. The slight difference in response can be traced to a change in light collection efficiency at the photocathode which is a function of the position of the scintillation event.[2]

A comparative analysis of representative spectra from ^{137}Cs, ^{54}Mn, and ^{65}Zn, obtained in each case from the NaI 4 x 11.5 inch crystal and plastic scintillator (Figures 3, 4 and 5), reveals that with the latter, (a) the photopeak response on a per channel basis is much lower, (b) secondary peaks such as backscatter, annihilation, and x-ray, are not resolved, (c) linear response is poor, especially above 1.0 MeV, (d) Compton continuum response is very nearly

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* ^{137}Cs, ^{54}Mn, ^{65}Zn in 400 ml cottage cheese containers.

equal in magnitude to the NaI crystal between 0.2 MeV and the lower energy side of the photopeak. Below 0.2 MeV the Compton electron (and combined x-ray) response rises sharply above the NaI detector.

From Table I and the results shown plotted in Figure 6, it can be seen that the photopeak efficiency measured at either one-half (for ^{65}Zn only) or two-thirds peak height are nearly identical for the plastic and NaI 4 x 11.5 inch crystals, either of which are higher than the 4 x 9 inch NaI crystal. As explained earlier, the peak/Compton trough count-rate ratio from the plastic detector never approached a value of two for ^{137}Cs and ^{54}Mn, so that no information is available at one-half peak height.

An interesting comparison can be made of the foregoing results with those of Table II, and from it, Figures 7, 8, and 9. The selected window efficiencies were normalized to unit activity for each separate isotope in the band width 0-1.99 MeV. For all window settings, the relative efficiency for the plastic crystal assumes values which range from a minimum of 2.5% (^{137}Cs, 0-199) to a maximum of 25% (^{54}Mn, 20-199) below corresponding efficiencies for the 4 x 11.5 inch NaI crystal.

It is apparent that the spread in window efficiency between the two crystals increases both with a reduction in size of the window and with the lowering of the gamma photon energy characteristic of each isotope. These results are due in part to and are complicated by the superimposition of secondary peaks upon the NaI generated spectrum such as the ^{65}Zn .51 MeV annihilation and ^{137}Cs backscatter peaks.

Referring once again to Table I, and Figures 10 and 11, the resolution of all three detectors was determined at one-half and two-thirds peak height. At the highest energy (1.12 MeV), the best resolution achieved

Table I. Gamma efficiencies and resolution at one-half and two-thirds peak height.

X-Ray Energy (MeV)	Gamma Efficiency at 1/2 peak-height (%)			Resolution at 1/2 peak-height $W_{1/2}/A \times 100$ (%) [a]		
	Plastic	NaI 4x11.5"	NaI 4x9"	Plastic	NaI 4x11.5"	NaI 4x9"
0.66	- [b]	-	-	≥ 89.0 [c]	9.90	10.4
0.84	-	-	-	≥ 49.5	9.32	9.04
1.12	0.13	0.14	-	39.6	8.20	-
	Gamma Efficiency at 2/3 peak-height (%)			Resolution at 2/3 peak-height $W_{2/3}/A \times 100$ (%) [a]		
0.66	0.089	0.088	0.038	54	7.55	8.30
0.84	0.092	0.089	0.032	39	7.45	7.35
1.12	0.074	0.074	-	26	6.54	-

(a) $W_{1/2}$ is width of peak at half-height.

A is peak position.

$W_{2/3}$ is width of peak at two-thirds height.

(b) (-) indicates no information available.

(c) ≥ indicates greater than or equal to.

Table II. Window efficiencies* from plastic and NaI(Tl) detector units.

Energy Band Width in Channels (10 KeV/Channel)	0.66 MeV (^{137}Cs)			0.84 MeV (^{54}Mn)			1.12 MeV (^{65}Zn)		
	(a) NaI 4x11.5 in.	(b) Plastic	Percent Below (a)	(a) NaI 4x11.5 in.	(b) Plastic	Percent Below (a)	(a) NaI 4x11.5 in.	(b) Plastic	Percent Below (a)
0-199	1.000	0.975	2.50	1.000	.810	19.0	1.000	0.950	5.00
10-199	0.958	0.833	13.1	0.883	.722	18.2	0.933	0.884	5.40
20-199	0.841	0.675	19.9	0.810	.606	25.3	0.859	0.760	11.6
40-199	0.633	0.475	25.0	0.547	.467	14.7	0.677	0.620	8.60

*Efficiencies have been normalized to unit activity in the energy band 0-1.99 MeV.

from the plastic detector was 39.6% compared to 8.20% from the NaI 4 x 11.5 inch detector. As the gamma energy decreases below about 1.0 MeV, the resolution at either one-half or two-thirds pulse-height becomes astronomical. Part of the explanation for the very poor resolution obtainable with the plastic detector lies in the use of a single photomultiplier tube. Better resolution can be achieved with the addition of phototubes of the same or larger size (which among other benefits, would increase the light collection efficiency).*

With the information from Tables I and II in mind, an interesting comparison can be made with the background observation shown in Figure 12. The background obtained first from the NaI 4 x 11.5 in crystal reveals the presence of ^{226}Ra decay peaks (which originate by radon emanation from the concrete walls below ground level) and the usual ^{40}K photopeak. The background from the plastic scintillator indicates (a) the absence of any photopeaks, (b) that the Compton continuum in an energy band from about 0.2 MeV to 2.0 MeV is nearly identical to NaI crystal, (c) that the rise in activity below 0.2 MeV accounts for by far the greatest response in total activity. These facts are borne out more clearly in Table III which presents data that has been single-channel analysed from Figure 12.

Of immediate concern is the four-fold increase of total activity (channel 0-199) from the plastic over the NaI crystal. As seen earlier, the plastic scintillator, using the same energy band width, gave a window efficiency slightly lower than the NaI crystal.

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*The best results for improving one-half resolution (for a plastic detector 6 1/2 x 10 x 20 in.) have come from the use of a smaller number of large diameter photomultipliers (two - 7 in tubes) rather than the use of a large number of smaller size photomultipliers (four - 5 in tubes).[3]

Table III. Response of a plastic and NaI(Tl) 4 x 11.5 inch detector units to background (CPM/CHANNEL).

Detector Unit	Channel Limits (10KeV/Channel) 0-199	0-10	11-20	21-40	41-80	81-130	131-199
Plastic Scintillator	8041	4944	1759	477	435	224	164
NaI(Tl)4x11.5 Inch	1978	654	248	494	506	237	157

Only a minimum of information was compiled from the whole-body counting of individuals in the arc chair under the plastic crystal. The primary problem involved is one of determining where the limits of a photopeak are located energy-wise since the subject (with normal body burdens of ^{137}Cs and ^{40}K) and room background spectra are almost identical in shape. If an arbitrary band width of channels 41-80 is chosen, corresponding to the approximate area under a ^{137}Cs photopeak, the counting statistics standard error for a 10 minute count under a .6 meter arc is ± 7.2 percent. A similar count using a NaI 4 x 11.5 inch crystal gives a standard error of $\pm 10.5\%$. The error may, of course, be reduced if either crystal is moved closer to the body. Thus, at a counting distance of 10 cm. from the plastic crystal center to the body navel, the error reduces to ± 3.7 percent.

A final study was made of the effects of moving a point source (Mn^{54}) a line distance away from the plastic and NaI 4 x 11.5 inch detectors. The results are shown in Figure 13, with all measurements made from the centers of both crystals and with channels 11-199 integrated to give total activity. As expected, the relative efficiency of the NaI detector is highest at all source distances and both detectors follow the inverse square law except for a distance greater than about 160 inches for which no measurement was made.

CONCLUSION

From the information presented, it is obvious that several errors operate in conjunction to give a poor reliability index in any series of whole-body counting measurements. Before using the plastic detector in this regard, it would be mandatory to assess and possibly reduce the contribution of all errors associated with either the gamma spectral analysis or with the detector system itself.

REFERENCES

1. Burch, P. R. J., Hughes, D., Iinuma, T. A., Overton, T. R., and Appleby, D. B.

   Proceeding of the Symposium on Whole-Body Counting, International Atomic Energy Agency, Vienna, Austria, (June 12-16, 1961), 65.

2. Ibid., p. 66.

3. Ibid., p. 64.

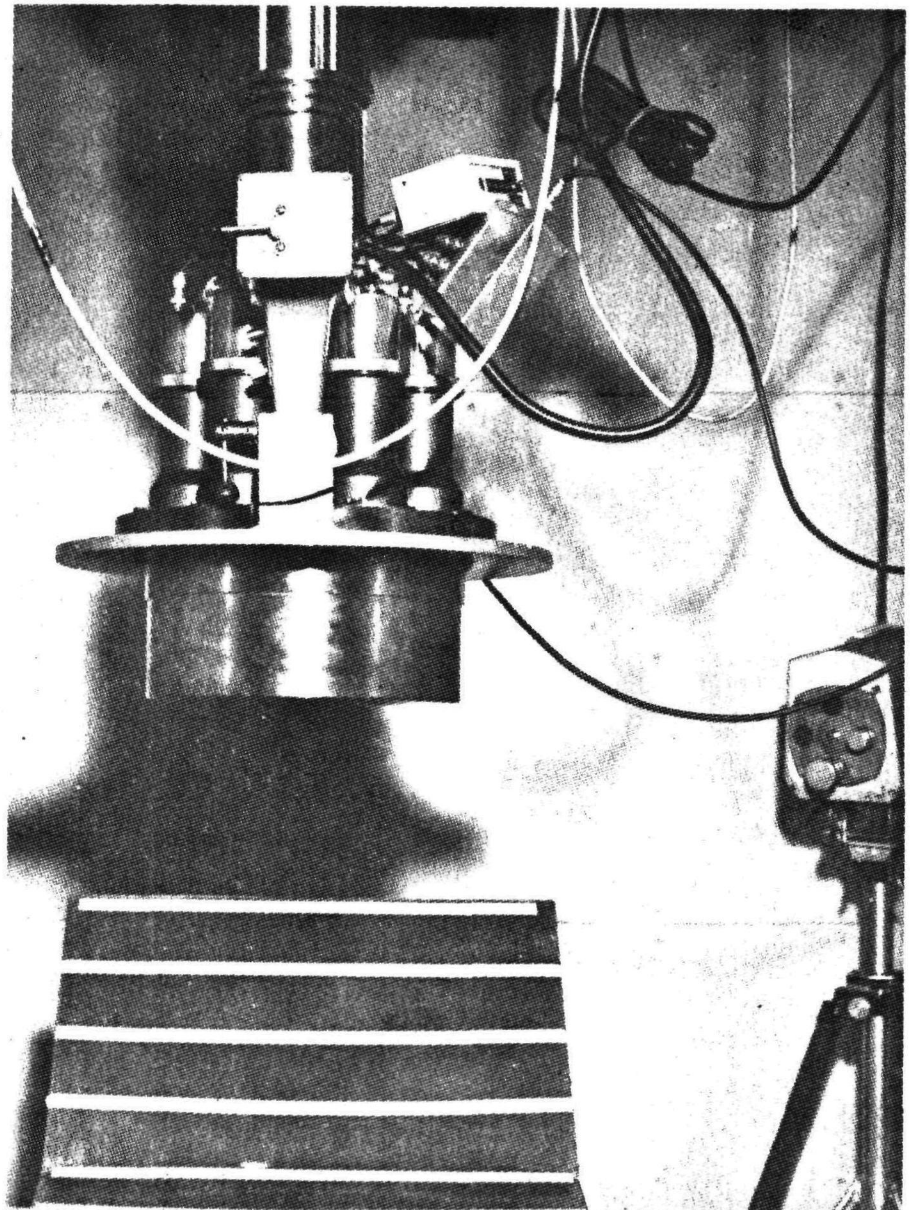


Figure 1. 4 x 11.5 inch NaI(Tl) crystal detector supported by a Picker X-Ray mount in the whole-body chamber.

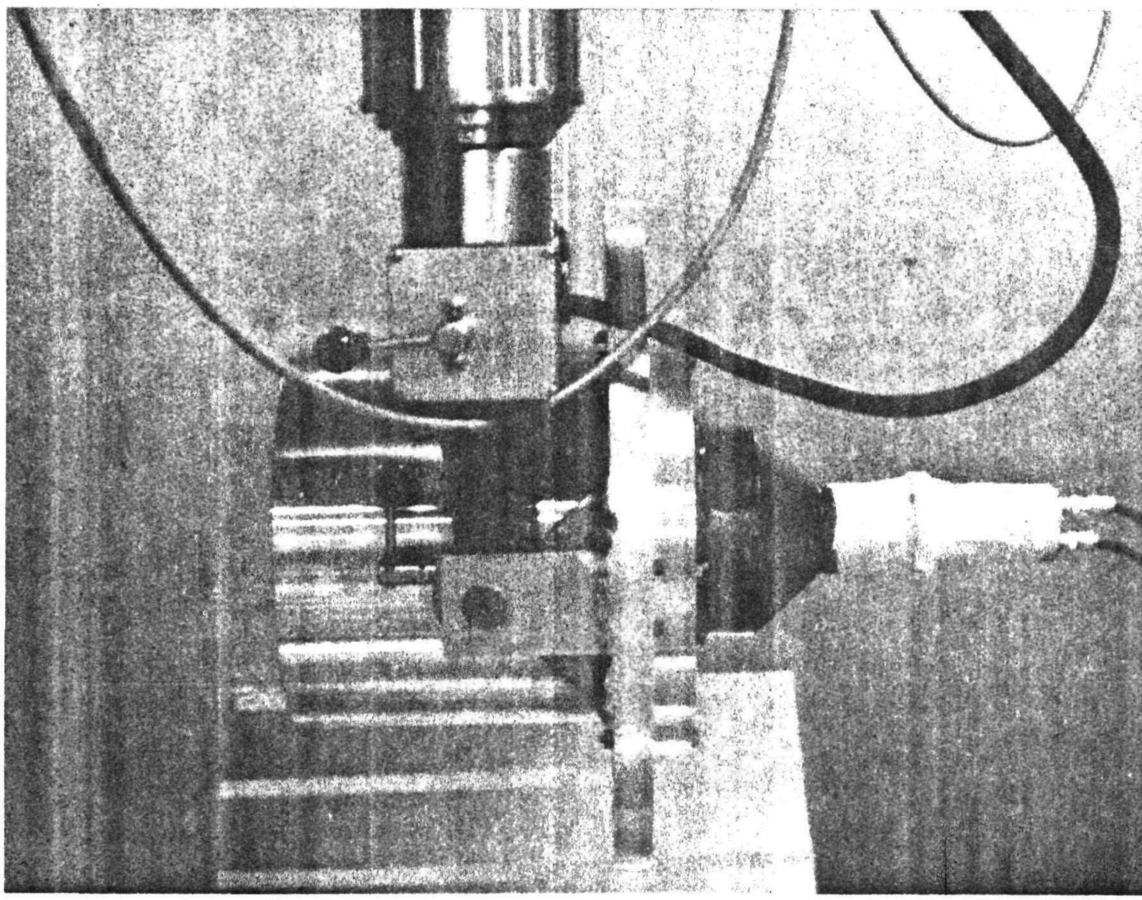
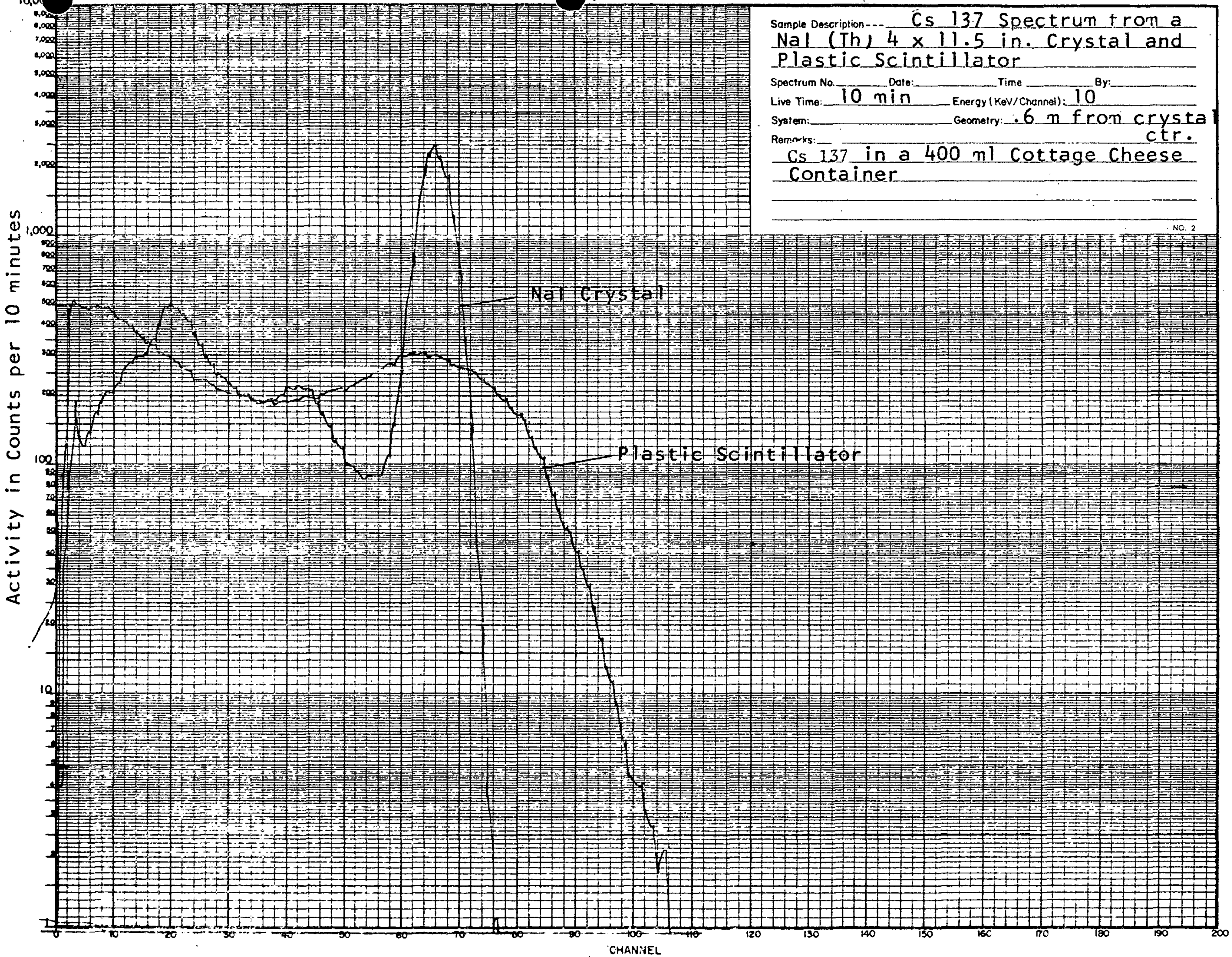


Figure 2. 10 x 10 inch plastic scintillator detector supported by a Picker X-Ray mount in the whole-body chamber.

Fi 3



Sample Description--- Cs 137 Spectrum from a NaI (Th) 4 x 11.5 in. Crystal and Plastic Scintillator
Spectrum No. Date: Time By:
Live Time: 10 min
Energy (KeV/Channel): 10
System:
Geometry: .6 m from crystal ctr.
Remarks:
Cs 137 in a 400 ml Cottage Cheese Container
NO. 2
NaI Crystal
Plastic Scintillator
Activity in Counts per 10 minutes
CHANNEL
10,000
1,000
100
10
1
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200

Fig. 4

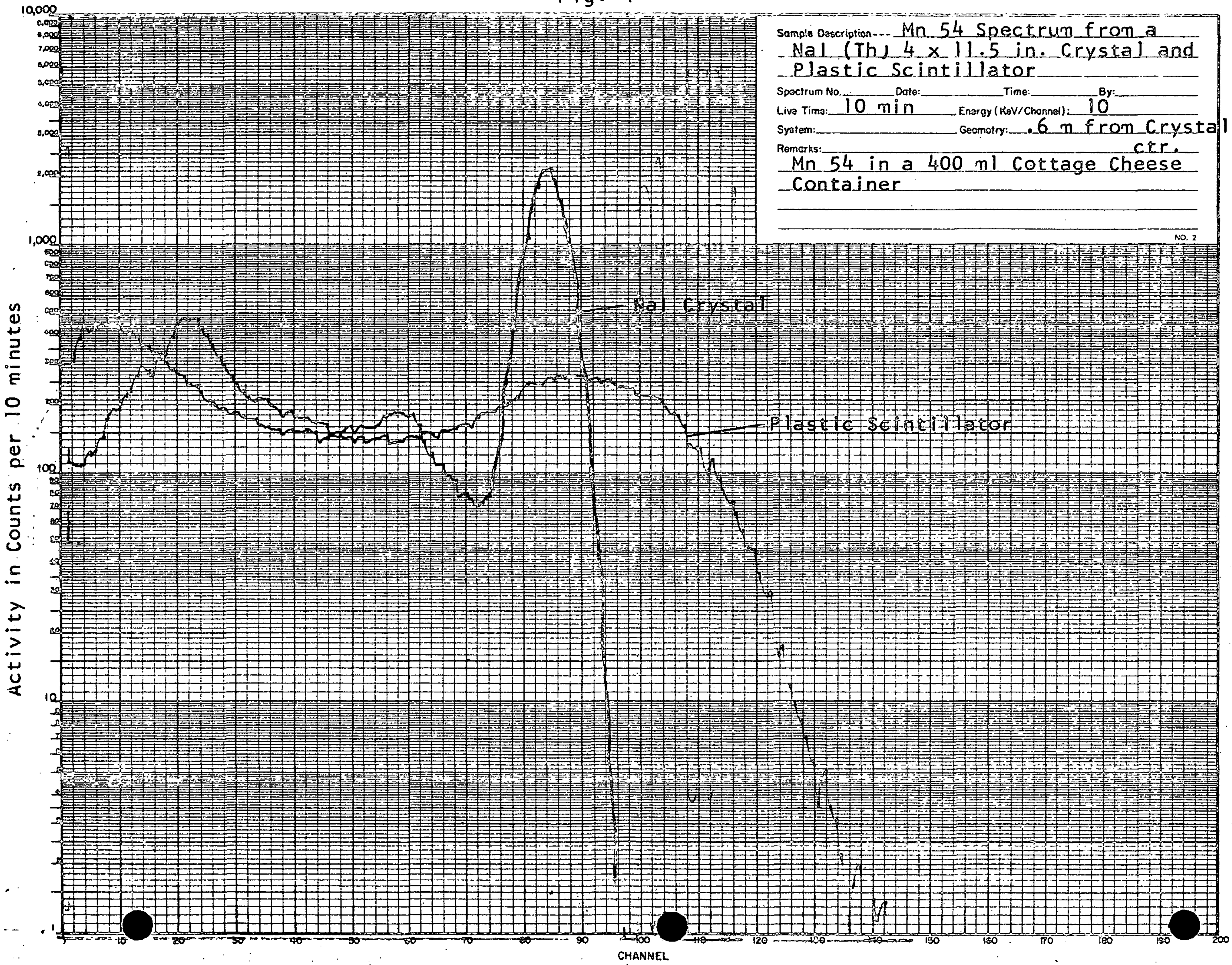

Sample Description--- Mn 54 Spectrum from a NaI (Th) 4 x 11.5 in. Crystal and Plastic Scintillator
Spectrum No. Date: Time: By:
Live Time: 10 min Energy (KeV/Channel): 10
System: Geometry: .6 m from Crystal ctr.
Remarks: Mn 54 in a 400 ml Cottage Cheese Container
NO. 2
NaI Crystal
Plastic Scintillator
Activity in Counts per 10 minutes
CHANNEL
10,000
1,000
100
10
1
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200

Fig. 5

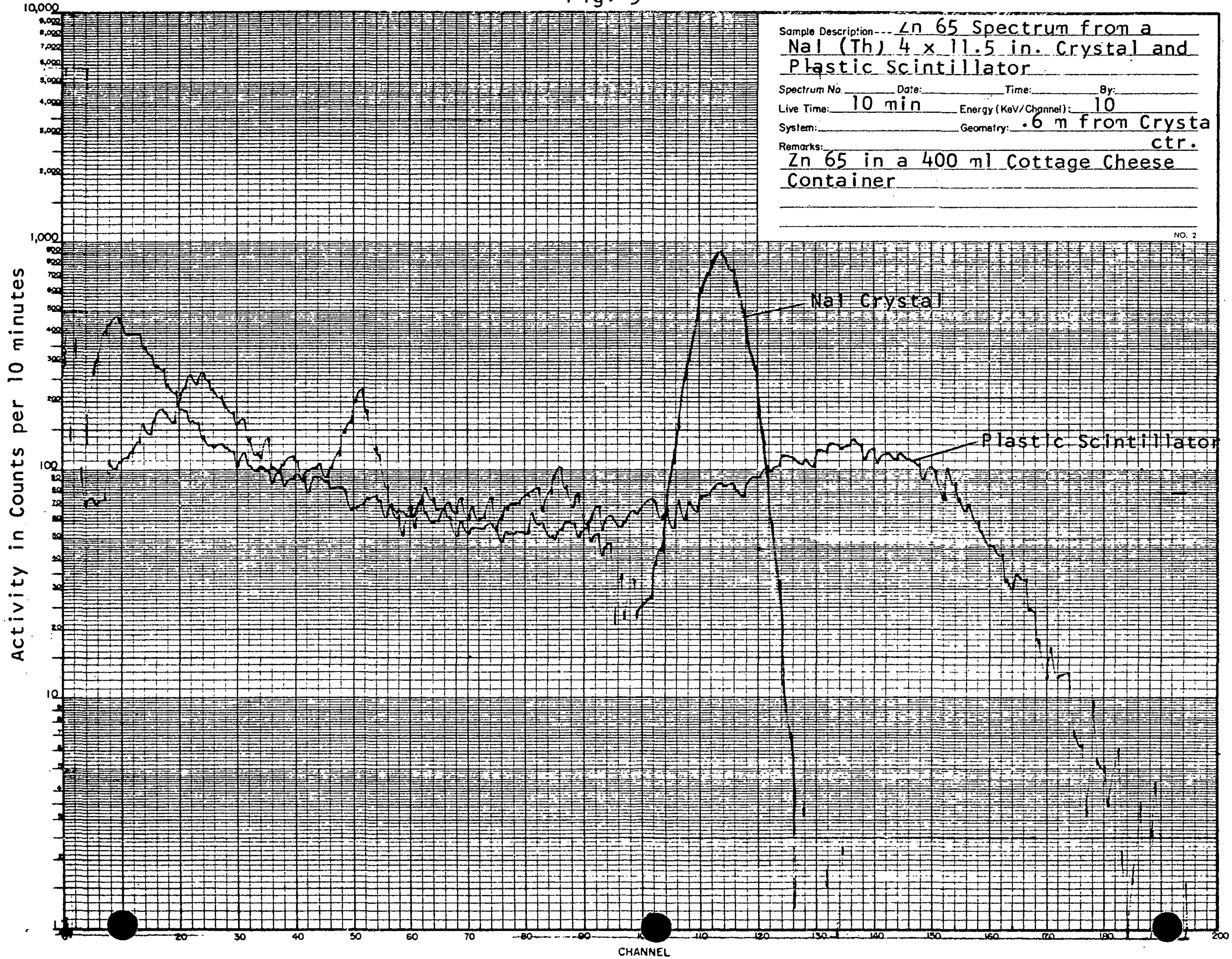

Sample Description--- Zn 65 Spectrum from a NaI (Th) 4 x 11.5 in. Crystal and Plastic Scintillator
Spectrum No. Date: Time: By:
Live Time: 10 min Energy (KeV/Channel): 10
System: Geometry: .6 m from Crysta ctr.
Remarks: Zn 65 in a 400 ml Cottage Cheese Container
NO. 2
NaI Crystal
Plastic Scintillator
Activity in Counts per 10 minutes
CHANNEL

Fig. 6 GAMMA EFFICIENCY OF PLASTIC SCINTILLATOR AND NA (Th) 4" x 11.5", AND 4' x 9' CRYSTALS AT TWO-THIRDS PEAK-HEIGHT

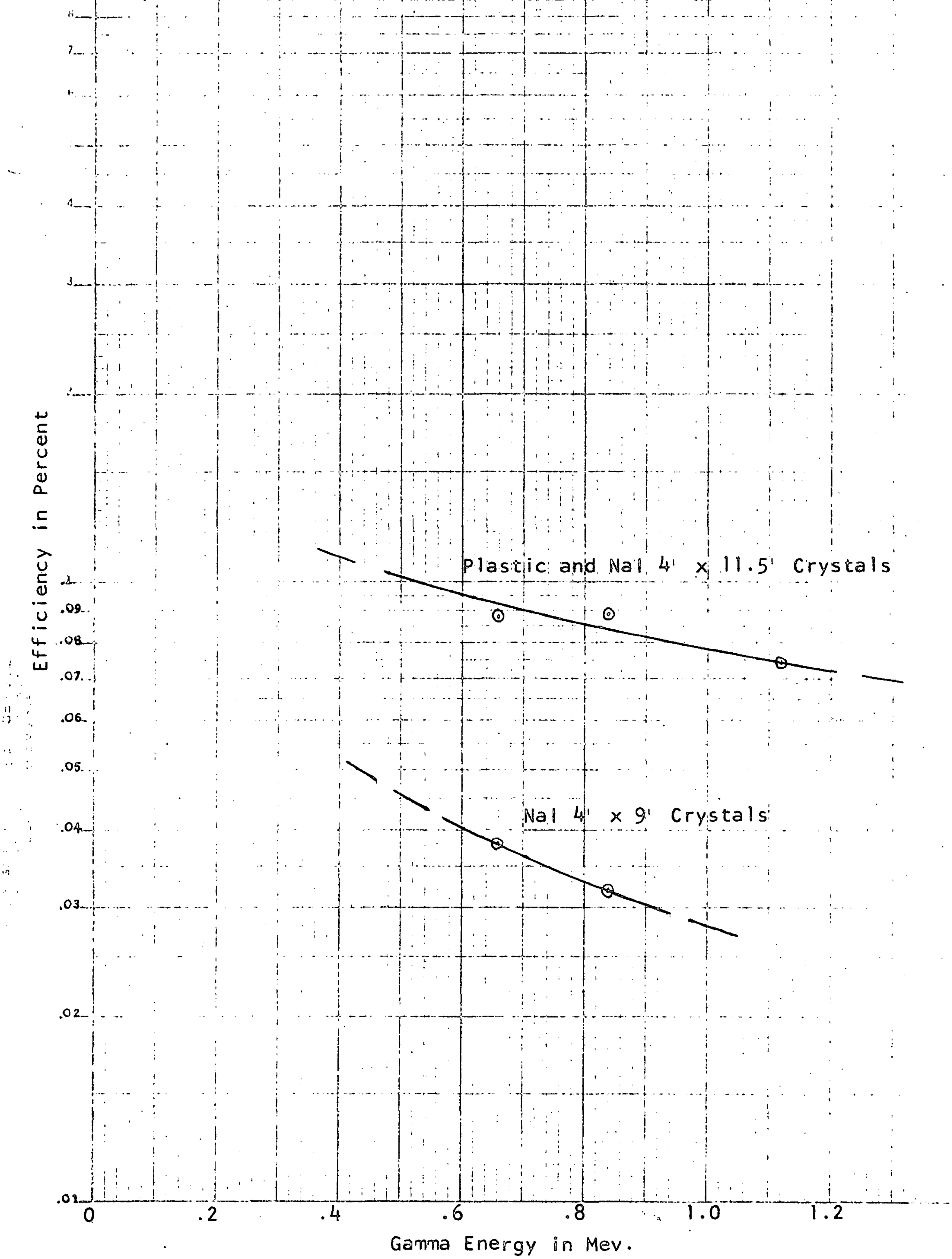


Fig. 7 WINDOW EFFICIENCY OF CS-137 (0.66 Mev.)

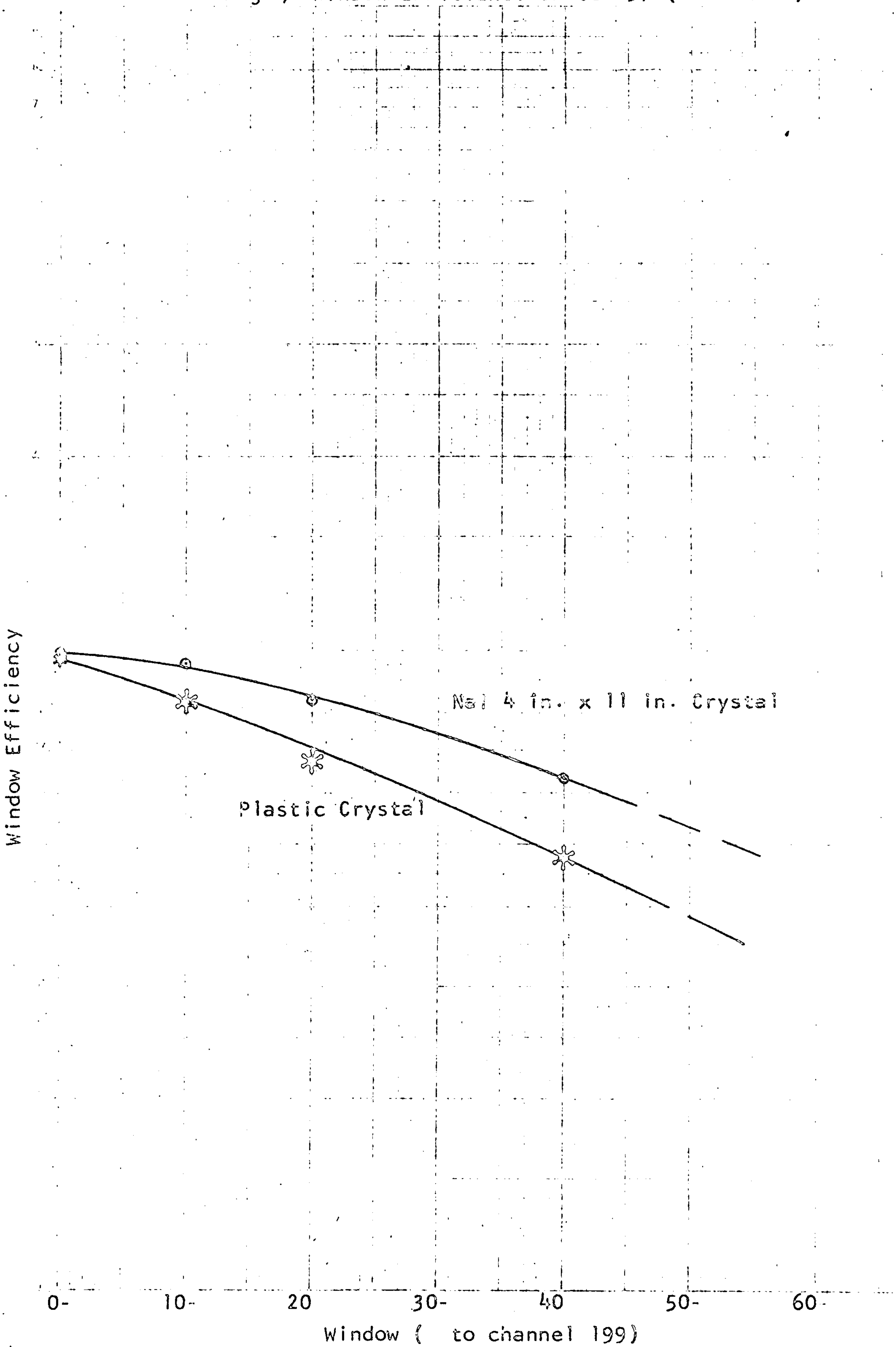


Fig. 8 WINDOW EFFICIENCY OF MN 54 (0.84 Mev.)

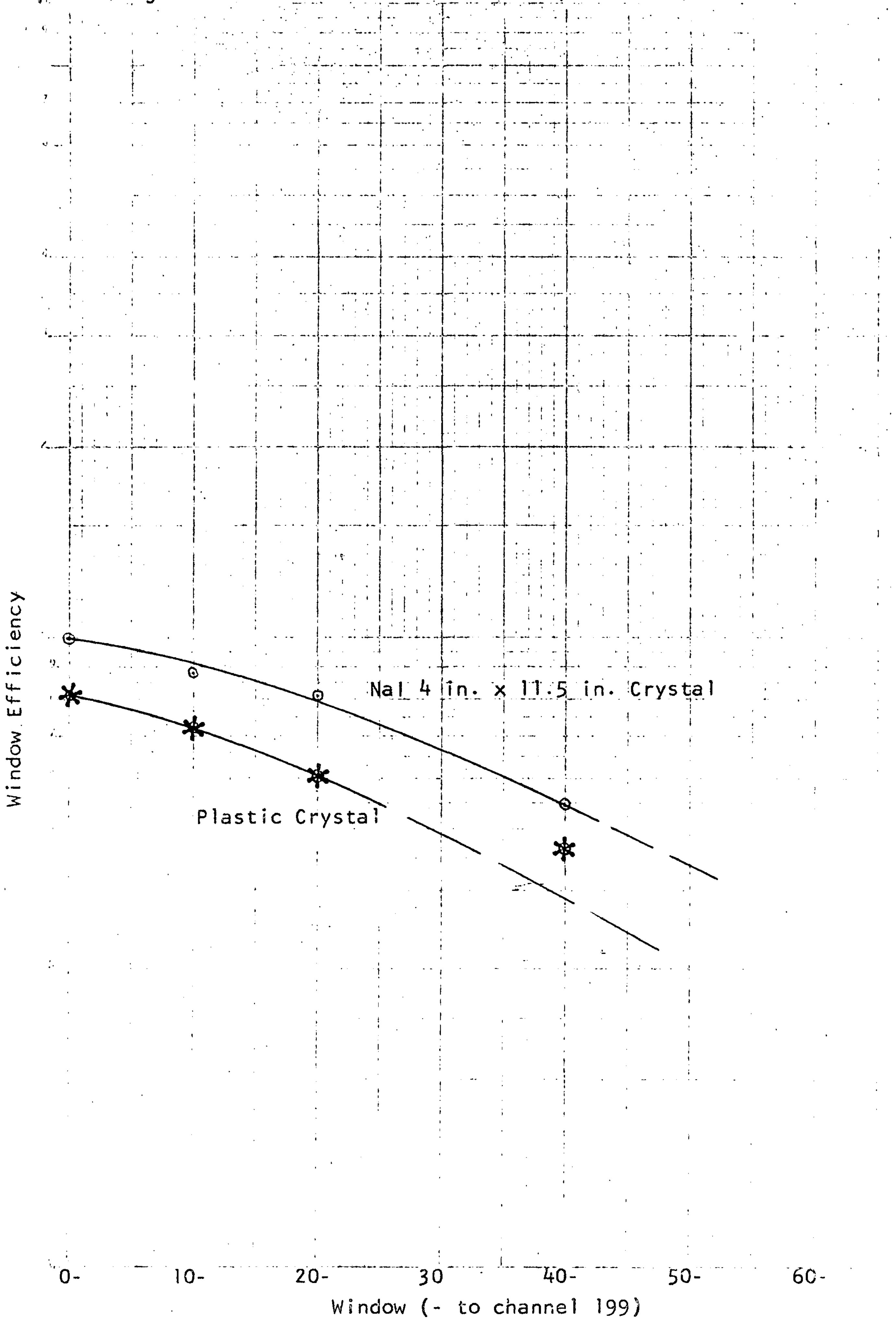


Fig. 9 WINDOW EFFICIENCY OF ZN-65 (1.12 Mev.)

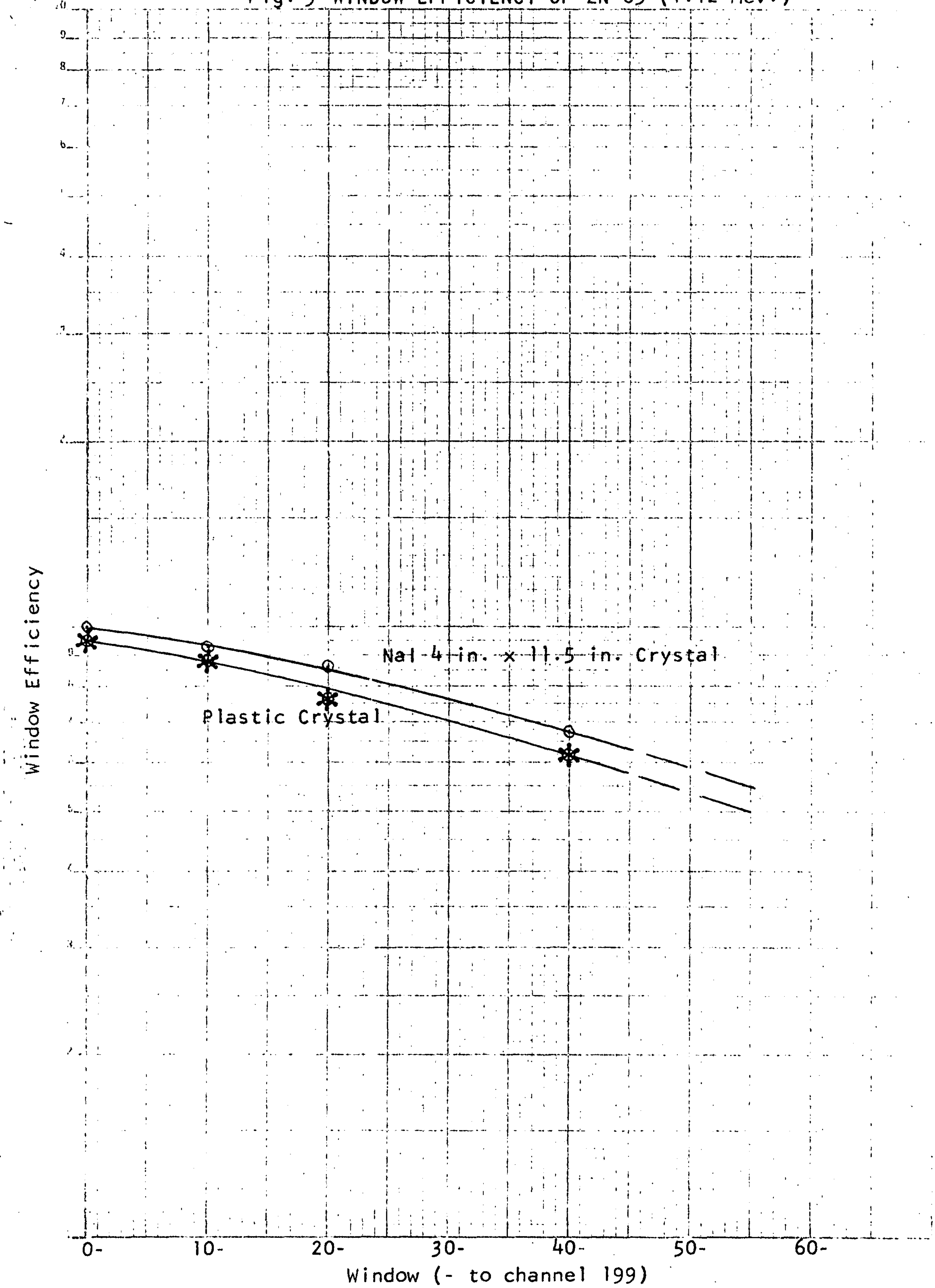


Fig.10 One-half Resolution of Plastic Scintillator and NaI 4" x 11.5" Crystal

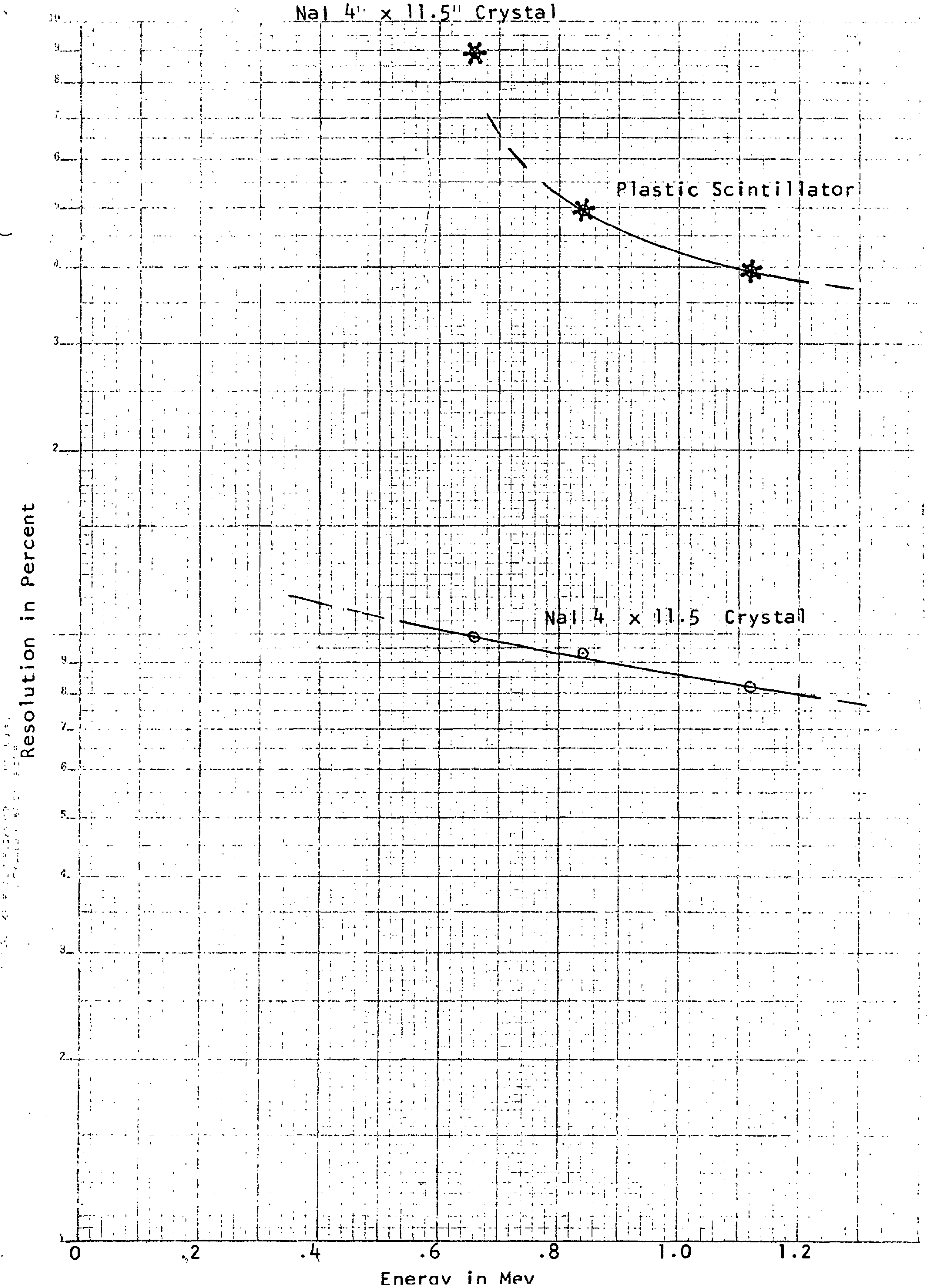


Fig. 11 Two-thirds Resolution of Plastic Scintillator and NaI 4" x 11.5" Crystal

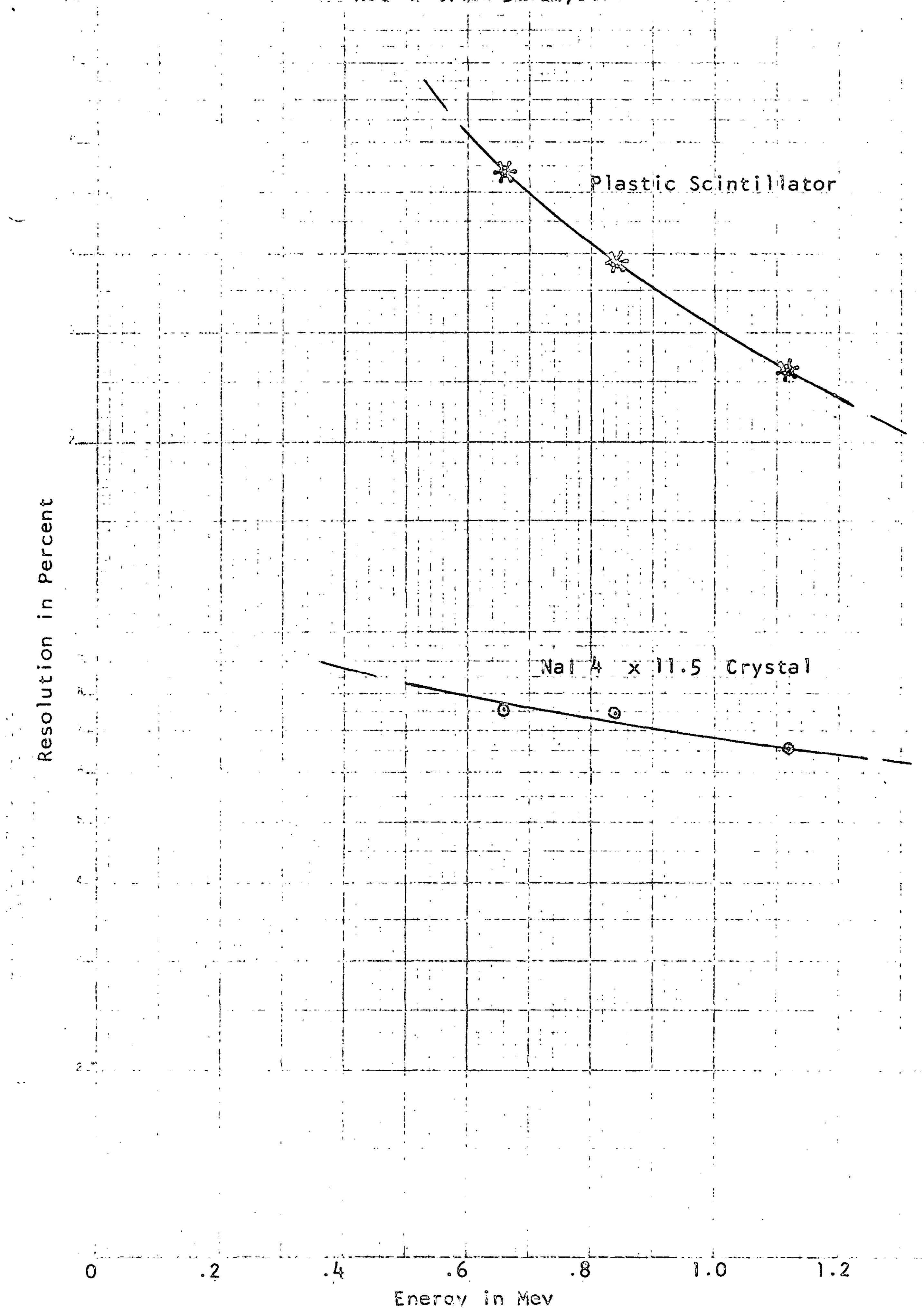
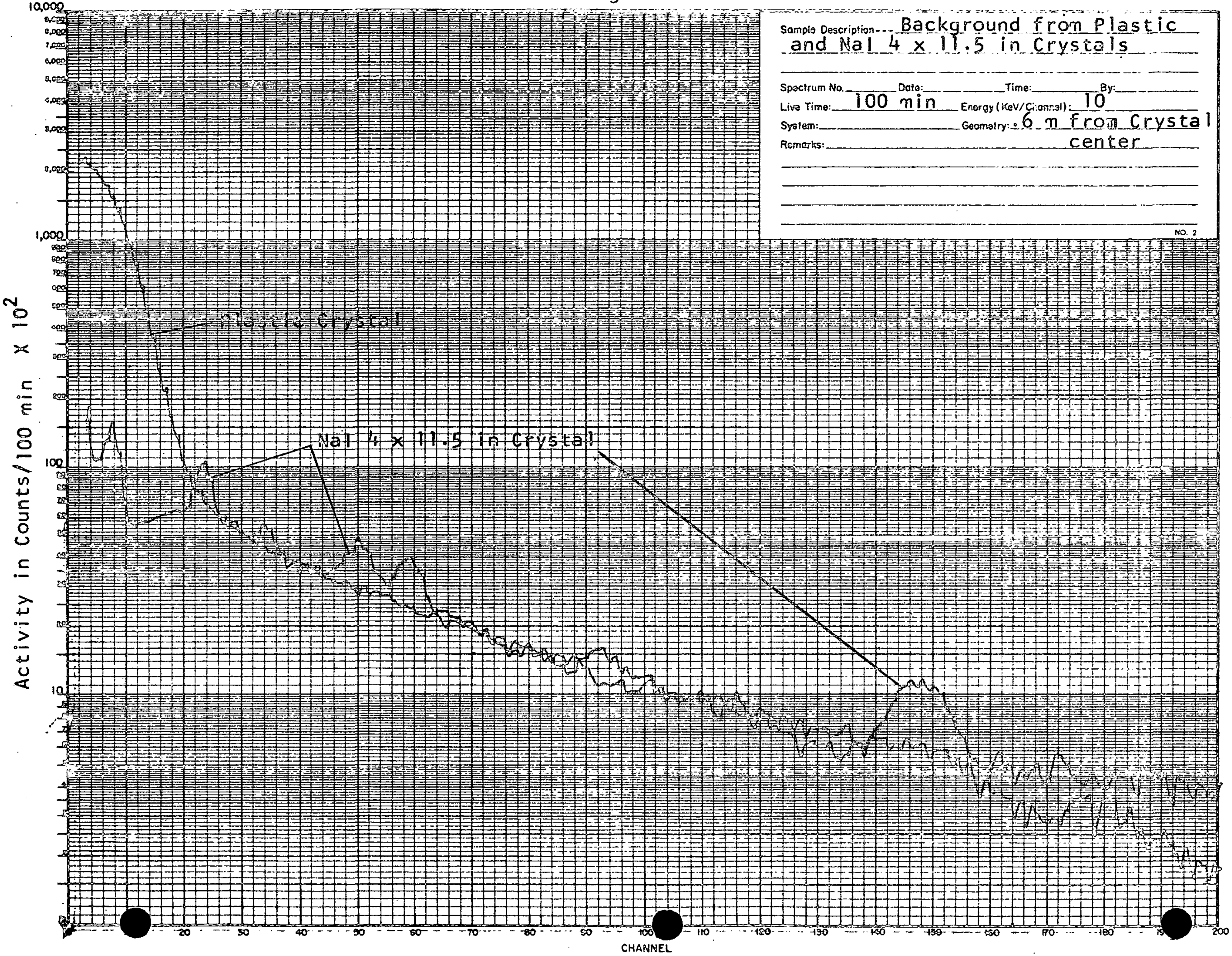


Fig. 12



Sample Description--- Background from Plastic
and NaI 4 x 11.5 in Crystals
Spectrum No. Date: Time: By:
Live Time: 100 min Energy (KeV/Channel): 10
System: Geometry: 6 m from Crystal center
Remarks:
NO. 2
Plastic Crystal
NaI 4 x 11.5 in Crystal
Activity in Counts/100 min X 10^2
CHANNEL
10,000
1,000
100
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200

Fig. 13

Response of a Mn 54 Point Source at an Increasing Distance from a NaI 4 x 11.5 in. and Plastic Detector