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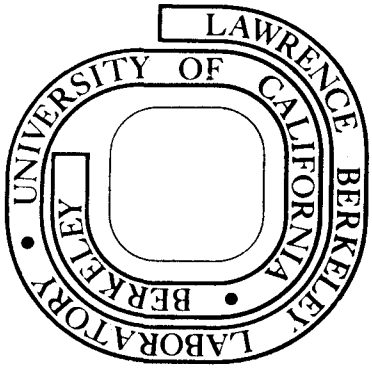

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DOSIMETRY FOR RADIOBIOLOGICAL EXPERIMENTS USING ENERGETIC HEAVY IONS

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Heavy Ion Dosimetry

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ABSTRACT

The availability of the Bevalac facility of energetic heavy ions with range greater than the size of small mammals makes possible the determination of the biological effects of relatively well defined high LET, whole body irradiation. With the increasing application of high-energy heavy ions in radiobiology there is a corresponding need to develop reliable techniques of both relative and absolute absorbed dose measurement.

This paper describes dosimetry studies by the Health Physics Department of the Lawrence Berkeley Laboratory with activation detectors, ionization chambers, nuclear emulsion, thermoluminescent dosimeters and X-ray film. The application of these techniques to an experiment designed to study the leukomegenic effect of the whole-body irradiation of mice by 250 MeV/amu carbon ions is briefly described. Values of absorbed dose in tissue, obtained during this experiment, with a nitrogen filled ionization chamber and ^{7}LiF thermoluminescent dosimeters are compared and shown to be in good agreement. As a result of this work a value for the average energy to produce an ion pair (W) in nitrogen by 250 MeV/amu $^{6+}$C ions of 37 ± eV was determined. Values of the efficiency of ^{7}LiF relative to ^{60}Co γ-rays for ions with dE/dx in the range 110-260 MeV g^{-1} cm^{2} are reported.

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1. INTRODUCTION

Until the early 1970's the energy of heavy ions available in the laboratory was limited to ~10-20 MeV/amu. There is considerable multidisiplinary interest in research using heavy ions of much higher energies. (Thomas 1972, 1975a) This interest led to the modification of existing proton synchrotrons for heavy ion acceleration. In the United States two proton synchrotrons have successfully accelerated heavy ions. In 1970 the Princeton Particle Accelerator--which has subsequently ceased operation--successfully accelerated deuterons and alpha particles. The following year a beam of N^{5+} ions at an energy of 279 MeV/amu was obtained. (White 1971) In August, 1971, heavy ions were first accelerated at the Bevatron with ions as heavy as O^{8+} being produced. (Grunder 1971, Crebbin 1973). This success at Berkeley stimulated development of the Bevalac facility (Ghiorso 1973) which uses the SuperHILAC as an injector to the Bevatron with heavy ions of energy 8.5 MeV/amu. The beam intensity available decreases with ion mass. For example, at the present time, intensities of 10^7-10^8 Ne^{10+} ions/sec have been produced at energies up to ~2 GeV/amu, but the intensity of Ar^{18+} is only about 10^4 ions/sec. Plans are underway to provide beam intensities of ~10^8 ions/sec for ions as heavy as lead up to energies of several hundred MeV/amu.

Although the interest in the use of energetic heavy ions in research is multi-disciplinary, we wish in this paper to describe only their application to radiobiology.

Figure 1 shows the range and energy loss of different species of heavy ion as a function of kinetic energy. Inspection of fig. 1 shows that the availability of heavy ions in the hundreds of MeV/amu energy range

has made feasible many radiobiological experiments hitherto impossible. One example would be the studies of biological effects resulting from the whole body irradiation of small mammals.

Patrick et al. (1974) have described the design of an experiment to study the incidence of leukemia in mice irradiated by C^{6+} ions: Kelly (1975) has reported the preliminary data obtained. In this experiment $\sim 10^7$ C^{6+} ions per sec were available at an energy of 250 MeV/amu. These were focused into a broad beam with full width at half intensity of about 11.5 cm so that several animals could be irradiated simultaneously. In such a beam typical absorbed dose rates in tissue were 5-10 rads/min. Variations in absorbed dose rate were ± 15% radially and ± 8% longitudinally. Whole-body irradiation of animals by neutrons of a few MeV produces recoil-protons having a wide range in LET in tissue. An experimental arrangement of the type described by Patrick et al. is therefore a great improvement when the radiation effects of well defined high LET are to be studied. As the Bevalac facility is improved it will be possible to design even more uniform radiation fields than that described in this experiment.

The increasing application of high energy heavy ions in radiobiology has led to a corresponding need to develop reliable techniques of dosimetry. This paper describes dosimetric studies using nuclear emulsion, ionization chambers, thermoluminescent dosimeters, and activation detectors by the Health Physics Department in collaboration with members of the Biomedical Division of the Lawrence Berkeley Laboratory.

2. RELATIVE DOSIMETRY

With the present heavy ion beam intensity available from the Bevalac

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it is often necessary to strike a compromise between the conflicting requirements for large, uniform radiation fields and reasonably high dose rates. Thus, it is usually necessary to accept some non-uniformity in irradiation fields. If such spatial variation in absorbed dose are accepted, good experimental practice requires their accurate determination, with suitable dosimetric techniques.

2.1. X-ray film.

In the design of an experiment for the uniform while-body irradiation of mice, we first explored the radiation field using DuPont NDT45 X-ray film. The optical density of the processed emulsion was first shown to be proportional to absorbed doses in the range 50 - 250 rad.

Figure 2 shows a typical spatial distribution of beam intensity determined from measurements of optical density of X-ray film exposed in a beam of 250 MeV/amu C^{6+} ions. The irradiation field is seen to be non-uniform and asymmetric about the beam axis.

2.2. Thermoluminescent dosimeters.

Similar measurements have been made using ^{7}LiF thermoluminescent dosimeters. We have found ^{7}LiF chips (1/8-in. × 1/8-in. × 0.035-in., mass ~25 mg) manufactured by the Harshaw Chemical Company convenient for our purpose. Figure 3 shows a dosimeter assembly that may be placed in the radiation field, while fig. 4 shows the spatial distribution of absorbed dose across a beam of 380 MeV/amu ^{10+}Ne ions (de Castro 1975).

It is of interest to compare the information obtained using thermoluminescent dosimeters and X-ray film. Figure 5 compares the radial variation of beam intensity across a 250 MeV/amu C^{6+} ion beam as determined

with Du Pont NDT 45 X-ray film and ^{7}LiF thermoluminescent dosimeters (Patrick) 1974). The beam distribution determined by x-ray film is seen to be in reasonable agreement with the more accurate TLD measurements.

Thermoluminescent dosimeters are also convenient for exploring absorbed dose distributions in experimental animals or phantoms. Figure 6 shows the longitudinal variation of dosimeter response along a lucite phantom irradiated by a wide parallel beam of C^{6+} ions whose kinetic energy is 251 MeV/amu. Also shown is the calculated absorbed dose distribution using energy-loss data of Steward et al. (1969). Secondary particles resulting from primary particle interactions are not taken into account in the calculated curve. Comparison between the calculated curve and dosimeter readings is not precisely possible because the dosimeter efficiency is a function of LET (Sec. 3.3) and changes along the length of the phantom.

2.3. Wire chambers

In recent exposures the use of a pair of multiwire proportional chambers has facilitated beam setup (Morgado 1974). These chambers provide a visual display of integrated beam intensity in the vertical and horizontal directions. Figure 7 shows a typical display--the spacing between wires being 6 mm. Use of these chambers greatly reduces the length of time necessary to optimize experimental beam conditions compared to that needed using X-ray film or TLD.

3. ABSOLUTE DOSIMETRY

To date we have used five techniques that may be used for absolute dosimetry--nuclear emulsions, thermoluminescent dosimeters, ionization chambers, and activation dosimeters. At the present time our absolute

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dose measurements by these techniques all depend upon calibration using nuclear emulsion. We intend to introduce other absolute techniques as this work develops.

3.1. Visual techniques--nuclear emulsion

One of the simplest techniques for absolute dosimetry is the use of nuclear emulsions. We have found Kodak nuclear track emulsion (NTA), normally used for neutron personnel dosimetry, extremely convenient. Films were exposed at an angle of 45° to the incident beam (fig. 8) and the large specific ionization of the heavy ions produces dense tracks which are readily identifiable (See fig. 9). Optimum exposures produce 40-120 tracks in a 245-μm square field.

The upper limit to track density that may be scanned with ease, with an air objective at a magnification of 430 ×, ~ 4 x 10^5 tracks cm^{-2}, would correspond to an absorbed dose of only ~ 1.3 rad at an LET of 20 keV/μ. Some increase in this limit could be obtained by scanning with an oil-objective, but even so the upper limit corresponds to an absorbed dose of ~ 10 rad. Alternative techniques must be used for absorbed doses in the tens of hundreds of rad region.

3.2. Thermoluminescent dosimeters--measurement of efficiency

The response of thermoluminescent dosimeters is known to be a function of the LET of the incident radiation (Cameron et al.(1968). LiF^7 thermoluminescent dosimeters may be used for the absolute dosimetry of heavy ions provided their response as a function of LET is known.

It is convenient to express the efficiencies, ε(S), of thermoluminescent dosimeters relative to that for ^{60}Co γ-rays. ε(S) may be expressed

in the form (Patrick et al. 1975b):

$$\varepsilon(S) = \frac{0.805}{1.602 \times 10^{-8}\ S} \left(\frac{\tau}{R}\right) \qquad (1)$$

where S is the mass stopping power of the ions (MeV g^{-1} cm^2)

τ is the dosimeter response to heavy ions in arbitrary units per unit fluence

R is the dosimeter sensitivity to ^{60}Co γ-rays in arbitrary units per roentgen

and the factor 0.805 arises from the fact that an exposure of 1 roentgen deposits 0.805 rad in ^{7}LiF (Attix 1969).

Patrick et al. (1975 a,b) have described measurements of $\varepsilon(S)$ using carbon, oxygen and neon ions with S in the range from 110 to 260 MeV g^{-1} cm^2 which are summarized in table 1.

The response of ^{7}LiF thermoluminescence as a function of absorbed dose has been studied and shown to be linear up to at least 1000 rad. To date this range has been adequate for our experiments but will be extended as the need develops.

3.3 Ionization chambers - measurement of W

Ionization chambers filled with nitrogen at atomospheric pressure have been designed by the Biomedical Group of the Lawrence Berkeley Laboratory that have adequate sensitivity down to absorbed doses of about 1 rad (Howard 1974). Ionization chambers therefore provide a useful means of dosimetry in the range of many radiobiology experiments and overlap with nuclear emulsion at the lower end of their sensitivity.

The absorbed dose, D, in tissue placed behind a parallel plate ionization chamber irradiated by an energetic heavy ion beam (where energy loss may be ignored) is given by:

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$$D = 10^5 \left(\frac{WQ}{m}\right) S' \qquad (2)$$

where W is the average energy required to produce an ion pair in the gas of the chamber (eV).

Q is the charge collected by the chamber (coulomb).

m is the mass of gas irradiated in the chamber (g).

S' is the ratio of the stopping powers of tissue to gas for heavy ions.

Evaluation of the parameter W permits the use of ionization chambers for absolute absorbed dose determination.

There are surprisingly few values of W published in the literature.

Myers (1968), in a recent review article, quotes values of W in nitrogen of 34.6 ± 0.3, 36.6 ± 0.5 and 36.39 ± 0.04 eV for γ rays, protons and α particles respectively. Varma et al. (1975) have recently determined a value of 38.6 ± 1.2 eV using 35 MeV O^{6+} ions.

Stephens et al. (1975) have measured W for C^{6+} ions of kinetic energy 250 MeV/amu in nitrogen. A parallel plate ionization chamber filled with nitrogen at ambient temperature and pressure was used and the incident heavy ion fluence was measured using ^{7}LiF thermoluminescent dosimeters that had been calibrated using nuclear emulsion. Three independent determinations of W were made having a weighted mean of 36.6 ± 0.8 eV (table 2).

The value of W is expected to be dependent upon LET and thus on the species of heavy ion and its velocity (Chatterjee 1975). As the LET of the ion increases, there will be a correspondingly greater energy density around the particle trajectory which in turn increases the probability

of ionic recombination leading to higher values of W. However, comparison of the published values of W shows this variation is probably not larger than about 10 - 15%. A preliminary determination of W of 37 ± 3 eV for 375 MeV/amu Ne^{10+} ions in nitrogen (Thomas 1975b), although of low accuracy at present, does not indicate any great difference from the other values of W quoted here.

3.4. Comparison of dose estimates using TLD and ionization chambers

Patrick et al. (1974) have compared estimates of absorbed dose in tissue derived from measurements using a nitrogen filled ionization chamber and ^{7}LiF TLD. Table 3 summarizes their data using a value of W of 36.6 eV/ion pair and ε of 0.89. The errors for the ionization chamber estimates are taken to be ±5%, whereas only statistical errors for the TLD measurements are given. The absolute accuracy of the TLD measurements is also judged to be ±5%. The two sets of estimates are seen to be in good agreement with the ionization chamber values consistently higher by a little less than 4%.

3.5. Activation dosimeters

Activation dosimeters have been used with great success in the absolute determination of particle fluences at conventional particle accelerators. There is no reason to doubt that they might be used to monitor high-energy heavy-ion beam intensities.

There are specific advantages to the development of activation dosimeters, which may be summarized as follows:

a. Suitable reactions give high activity enabling relative data of high statistical precision to be obtained. Such reactions may therefore be used as a standard with which the reproducibility of all other dosimetric

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systems may be compared.

b. Suitable reactions may be used as a standard against which the linearity of thermoluminescent dosimeters, ionization chambers, secondary-emission chambers and other dosimeters may be compared.

c. The use of several activation detectors with the dosimetric techniques can give information on the incident heavy ion beam composition (beam purity).

Smith (1974) has reported initial tests of aluminum activation detectors irradiated by 375 MeV/amu $^{10+}$Ne ions. The reaction $^{27}Al \rightarrow ^{24}Na$ was utilized and the induced ^{24}Na activity was measured using a NaI(Tl) γ-spectrometer situated in the Health Physics Department Low Background Facility (Smith 1966).

The absolute efficiency of the spectrometer used was ~ 35% for ^{24}Na. Competing radionuclides (other than ^{24}Na) produced were ^{11}C(20.3 min) and ^{18}F (110 min). Simultaneous counting of six aluminum discs (0.875 in. diam, 0.250 in. thick, 1.71 gm cm^{-2}) gave an adequate counting rate to easily obtain a statistical precision of ± 1% for exposures corresponding to an absorbed dose in tissue of ~ 30 rad. The production of ^{18}F in aluminum is capable of comparable statistical precision but correction for the production of ^{11}C (which also emits positrons) is an added complication.

Many suitable reactions are available, but, provided there is adequate sensitivity, as a general rule those reactions that produce radionuclides with half-lives comparable to the length of irradiation will prove to be most convenient. Table 4 summarizes some possible activation reactions.

In radiobiological experiments it will often be convenient to use activation targets of composition similar to that in tissue, such as polyethylene, lucite or polystyrene. In such materials the production of ^{11}C from ^{12}C is a convenient reaction. For absolute dosimetry, the reaction cross section must be known. Smith and Thomas (1975) have reported a value of 75 ± 7 mb for the production cross section for ^{11}C by 375 MeV/amu Ne^{10+} ions on carbon. Using an activation target of polystyrene 3 in. diam × 0.25 in. (30.4 g) and an irradiation of 2.40×10^9 ions (average fluence 5.27×10^7 ions cm^{-2} corresponding to an absorbed dose in tissue of ~267 rad) counting rates about a factor of a thousand greater than background in positron annihilation peak. Statistical precision ~ 0.1% was readily obtained. Thus, if statistical precision of ~ 1% is acceptable, absorbed doses down to a ~ 1 rad may be measured. In most radiobiology experiments, however, an activation 0.25 in. thick would be unacceptable in front of the target because of the large energy loss involved. A reasonable compromise between energy loss in the target and sensitivity puts the lower limit of sensitivity for this reaction at an absorbed dose of ~ 10 rad in tissue.

Activation detectors would be more acceptable in some experiments if they could be placed behind the irradiated biological sample to determine the particle fluence leaving the experiment. In this case it is first necessary to study the production of the radionuclide to be measured as a function of depth in an irradiated sample.

Smith (1975b) has reported some preliminary studies of the distribution of ^{18}F and ^{24}Na in aluminum irradiated by 375 MeV/amu Ne^{10+} ions. Figure 10 shows the distribution of ^{18}F in aluminum. The initial portion of the ^{18}F curve is caused by the production of ^{18}F in the aluminum target material;

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the peak in the region 14-20 g cm^{-2} is due to ^{18}F fragments from the original neon ion beam. ("Autoactivation", Tobias et al. 1971). Such fragments have a range of ~ 17 g cm^{-2} in aluminum and are thus seen superposed on the continuous distribution of ^{18}F due to target activation. Beyond the range of the primary ions (~16-17 cm^{-2}) ^{18}F is produced by the reaction of lighter fragments with the target aluminum (residual activation). The total ^{18}F due to stopped fragments is approximately equal to that due to target activation. Residual activation is not insignificant being nearly of the same magnitude to that due to target activation at the entrance of the stack. The total quantity of residual ^{18}F activity is, however, only a few percent of that due to target activation because it rapidly decreases with increasing depth, beyond the primary ion range.

The distribution of ^{24}Na is shown in Fig. 11 and exhibits the typical buildup of activity as a function of depth (~ factor 3 increases) observed in high-energy irradiations. Beyond the range of the primary ions there is a sharp reduction in ^{24}Na production. Residual activation is seen to be higher beyond the neon ion range than the target activation at the target entrance. Since ^{24}Na is heavier than the primary ions (^{20} Ne) autoactivation is not feasible.

These preliminary studies indicate the need to study the three mechanisms of:

a. autoactivation

b. target activation

c. residual activation

in some detail if activation techniques are to be used for absolute dosimetry behind considerable thickness of material.

If one uses the "in-beam" techniques employed in the autoactivation

studies of Chatterjee et al. (1975) then the shorter-lived radionuclides could be used in target activation beam monitoring. For example, the positron-emitters ^{15}O (2.05 min), ^{17}F (66 sec), and ^{19}Ne (19 sec) might be useful to provide almost immediate monitor results from irradiations that required from one to a few beam pulses.

Smith (1975) has also reported approximate cross sections for the production of ^{18}F and ^{24}Na in several materials irradiated by 375 MeV/amu Ne^{10+} ions. Table 5 summarizes these values.

4. SUMMARY AND CONCLUSIONS

Preliminary studies of both relative and absolute dosimetric techniques for high-energy heavy ions have been described.

At the Bevalac, beam setup is most conveniently achieved using multiwire proportional chambers. Detailed exploration of the relative field is then conveniently done using thermoluminescent dosimeters.

Nuclear emulsions have been used to provide an absolute basis for dosimetry, but have an upper limit of ~ 10 rad. Absolute calibration of ^{7}LiF thermoluminescent dosimeters using nuclear emulsion at the 0.1 - 5 rad region, and their known linear response up to ~ 1000 rad extends the range of absolute dosimetry into the range needed for many radiobiological experiments. The efficiency of ^{7}LiF thermoluminescent dosimeters to heavy ions in the range of LET from 11-26 keV/μm are consistent with published experimental data and theoretical predictions.

A value of W 36.6 ± 0.7 eV has been determined for 250 MeV/amu ^{6+}C ions in nitrogen. Use of this value gives estimates of absorbed dose in tissue in agreement with those obtained using TLD to better than 4%.

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Preliminary studies show that activation techniques will continue to be important in heavy ion dosimetry, as they have been for protons and neutrons. Studies of the fundamental data needed for absolute dosimetry are well underway.

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Table 1. Measurements of ε

Ion species	$\frac{dE}{dx}$ in ^7LiF (MeV $g^{-1}cm^{-2}$)	τ/R (roentgen/unit ion fluence)		ε
C^{+6}	116	2.06	10^{-6}	0.89 ± 0.02
O^{+8}	112	2.01	10^{-6}	0.90 ± 0.05
O^{+8}	186	3.03	10^{-6}	0.82 ± 0.05
Ne^{+10}	259	3.76	10^{-6}	0.73 ± 0.03

Table 2. Measurements of W for 250 MeV/amu C^{6+} ions in Nitrogen (Stephens et al. 1975)

Run No.	W(ev/ion pair)
1	35.3
2a	37.4
b	38.3
3a	34.7
b	37.1
Mean value:	36.6 ± 0.8

*Collected from data presented in Patrick et al. (1974). Preliminary measurements with 375 MeV/amu Ne^{10+} ions indicate a value of W close to 37 eV/ion pair.

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Table 3. Comparison of entrance absorbed dose in tissue irradiated by 250 MeV/amu C^{6+} ions.

Irradiation No.	Group No.	Entrance absorbed dose in tissue (rad)			Ratio ionization Chamber to TLD
		Ionization* Chamber	^{7}LiF Thermoluminescent Dosimeters**		
1	a	64.0 ± 3.2	61.2	0.5	1.045
1	b	96.6 ± 4.8	93.6	0.9	1.032
2	a	128 ± 6.4	124	2	1.032
2	b	193 ± 10	186	4	1.038

*Using a value W = 36.6 eV/ion pair. Errors ±5%.

**Using a value $\varepsilon = 0.89$. Statistical errors only.

Table 4. Some useful target activation reactions that produce radionuclides with halflives longer than about 10 minutes.

Target material	Reactions useful for dosimetry				Competing and Reactions
1. ^{27}Al in aluminum	$^{27}Al \rightarrow ^{24}Na$	15.0 hr	β-	1368, 2754 keV	
	$^{27}Al \rightarrow ^{22}Na$	2.60 yr	e-capt, β+	511, 1275 keV	
	$^{27}Al \rightarrow ^{18}F$	109.7 min	β+	511 keV	
	$^{27}Al \rightarrow ^{13}N$	9.93 min	β+	511 keV	
	$^{27}Al \rightarrow ^{11}C$	20.34 min	β+	511 keV	
	$^{27}Al \rightarrow ^{7}Be$	53.6 day	e-capt	478 keV	
2. ^{9}Be in beryllium	$^{9}Be \rightarrow ^{7}Be$	53.6 day	half-life, e-capt	478 keV	
3. ^{12}C in graphite,	$^{12}C \rightarrow ^{11}C$	20.34 min	β+	511 keV	
polystyrene, or	$^{12}C \rightarrow ^{7}Be$	53.6 day	e-capt	478 keV	
polyethylene					
4. ^{19}F in Teflon	$^{19}F \rightarrow ^{18}F$	109.7 min	β+	511 keV	$^{12}C \rightarrow ^{11}C$
	$^{19}F \rightarrow ^{13}N$	9.93 min	β+	511 keV	$^{12}C \rightarrow ^{7}Be$
	$^{19}F \rightarrow ^{11}C$	20.34 min	β+	511 keV	
	$^{19}F \rightarrow ^{7}Be$	53.6 day	e-capt	478 keV	
5. ^{14}N in boron	$^{14}N \rightarrow ^{13}N$	9.93 min	β+	511 keV	$^{11}B, B^{10} \rightarrow Be^{7}$
nitride	$^{14}N \rightarrow ^{11}C$	20.34 min	β+	511 keV	
	$^{14}N \rightarrow ^{7}Be$	53.6 day	e-capt	478 keV	
6. ^{16}O in water	$^{16}O \rightarrow ^{13}N$	9.93 min	β+	511 keV	
	$^{16}O \rightarrow ^{11}C$	20.34 min	β+	511 keV	
	$^{16}O \rightarrow ^{7}Be$	53.6 day	e-capt	478 keV	
7. ^{16}O in beryllium	$^{16}O \rightarrow ^{13}N$	9.93 min	β+	511 keV	
oxide	$^{16}O \rightarrow ^{11}C$	20.34 min	β+	511 keV	
	$^{16}O \rightarrow ^{7}Be$	53.6 day	e-capt	478 keV	$^{9}Be \rightarrow ^{7}Be$
8. $^{28}Si, ^{29}Si, ^{30}Si$ in fused quartz	$Si \rightarrow Na^{24}$				

0 0 0 4 4 0 2 9 0 4

Table 5. ^{11}C production sections - 375 MeV/amu Ne $^{10+}$ ions.

Target	Reaction	Production cross section (mb)
Al^{27}	$\rightarrow^{24}Na$	63
Si	$\rightarrow^{24}Na$	15
S	$\rightarrow^{24}Na$	11
Al	$\rightarrow^{18}F$	40
Si	$\rightarrow^{18}F$	36
S	$\rightarrow^{18}F$	16

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Fig. 1. Range and dE/dx as a function of kinetic energy for different species of heavy ions. (Courtesy Biomedical Division, LBL.)

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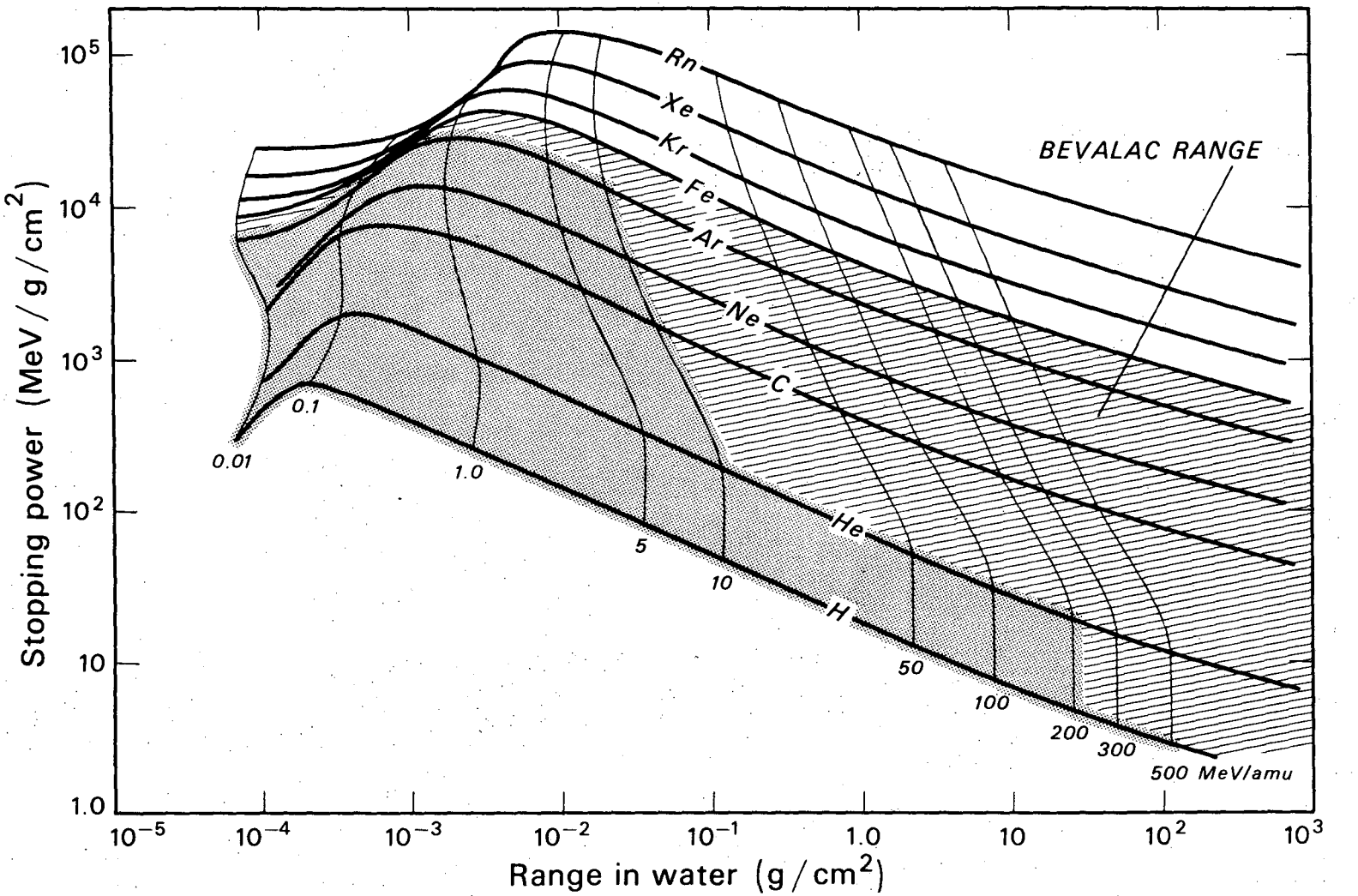
Fig. 10. The distribution of ^{18}F along an aluminum target bombarded by 375 MeV/amu $^{10+}$Ne ions (from Smith 1975a).

Fig. 11. The distribution of ^{24}Ne along an aluminum target bombarded by 375 MeV/amu $^{+10}$Ne ions (from Smith 1975a).

0 0 0 4 4 0 2 0 5



DBL 682-4598 A

Fig. 1

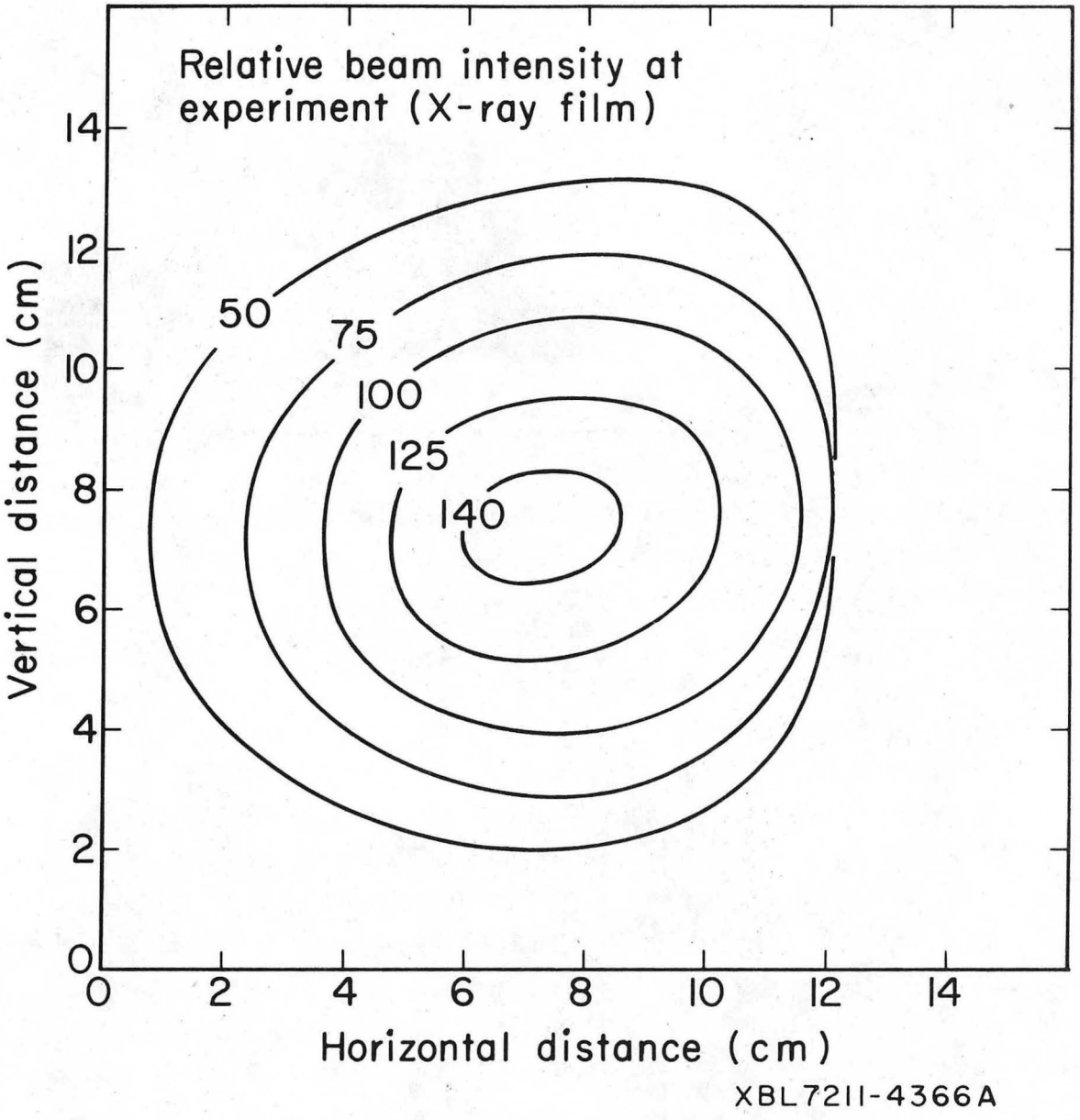


Fig. 2

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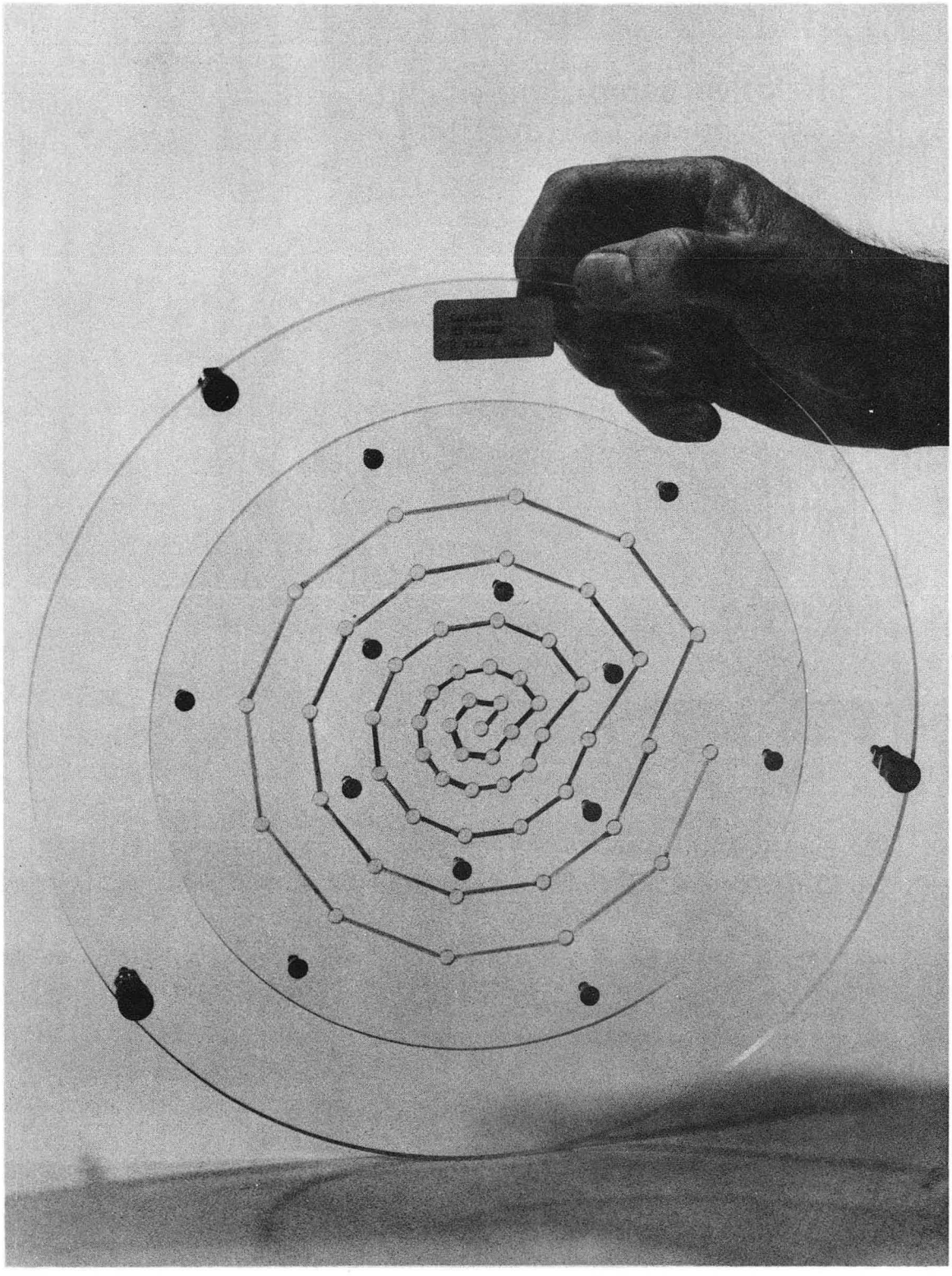


XBB 756-4355

Fig. 3

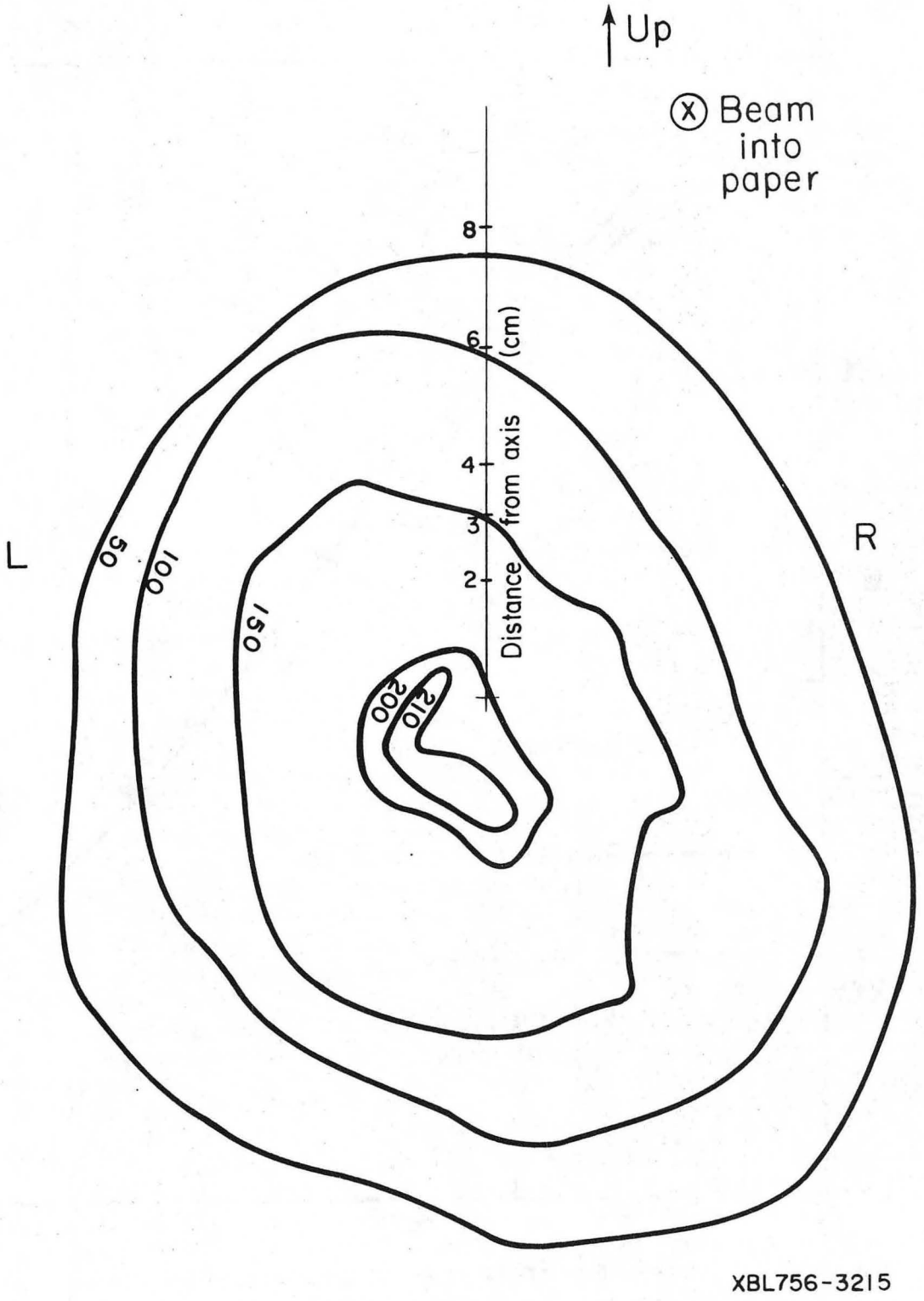


Fig. 4

0 0 0 0 4 4 0 2 0 0 7

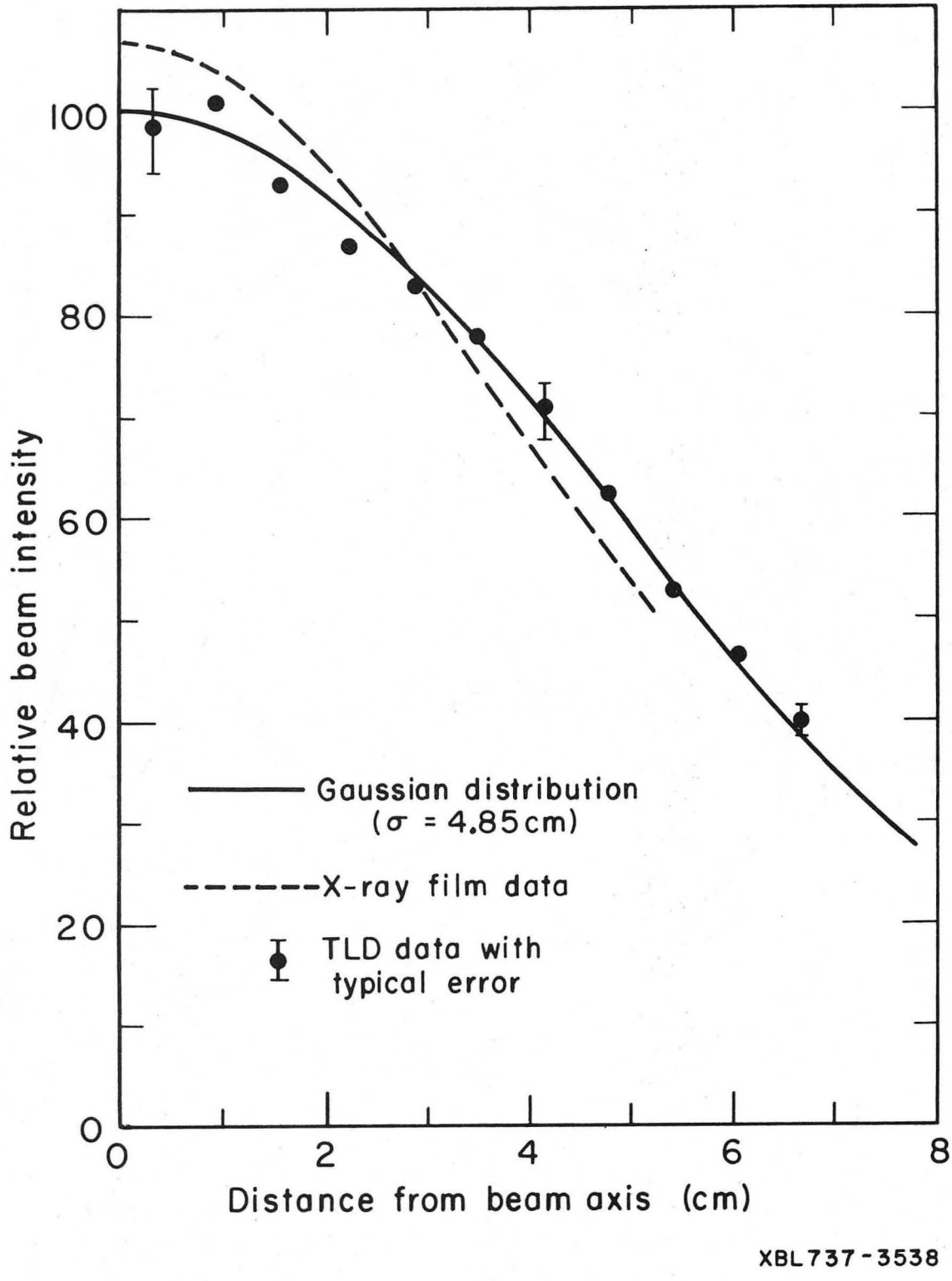

Relative beam intensity
100
80
60
40
20
0
0
2
4
6
8
Distance from beam axis (cm)
Gaussian distribution
(σ = 4.85cm)
X-ray film data
TLD data with
typical error
XBL737-3538

Fig. 5

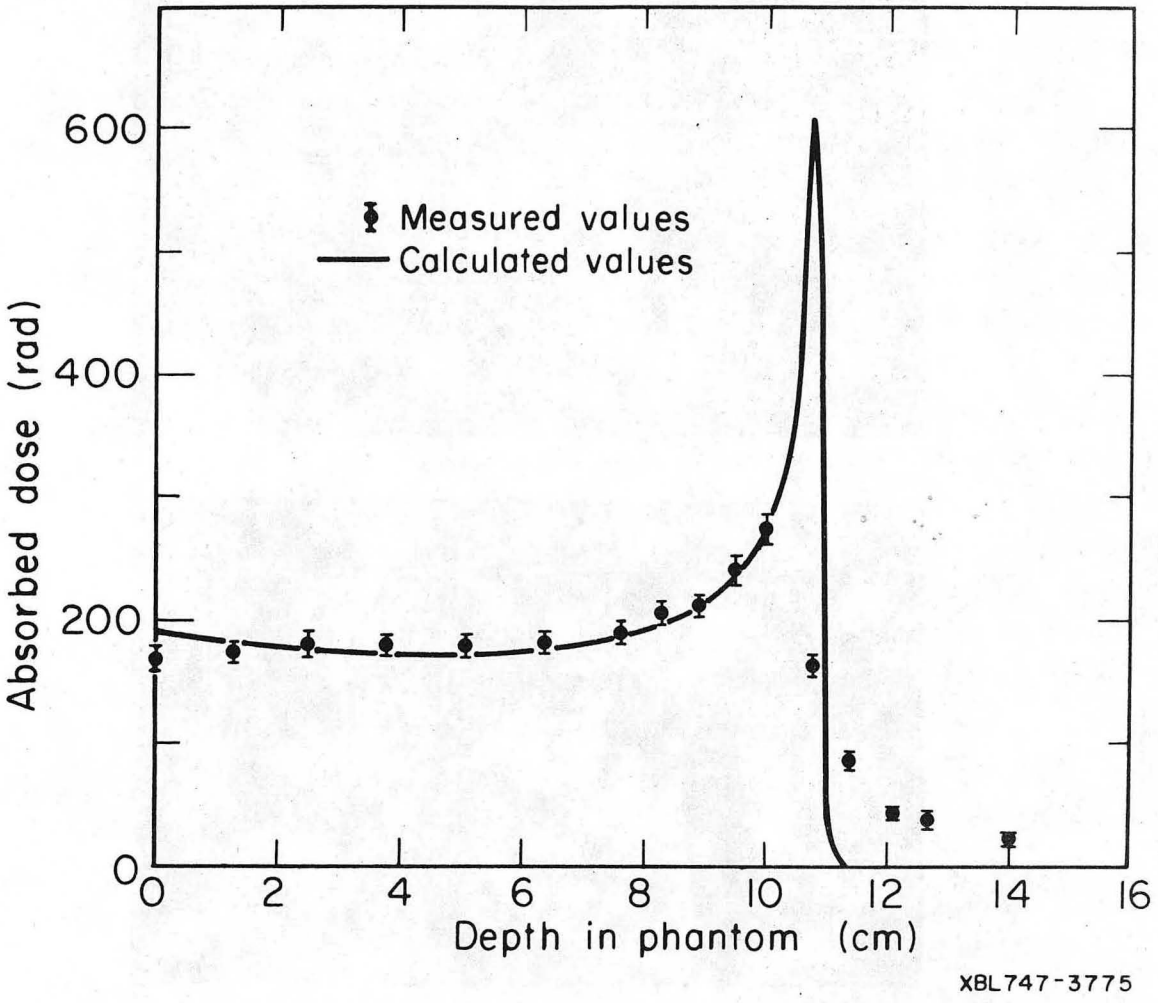
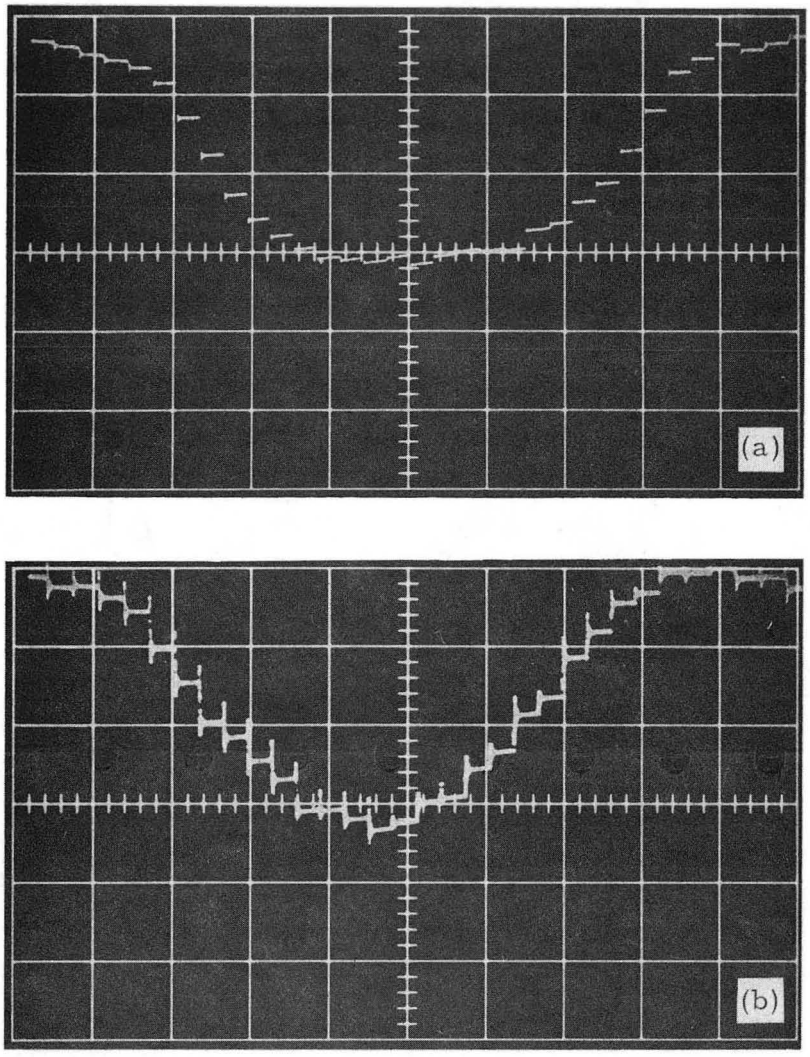


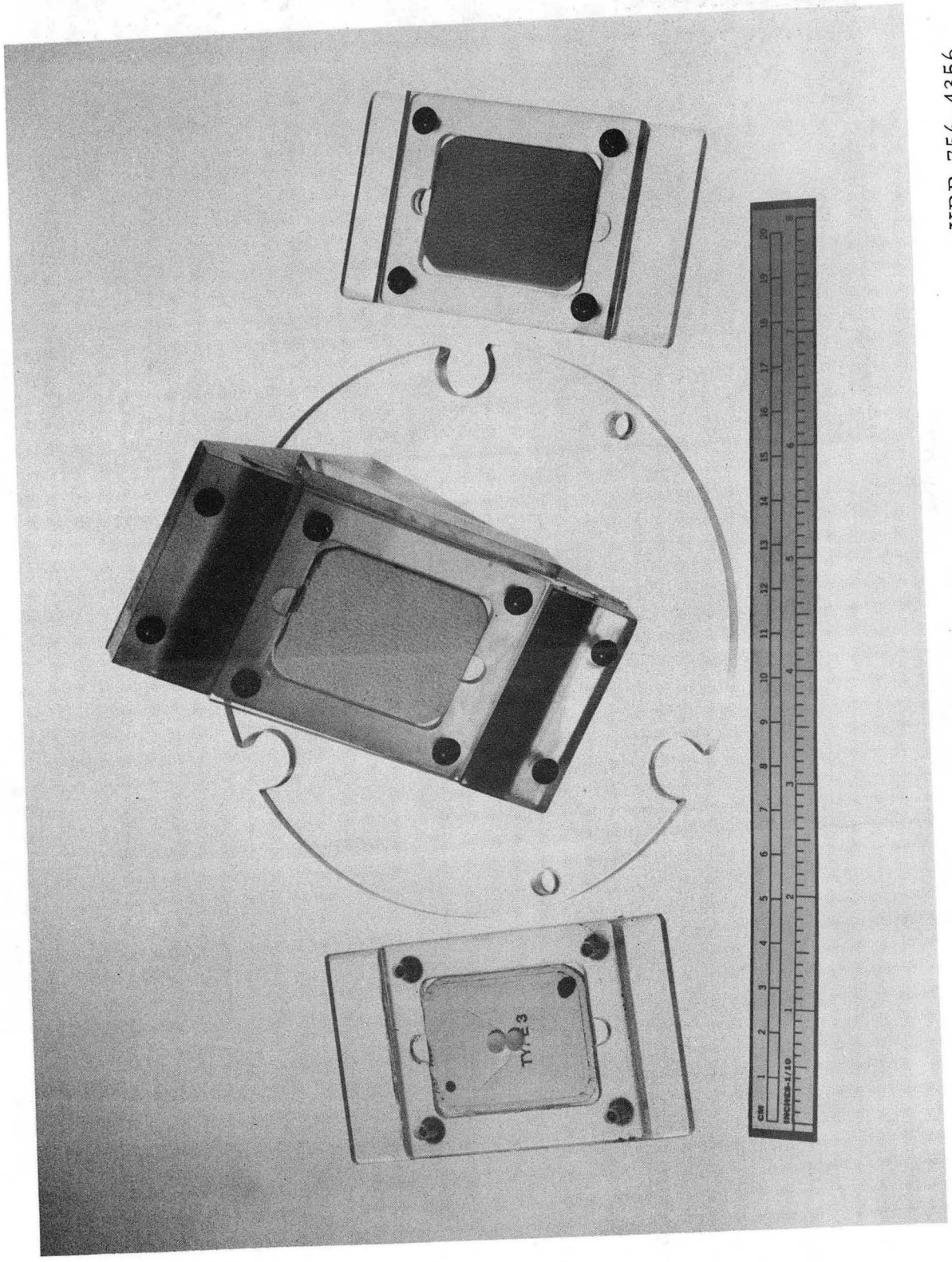
Fig. 6

0 0 0 0 4 4 0 2 0 0 8



XBB 748-5521

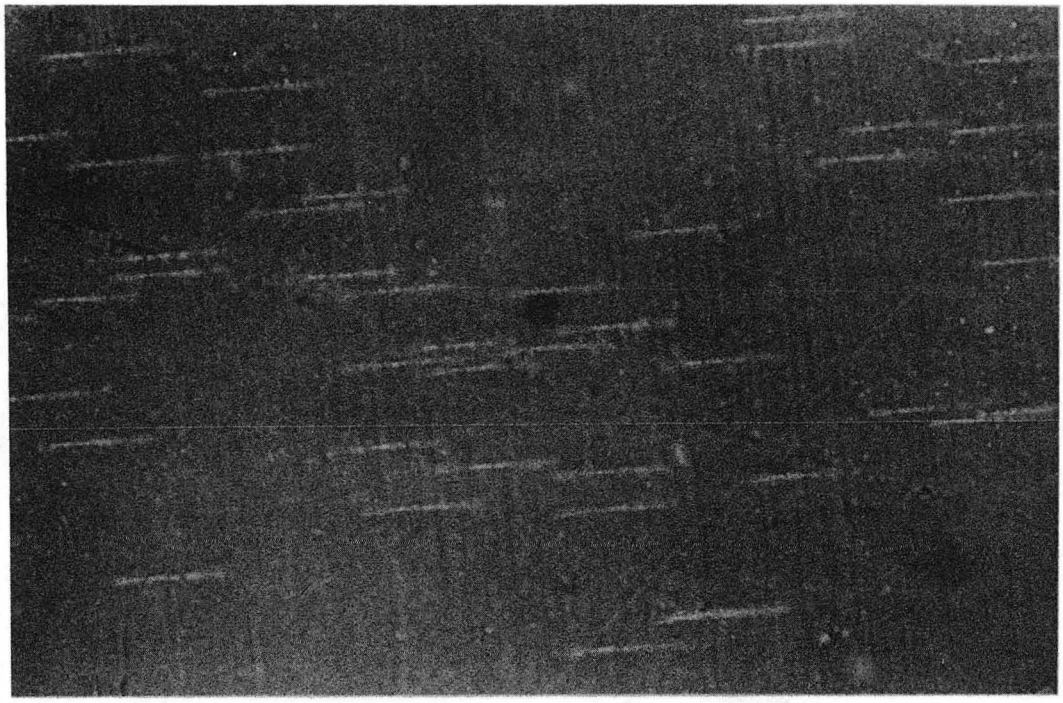
Fig. 7



XBB 756-4356

Fig. 8

0 0 0 0 4 4 0 2 0 0 9



XBB 759-6586

Fig. 9

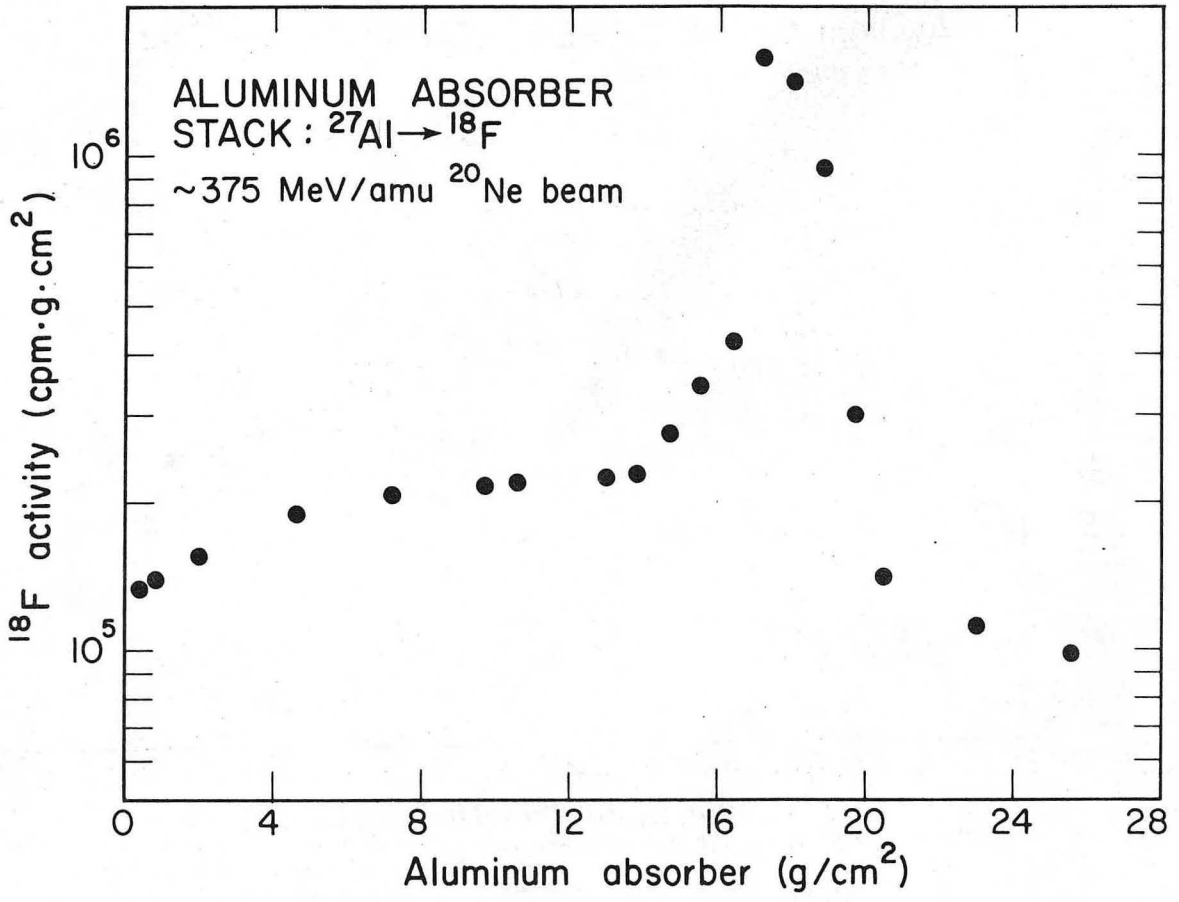


Fig. 10

0 0 0 4 4 0 2 0 1

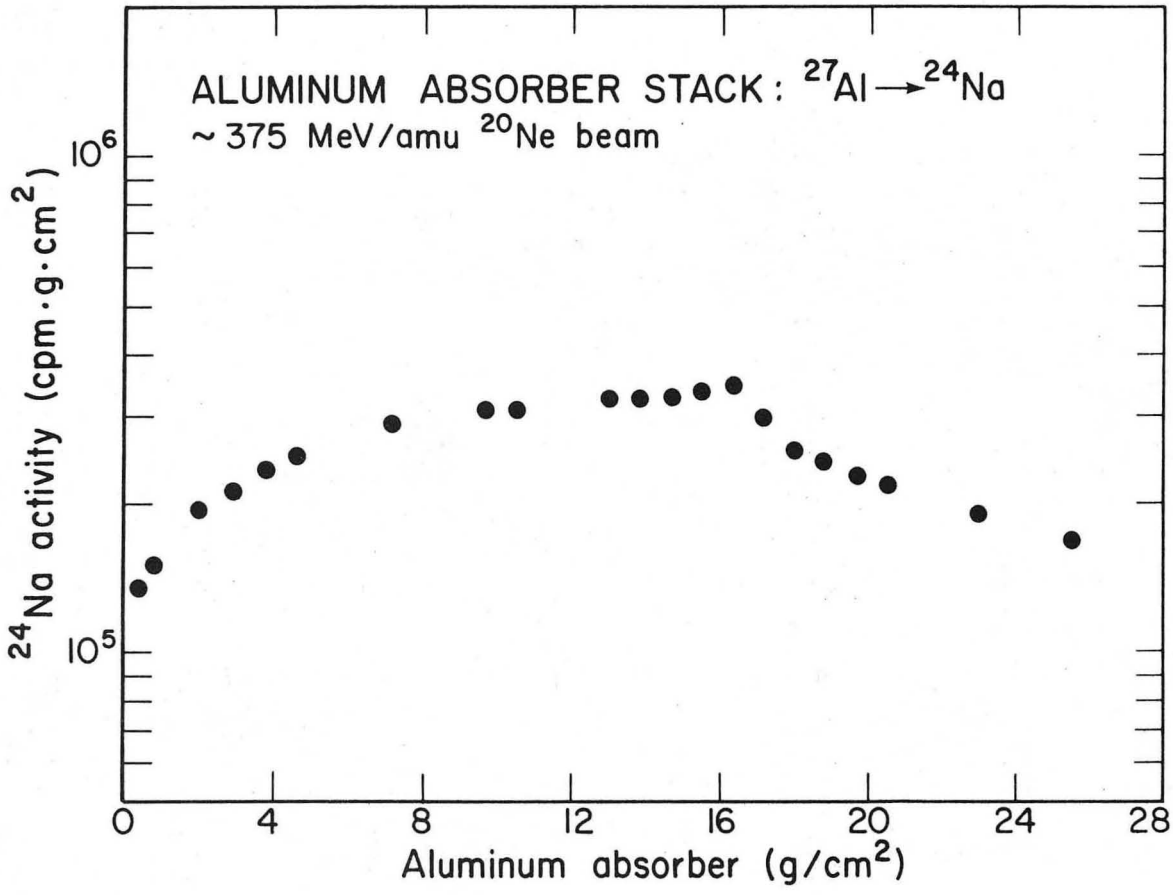

ALUMINUM ABSORBER STACK: $^{27}Al \rightarrow ^{24}Na$
~ 375 MeV/amu ^{20}Ne beam
^{24}Na activity (cpm·g·cm^2)
10^6
10^5
0
4
8
12
16
20
24
28
Aluminum absorber (g/cm^2)
XBL 757-3417

Fig. 11

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