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DISCLAIMER

PHYSICAL AND RADIOBIOLOGICAL ASPECTS OF NEGATIVE PIONS WITH REFERENCE TO RADIOTHERAPY

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September 1969

Abstract

The dose delivered by negative pions as they pass through a tissue-like medium increases slowly with depth, giving rise to a distinct maximum known as the Bragg peak near the end of the range, as do other heavy charged particles. In addition, when the negative pions come to rest, they are captured by the nuclei in the medium and produce stars consisting of many short-range, heavily ionizing fragments. These fragments enhance the dose as well as the biological effect at the Bragg-peak region, while the damage produced is less dependent on the oxygenation status of cells irradiated.

In the present contribution the production of π mesons and their interaction with tissue is briefly discussed. Subsequently the results of physical and radiobiological measurements of negative π mesons with reference to radiotherapy will be discussed.

Physical measurements of depth-dose distribution indicate that the dose at the peak region is 2 to 3 times higher than that at the entrance. LET (linear energy transfer) measurements indicate that at the Bragg peak region a significant portion of the dose is due to high-LET components.

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Radiobiological measurements at the peak of the depth-dose distribution gave RBE (relative biological effectiveness) values in the region of 2 to 5, depending on the biological end point used. The OER (oxygen enhancement ratio) at the peak is found to be significantly low compared with low-LET radiations such as x-rays and γ-rays commonly used in radiotherapy.

I. INTRODUCTION

Radiation therapy is one of the important modalities of cancer treatment and this may be true for many years to come. Historically, there has always been a search for penetrating radiations that would minimize radiation damage to the surrounding normal tissue for a given dose to a deep-seated tumor.

The administration of a large dose of conventional radiation to the tumor relative to normal tissues seem to be required whenever anoxic but viable cells are present in the tumor. For successful treatment a sufficient number of cells in the normal vital structures within the tumor region should survive. A careful selection of fractionation schedule may provide a satisfactory solution in dealing with this anoxic cell problem in certain cases, but probably not in all tumors (see Van Putten and Kallman,[40] Thomlinson[36]). Other approaches in solving this problem include hyperbaric oxygen therapy (see Churchill-Davidson[8]), the use of highly ionizing radiations such as neutrons (see Fowler,[15] Barendsen[4]), and heavy ions (see Lawrence and Tobias,[23] Tobias and Todd[39]).

Negative π mesons (also called pions) have a mass 273 times that of an electron. The dose delivered by negative pions as they pass through a tissue-like medium increases slowly with depth, giving rise to a distinct maximum

known as the Bragg peak near the end of the range, as do other heavy charged particles. The unique characteristic of negative pions is that when they come to rest they get captured by the nuclei of the medium, which causes the nuclei to disintegrate into smaller fragments. Some of these fragments have ranges shorter than a millimeter and are of high LET. These high-LET fragments dissipate a large amount of energy locally and have RBE in excess of 1. As a consequence the biological effect at the peak is enhanced and the radioresistance of anoxic cells is of lesser importance. Negative π mesons can be made to stop in the tumor region by properly selecting the energy and energy spread of the beam. Hence, negative pions, in principle, have important applications in the treatment of deep-seated tumors containing anoxic cells.

This possibility has been appreciated by many people. It was discussed by one of the authors (Richman) with Dr. C. A. Tobias at Berkeley in 1952. Dr. Hill at Illinois wrote a memorandum on this possibility. Fowler and Perkins[16] were the first to make detailed calculations, and this work generated heightened interest in the use of π^- mesons for radiotherapy.

Physical and radiobiological measurements for pions have been carried out at the Lawrence Radiation Laboratory, Berkeley, over the past 6 years (see references 1, 6, 9, 12, 13, 24, 25, 27-32). Some physical measurements have also been made at CERN, Switzerland and at Brookhaven National Laboratory (see references 3, 19, 37, 38).

This paper gives the results of physical and radiobiological measurements of negative π mesons with reference to radiotherapy. In addition, we will discuss briefly the production of mesons and speculate on future availability of pion facilities.

II. PRODUCTION OF PION BEAMS

Pions can be produced in any nuclear interaction if the energy of the primary particle is sufficient to create a pion (rest mass ~ 140 MeV) and also satisfy energy and momentum conservation. Pions of different energies will be produced; the maximum energy is limited by the energy of the primary particle. Pions are most abundantly produced by a primary beam of protons. Our experiments at Berkeley are carried out at the 184-inch synchrocyclotron. This machine provides an accelerated beam of 732-MeV protons that in their outer orbit strike a 5-cm-thick beryllium target and produce neutral, positive, and negative pions. The experimental arrangement is shown in Fig. 1. The negative pions are deflected out of the cyclotron by the cyclotron fringe field and, after leaving the cyclotron tank through a vacuum window, enter a small quadrupole focusing magnet (meson quad), then travel along a channel (dashed line in Fig. 1) through the main cyclotron shielding (hatched area). The pions then enter the meson cave, where various arrangements of magnets are used for energy selection and focusing of the pion beam. A bending magnet is used for momentum selection. The cyclotron produces pions in a range of energies from 0 to about 450 MeV. In the change from a negative to a positive pion beam, all the magnetic fields are reversed. The magnetic-lens system remains unchanged for pions of the same energy, regardless of charge.

Neutral pions have a very short lifetime, $\sim 10^{-16}$ sec, and decay into two gamma rays in the target. The gamma rays get converted into electron-positron pairs that go mainly in the forward direction. The electrons from this conversion constitute the electron background in the negative-pion beam.

Charged pions have a mean life of 2.54×10^{-8} sec, hence some of them decay in flight and this constitutes the muon background in a pion beam.

The presently available negative pion beams are too low in intensity for therapeutic applications.[*1] The pion beam at the 184-inch synchrocyclotron at Berkeley is the most intense source available today (10^6 particles/sec). In terms of dose rate, it is ~ 0.5 rad/min at the peak, over an area of 3×5 cm^2. With such a beam, physical measurements can be carried out quite well, but biological experiments, though feasible, are limited to low doses.

III. INTERACTION OF CHARGED PION WITH TISSUE

Charged pions travel through tissue in a manner similar to that of any other heavy charged particle, and stop after traveling a given range that depends on energy; e.g., a 50-MeV pion has a range of about 9 cm in tissue. A plot of range versus energy for pions is shown in Fig. 2.

When a negative pion is brought to rest in a tissue medium, it may be captured by any one of the carbon, nitrogen, or oxygen atoms. When captured by hydrogen, however, the resulting neutral mesic atom diffuses through the medium, and when it gets close to a heavier nucleus the pion is transferred to it because the resulting energy is lower. As a result, the pion is captured by the main tissue elements and cascades down the atomic levels to the ground state of the atom in a time that is short compared with its lifetime. During the last stages of the cascade, x-rays will be emitted. These have special

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*1 Pion facilities with intensities two to three orders of magnitude higher than the one presently available are under construction at Los Alamos Scientific Laboratory, U.S.A.; Vancouver, Canada; and Zurich, Switzerland.

interest which will be mentioned later; they are called π-mesic x-rays. From the ground state a pion is captured by the constituent nucleus, which explodes into a star consisting of short-range heavily ionizing fragments and neutrons. In such interactions about 30 MeV appears in the form of alpha particles, protons, and heavier fragments with ranges less than 1 mm in tissue. A further 40 MeV is expended in breaking up the nucleus, and the remaining 70 MeV is carried off by neutrons (Fowler[17]). A few examples of negative-pion capture in carbon, nitrogen, and oxygen as observed in photographic emulsions are shown in Fig. 3.

The relative frequency with which different elements capture pions is closely proportional to their relative abundance by mass. In bone-free parts of the body we expect 73% of the captures to be in oxygen, 20% in carbon, and 3% in nitrogen, which leaves only 4% in heavier atoms. It is important, therefore, to know the characteristics of capture in oxygen nuclei. Fowler and Mayes[18] made measurements on tracks of particles stopping in wet and dry emulsions in order to get the data on pions captured in oxygen alone. They found that interactions with oxygen produce tracks of multiply-charged particles. Some of the dominant reactions in oxygen are given below.

$$\pi^- + {}^{16}O \rightarrow {}^{12}C + p + 3n$$
$$3\alpha + p + 3n$$
$${}^{14}N + 2n$$
$${}^{10}B + \alpha + 2n\,.$$

The type of particle, its energy, and frequency per π^- capture in water as measured by Fowler and Mayes,[18] along with

calculated results of Guthrie et al.[20] are shown in Table I. Neutron kinetic energy experimental data is from Anderson et al.[2]

Table I. Energy Partition for π^- Capture in Water.

	Average energy per pion star (MeV)		Average number of particles per pion star	
Particle type	Measured	Calculated	Measured	Calculated
Protons	15.2	20.03	0.95	1.25
Deuteron	—	2.45	—	0.210
Alphas	7.8	10.62	0.99	1.08
$Z \geq 3$	4.4	2.42	0.78	0.631
Neutrons	69	60.65	2.7	2.94

The capture reactions in carbon, nitrogen, and oxygen are quite similar in their yield of protons and alpha particles, and in their mean energies.

Calculations of the capture of negative pions in light elements by Guthrie et al.[20] indicate an average excitation energy of about 5 MeV of residual nuclei per π^- capture. Particle emission is no longer energetically possible, so this results in gamma emission. About 2% of stopping pions produce high-energy gamma rays, peaking in the energy region of 100 MeV.[11] The gamma rays have special interest which will be mentioned later.

The characteristic difference in behavior between a positive and a negative pion occurs at the end of the range. When the positive pion comes to rest, the coulomb repulsion between its positive charge and that of the nucleus keeps it from interacting with the nucleus. It goes through two decay processes:

$$\pi^+ \rightarrow \mu^+ + \nu$$

$$\mu^+ \rightarrow e^+ + \nu + \bar{\nu}\,.$$

The ν and $\bar{\nu}$ are neutrinos and do not contribute to the dosage. The μ^+ is a short-range 4.12-MeV muon which contributes a small dose. The positron has a beta decay distribution in energy with a peak around 30 MeV.

IV. PHYSICAL MEASUREMENTS

The negative pion beam produced at the 184-inch cyclotron at Berkeley has a contamination (expressed as percent of total particles) of 25% e^- and 10% μ^- whereas the positive pion beam has 10% e^+ and 10% μ^+, (Richman et al.[31]). The muon contamination can be reduced by reducing the flight path of the pions from the target to the experimental area. The electron contamination can be minimized by using an electrostatic separator in the beam optics. The depth-dose distribution of a pure pion beam is of interest since such a beam will be used in actual therapy. By using the contaminated beam, the depth-dose distribution for the pure pion component is obtained with a semiconductor detector as a sensing element in a water phantom and gating semiconductor systems with the signal due to pions only. The depth dose distribution as measured with silicon detectors agreed well with the calculated distribution (Curtis and Raju[9]). A time-of-flight system was used to resolve the signal due to pions from muons and electrons (Raju et al.[29]). Some of the important results will be presented here.

Nearly 50% of the dose at the peak of the depth-dose distribution for a pure π^- beam is found to be due to nuclear events, as demonstrated by a comparison between a π^- and a π^+ beam.

The depth-dose distributions of pure negative and positive pion beams of energy 65 MeV in water is shown in Fig. 4. The increase in dose for a π^- beam at the peak is due to the star events except for the small contribution due to μ^+ and e^+ resulting from π^+ decay.

Isodose contours give a much clearer picture of dose distribution. Such curves can be constructed from a series of beam profiles taken at various depths in the medium. Figure 5 shows such isodose contours for a pure π^- beam of energy 65 MeV in water.

Integral dose distribution in the regions of interest plotted as percent dose above a threshold LET as a function of threshold LET is of interest. From such a plot one can easily find out the percent of dose above a given LET. Such a plot is shown in Fig. 6. The plots for pions at the peak position are obtained by integrating calculated pion LET spectra (Curtis and Raju[9]). For comparison purposes, neutron curves obtained from calculations of Bewley[7] are also shown.

Pulse-height spectra were taken at various depths of lucite for a contaminated pion beam by using a spherical proportional counter (Lucas et al.[25]). The pulse height was calibrated in terms of keV/μ by using an ^{241}Am source. The proportional counter was also used to measure the dose in different LET regions by connecting the pulse-height analyzer in such a way that it formed the product of number of channel and the count in that channel. The experimental results are shown as data points in Fig. 6; a fairly good agreement with the calculated results can be noted. However, this may be somewhat fortuitous because of slight differences in the beams used in calculations and

measurement. In addition, certain questions regarding the validity of calibration procedures for the detection of many-pronged stars are yet to be resolved.

In comparing with neutrons, it must be pointed out, however, that the LET spectra of neutrons practically remain unchanged with depth whereas for negative pions the distribution shown in Fig. 6 is present only at the peak, while for the intervening tissue the LET is similar to that of conventional radiation. It can be seen that the percent dose at the peak region for pions and fast neutrons above 100 keV/μ is similar. The figure also shows that pion dose extends to considerably lower LET than does the fast neutrons.

V. RADIOBIOLOGICAL MEASUREMENTS

Although the Berkeley 184-inch synchrocyclotron is the most intense source of low-energy pions available today [10^6 pions/sec (in terms of dose rate, 5 to 30 rads/hr at the peak, depending on the size of the beam)], the intensity is not adequate to do pretherapeutic radiobiological work. A contaminated beam is used in all the radiobiological work since purification of the beam reduces the pion intensity considerably. A summary of the radiobiological work follows.

The proliferative capacity of tumor cells irradiated in vivo in mice was measured as follows. Mice (LAF_1) bearing 5-day-old lymphoma ascites tumors were exposed to a pion beam at the plateau and peak region. The dose rate at the peak was about 5 rads/hr. The animals were sacrificed after the exposure, and then lymphoma cells were withdrawn and titrated into adult female LAF_1 mice. The proliferative capacity of the irradiated tumor cells

was evaluated after 8 weeks by observing the percentage of animals developing ascites tumors. An RBE value of 5.4 ± 1.8 was obtained for negative pions at the peak region when compared with gamma rays from ^{60}Co, (Feola et al.[12]). This high value is probably due to recovery from gamma radiation at a low dose rate. The RBE at the plateau was found to be very close to 1.

The same value of RBE was found for 2-day-old ascites tumor cells, which are known to have more oxygen available (Feola et al.[13]).

The ascites tumor cells of some of the exposed mice were also used for cytological examination. Poliploidy induction was used as a criterion for the radiation effect. The RBE at the plateau when compared with ^{60}Co gamma rays was found to be 1, whereas at the peak region it was 2.5 (Loughman et al.[24]).

In our early experiments with Vicia faba, we wanted to see if there was a significant enhancement of biological damage at the peak region when compared with the plateau region. One group of bean roots were exposed at the plateau and the other at the peak region (at a dose rate of about 5 rads/hr.) The biological end points used in this investigation were a) growth rate following irradiation, b) the percentage of cells containing micronuclei, and c) the percentage of cells with abnormal anaphases. In all these cases significant enhancement of damage was observed at the peak region when compared with the plateau region. The number of abnormal anaphases at the peak region were found to be about 2.4 times that at the plateau region (Richman et al.[32]).

After having established significant enhancement of the radiation damage at the peak position, experiments were continued with Vicia faba

to measure RBE and OER at the peak region. The beam was focused to a small area (3×5 cm^2) and the resulting dose rate at the peak was about 30 rads/hr. Five pairs of irradiation boxes with 30 beans in each box were exposed at the peak position to different doses in the range of 50 to 150 rads at room temperature. Air was bubbled into one box and nitrogen into the other as each pair was exposed.

The OER is dependent on dose rate when the roots are exposed at room temperature. From growth measurements, the measured OER at the peak was found to be 1.35 (Raju et al.[30]). This value may be compared with the value of about 2 for conventional radiation such as ^{60}Co gamma rays, at a dose rate corresponding to that of the π^- meson beam. The RBE of π^- mesons at the peak position was found to be 3 by comparing it with ^{60}Co gamma rays at a dose rate of 1 rad/min.

The OER is relatively independent of dose rate when the bean roots are exposed at low temperatures (Hall and Cavanagh[21]). The OER for the π^- meson at the peak was also measured when the roots were exposed at a low temperature (4°) and it was found to be 1.5, and this value may be applicable to an acute dose rate of π^- mesons (Raju et al.[30]).

Cytological preparations of root tips exposed to π^- mesons at the plateau and peak positions were made. Severe types of aberrations involving many chromatids were observed in root tips exposed at the peak position. These severe aberrations are presumably due to star events. Figure 7 shows some severe aberrations along with a normal cell and a simple type of aberration.

The RBE for pions at the peak (30 rads/hr) was also measured for human kidney (T-1) cells in culture by exposing the cells at room temperature as well as in the frozen state at liquid nitrogen temperature. Preliminary measurements indicate an RBE of about 2 in both the systems. In the frozen state the RBE is independent of dose rate (Burki et al.[6]).

RBE and OER for pions at the peak are also being measured for reversions to arginine independence in Saccharomyces cerevisiae Z-34 strain of yeast. Doses as low as 25 rads can induce significant number of arginine reverse mutations in this strain. Preliminary measurements indicate that the OER measured with this system is 2.5 to ^{60}Co gamma rays and that it is independent of dose rate. Preliminary results indicate an OER of 1.5 to 1.8 and RBE of 1.8 for pions at the peak position. This work is in progress. A summary of our radiobiological data for pions is given in Table II.

Further work is in progress on RBE and OER in other biological systems such as tissue culture and lymphocytes in culture.

VI. DISCUSSION ON RADIOTHERAPEUTIC ASPECTS OF NEGATIVE PIONS

It is clear from the interaction of negative pions with tissue, that this radiation has unique properties that have therapeutic application. The dose to the surrounding normal tissue is low and of low LET whereas in the region of interest, i.e., in the tumor, the dose is high and of high LET. The results of physical and radiobiological measurements indicate the following features that are very useful in radiotherapy.

Table IIa. RBE of π^- Mesons at the Peak of Depth-Dose Distribution for Berkeley Beam with 35% Contamination. [a]

Biological system	RBE	Reference
Abnormal anaphases in Vicia faba root meristems	2.4	Richman et al., Rad. Res. suppl. 7, 182 (1967).
Vicia faba, 10-day growth	3	Raju et al. (unpublished).
Arginine reverse mutations in yeast [b]	1.8	Raju et al. (unpublished).
Proliferative capacity of ascites tumor cells	5	Feola et al., Rad. Res. 34, 70 (1968).
Poliploidy induction in ascites tumor cells	2.5	Loughman et al., Rad. Res. 34, 56 (1968).
Human kidney cells T-1 [b]	2	Barendsen et al. (unpublished).
Human kidney cells in frozen state [b]	~2	Burki et al., UCRL-18793 (1968), p. 100.

a) RBE of π^- mesons at the plateau is 1.

b) Preliminary results.

Table IIb. OER of π^- Mesons at the Peak of Depth-Dose Distribution for Berkeley Beam with 35% Contamination. [a]

Biological system	OER	Reference
Vicia faba (growth)	1.35-1.5	Raju et al. (to be published in Rad. Res.)
Arginine reverse mutations in yeast [b]	1.5-1.8	Raju et al. (unpublished)
Human kidney cells T-1 [b]	1.8	Barendsen et al. (unpublished)

a) OER at the plateau is the same as conventional radiation, i.e., 2.6.

b) Preliminary results.

SURROUNDING NORMAL TISSUE REGION	TUMOR REGION
A. Low dose	High dose
B. Low LET	High LET
C. Low RBE (same as conventional radiation)	High RBE
D. High OER (same as conventional radiation)	Low OER
E. More recovery during fractionated treatment	Less recovery during fractionated treatment

For further discussion on response of cultured cells, normal tissue, and tumor for low- and high-LET radiations, see Barendsen.[5]

Pi meson radiotherapy promises to minimize damage to normal tissues surrounding tumors. Hence one can expect a diminution in the morbidity of radiotherapy over that of conventional radiation for a given tumor dose. Because of a more rapid decrease in dose with distance from the tumor over that of other radiations, it is possible to deliver a higher dose by using π^- mesons. In addition the damage produced to the tumor region is less dependent on the oxygenation status of irradiated tumor cells.

Implementation of π^- mesons for radiotherapy of tumors in humans awaits the availability of adequate beam intensity. The pion facility is very complex and expensive. The machines being built at Los Alamos, New Mexico (e.g., see Rosen,[33,34]); Vancouver, B. C., Canada; and Zurich, Switzerland, cost in the range of 25 to 50 million dollars. Plans have been made to include biomedical capabilities at these basically high-energy-physics facilities. There is a possibility with the continued improvement in accelerator technology that a much less expensive meson facility can be built by using superconducting

technology based on the research at Stanford University (Stanford, California, U. S. A.).

Biological Dosimetry

In planning of treatment with conventional radiation, isodose contours are quite adequate since with the biological effect the same, isodose contours and isoeffect contours are very nearly the same. With π^- mesons the LET increases very slightly with depth of penetration, but near the end of the range the LET increases considerably because of star events. The changes in LET with depth of penetration before star formation occurs, are not very significant in terms of changes in biological effects. The peak of the depth-dose distribution as shown in Fig. 4 is not broad enough for most of the radiotherapeutic procedures. This can be broadened to cover large tumors by using a variable absorber (Karlsson[22]) as is done in radiotherapy with protons. This can also be done by accepting a given spectrum of pion energies produced at the target so that the peak covers the region of interest. When such broad peaks are used there will be significant variation in RBE: it will increase with depth within the peak region. This variation can be reduced by exposing the region of interest to two opposing fields. Isoeffect within the region of interest can be more effectively achieved by the proper selection of energy spectrum so that the dose within the broad peak region decreases slowly with depth in order to compensate for the changes in RBE within this region. Such a depth-dose distribution is shown in Fig. 8 (Curtis[10]).

The pion beam optics should be designed so that the desired depth-dose distribution can be achieved easily to cover various size tumors at

different depths (see Rosen[34]). RBE and OER at different depths in different biological systems have to be determined for different beams before this radiation can be used for radiotherapy. The presently available pion beams are not intense enough to permit such measurements.

As discussed in the section on interaction of negative pions with tissue, π-mesic x-rays, gamma rays and neutrons will also be emitted from the region where negative pions stop and produce stars. The neutron dose at the peak is small and is favorable.[9] The dose contribution due to x-rays and gamma rays is negligible. Significant numbers of these radiations may be detected outside the exposed patient and this may provide a good method of externally observing the stopping-pion region during exposure. This helps in making sure that the treatment region (tumor) and the stopping-pion region coincide (Rosen[35], Perez-Mendez[26]).

VII. CONCLUSION

Negative pions share the advantages of heavy charged particles in having an excellent depth-dose distribution. In addition, the damage produced at the tumor region is less dependent on the oxygenation status of the cells. The problem of dealing with hypoxic cells may not be completely solved by proper fractionation schedule alone. Negative pions that have the characteristics of delivering a high LET dose in the region of interest may prove to be very useful in radiotherapy. The maximum benefits could be achieved with this radiation if the problems of detection of tumors are solved, so a parallel effort to improve the tumor site detection is very important.

The meson facilities now being built are quite complex and expensive. However, this should not discourage the use of pions in radiotherapy, because

it may turn out that the patients need not necessarily receive the complete treatment at these complex facilities. Patients probably could be treated at their local therapy centers for several weeks with conventional radiations, and finally with two or three substantial dose fractions with negative pions during the last week of their treatment schedule to eliminate any remaining hypoxic cells (Fowler[14]).

Future improvements in accelerator technology may reduce the cost and size of the pion facility. Thus it may be possible within a few years to have pion facilities at a number of large radiotherapy centers, if the results of radiotherapeutic trials at the three pion facilities now being built show significant improvement in cancer therapy.

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FIGURE CAPTIONS

Fig. 1. Experimental setup for producing a pion beam.

Fig. 2. Range versus energy for pions in water.

Fig. 3. Examples of capture of negative pions and the resulting nuclear disintegrations in the light elements carbon, nitrogen, and oxygen as observed in nuclear emulsions. The pion traces are labelled π^-; the stars produced following their capture have various number of prongs. (Courtesy of Powell, Fowler, and Perkins.)

Fig. 4. Depth-dose distribution of 65-MeV π^- and π^+ beams (pure pions) in water.

Fig. 5. Isodose distribution of 65 MeV π^- beam (pure) in water.

Fig. 6. Integral dose distribution (at the peak of the depth-dose distribution for π^- mesons) showing percent dose above threshold LET as a function of threshold LET. Neutron curves are also shown for comparison; the 6-MeV neutron curve is for a Hammersmith neutron beam.

Fig. 7. Chromatid aberrations of Vicia faba root meristems exposed to pions at the peak of depth dose distribution.

(a) Simple aberration.

(b) and (d) Severe aberrations.

(c) Normal cell.

Fig. 8. Depth-dose distribution of a beam of a selected energy spectrum so as to give a uniform biological effect over the entire peak region.

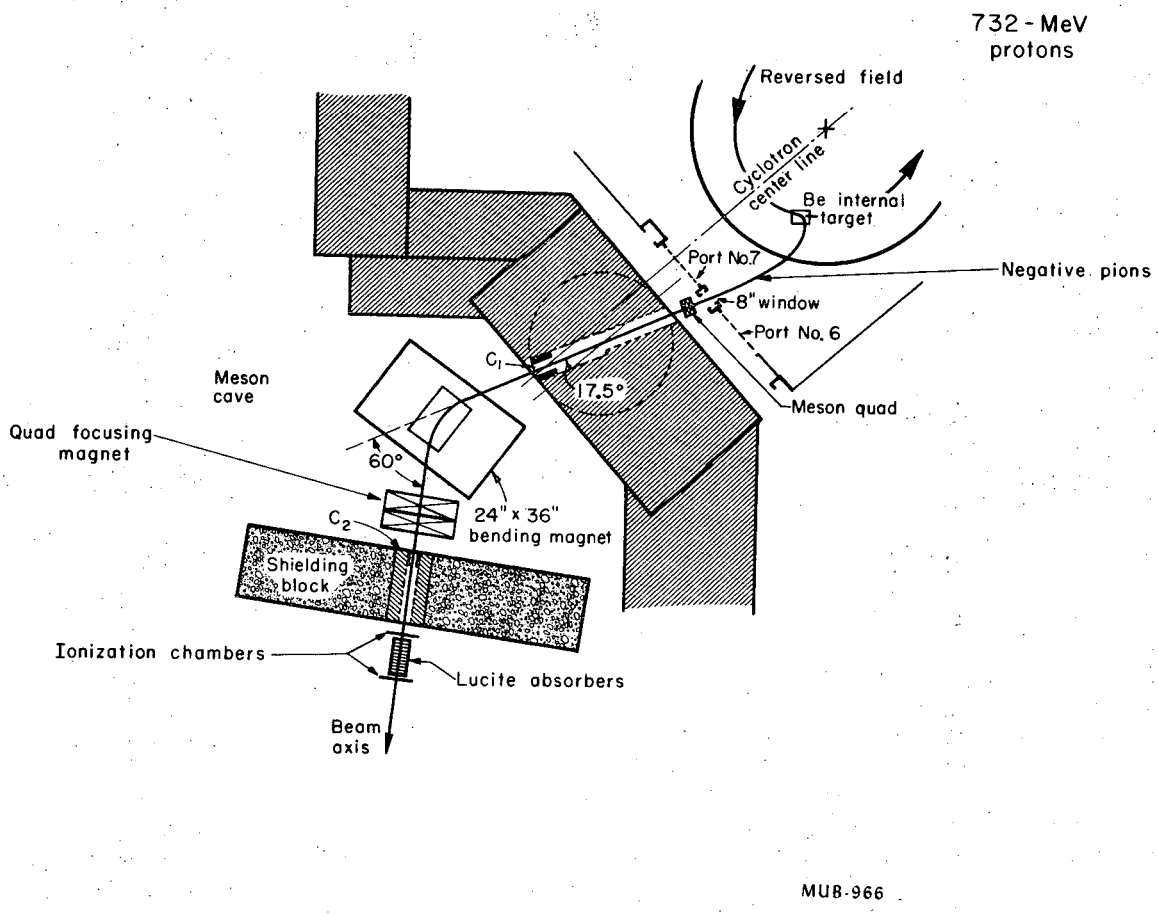

732 - MeV
protons
Reversed field
Cyclotron
center line
Be internal
target
Port No.7
Negative pions
8" window
Port No. 6
Meson quad
C_1
17.5°
Meson
cave
Quad focusing
magnet
60°
24" x 36"
bending magnet
C_2
Shielding
block
Ionization chambers
Lucite absorbers
Beam
axis
MUB-966

Fig. 1

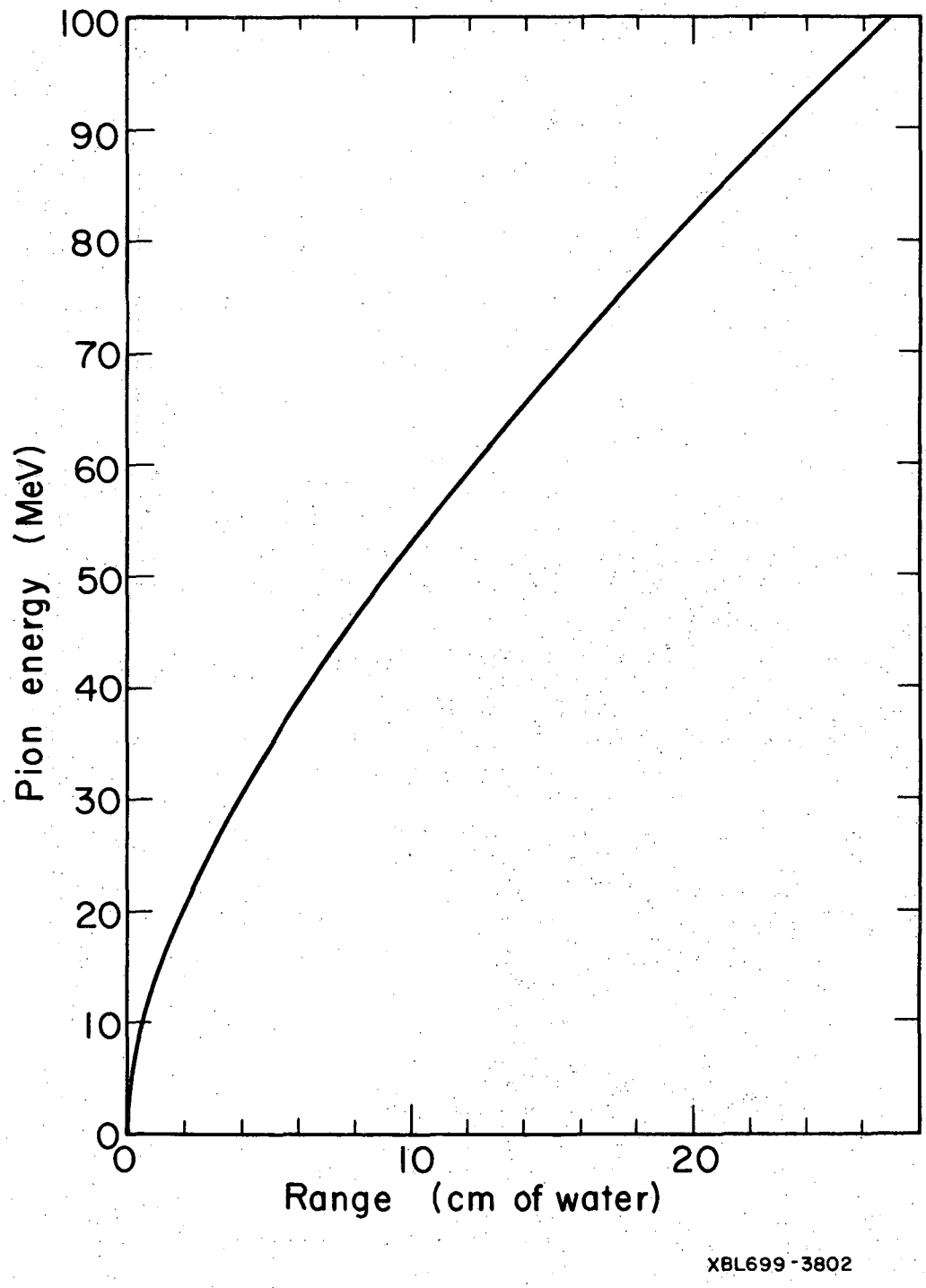
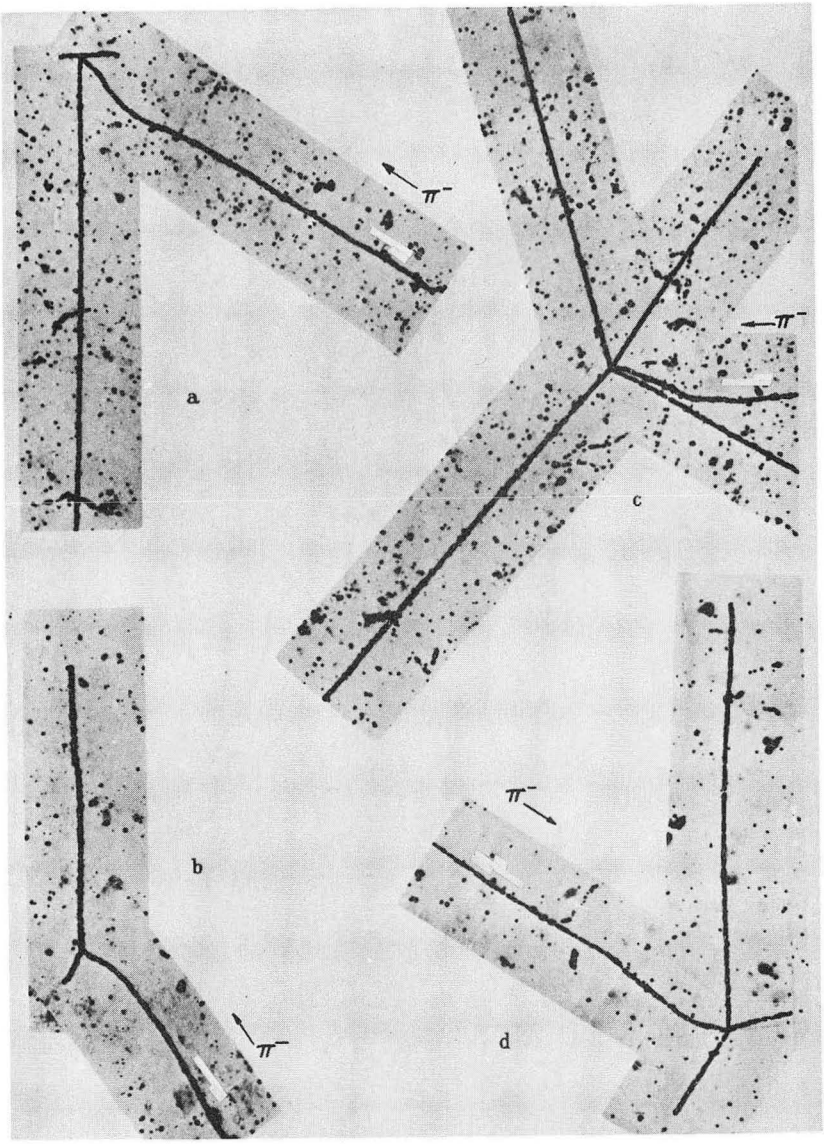

100
90
80
70
60
50
40
30
20
10
0
Pion energy (MeV)
0
10
20
Range (cm of water)
XBL699-3802

Fig. 2



JHL 4962-A

Fig. 3

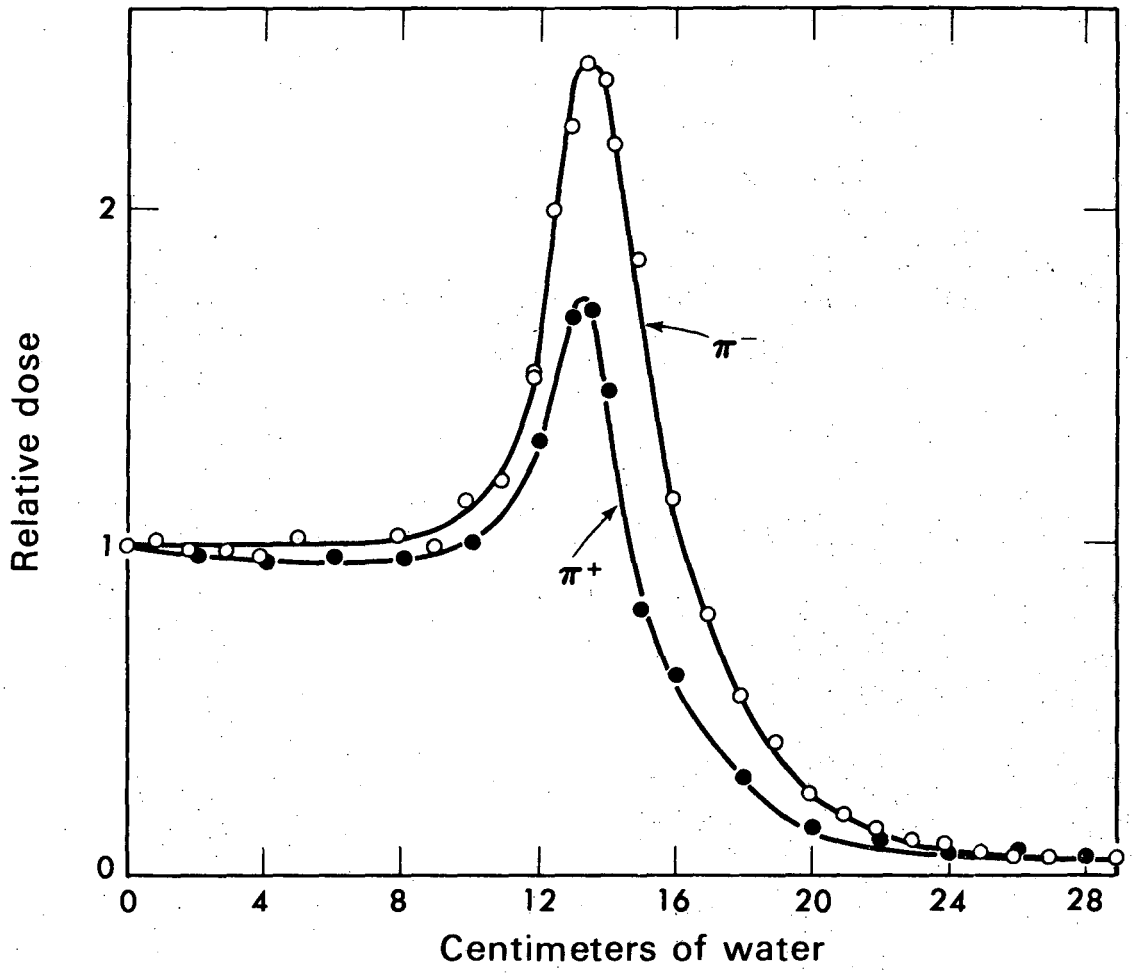
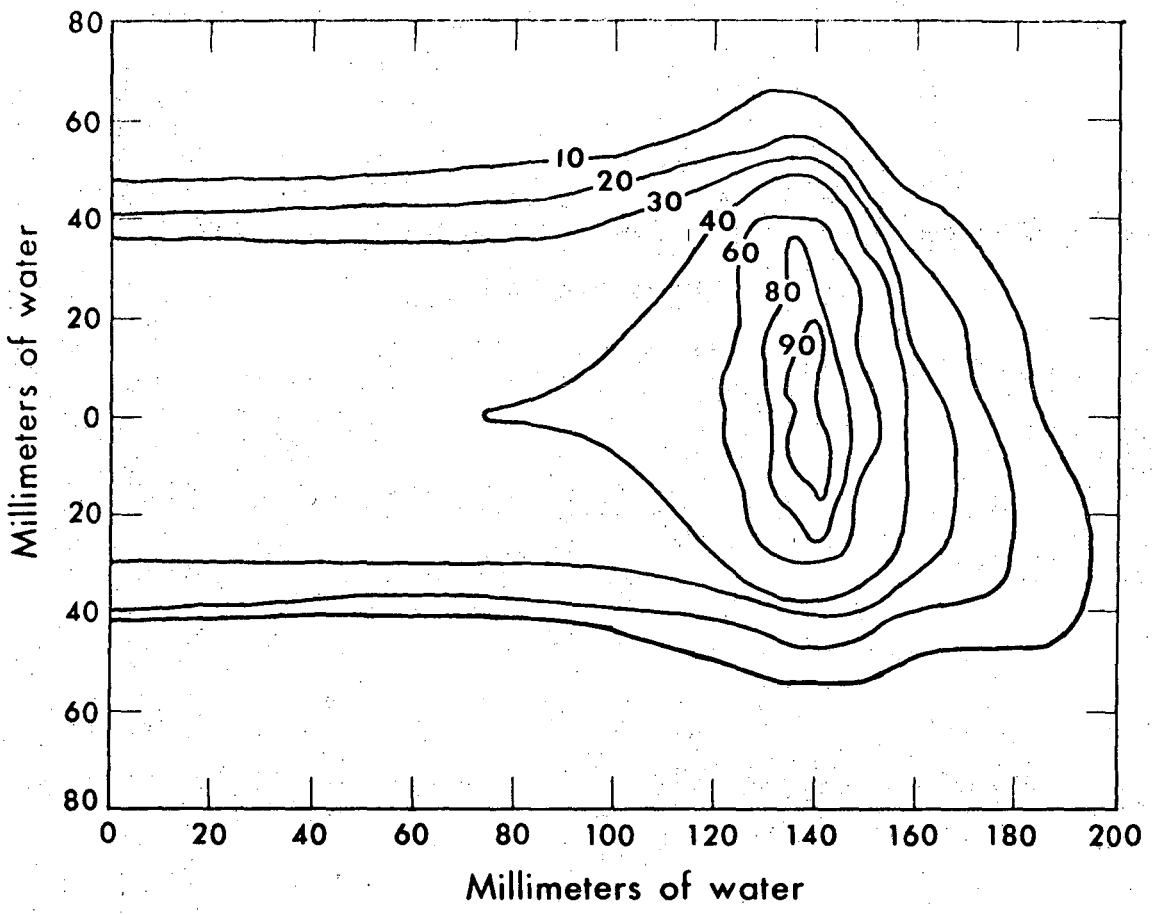
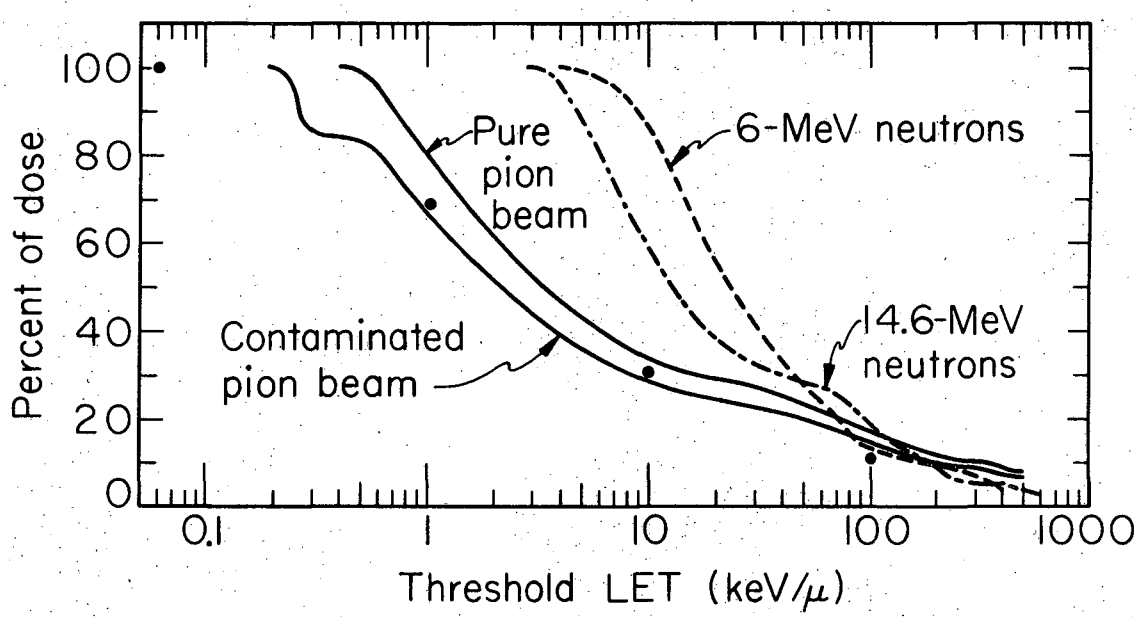

Relative dose
2
1
0
0
4
8
12
16
20
24
28
Centimeters of water
π^-
π^+
DBL 677-1698-A

Fig. 4



DBL 677-1704

Fig. 5



XBL699-3832

Fig. 6

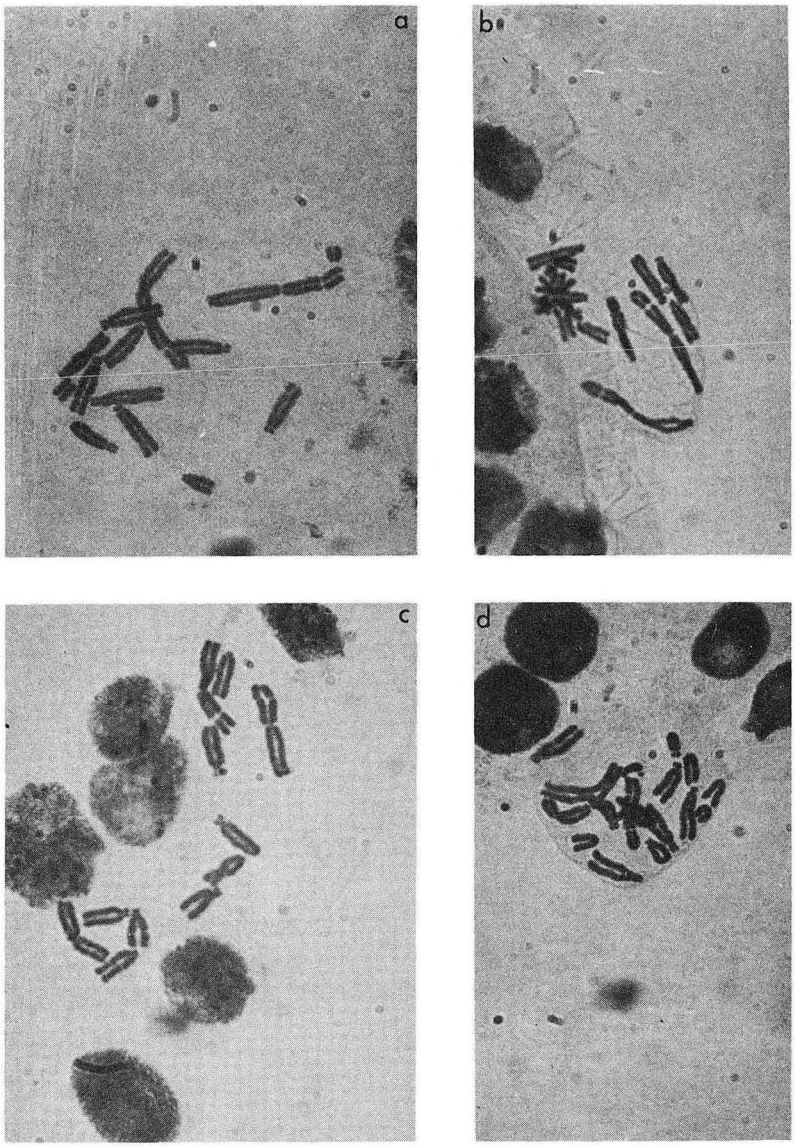


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Fig. 7

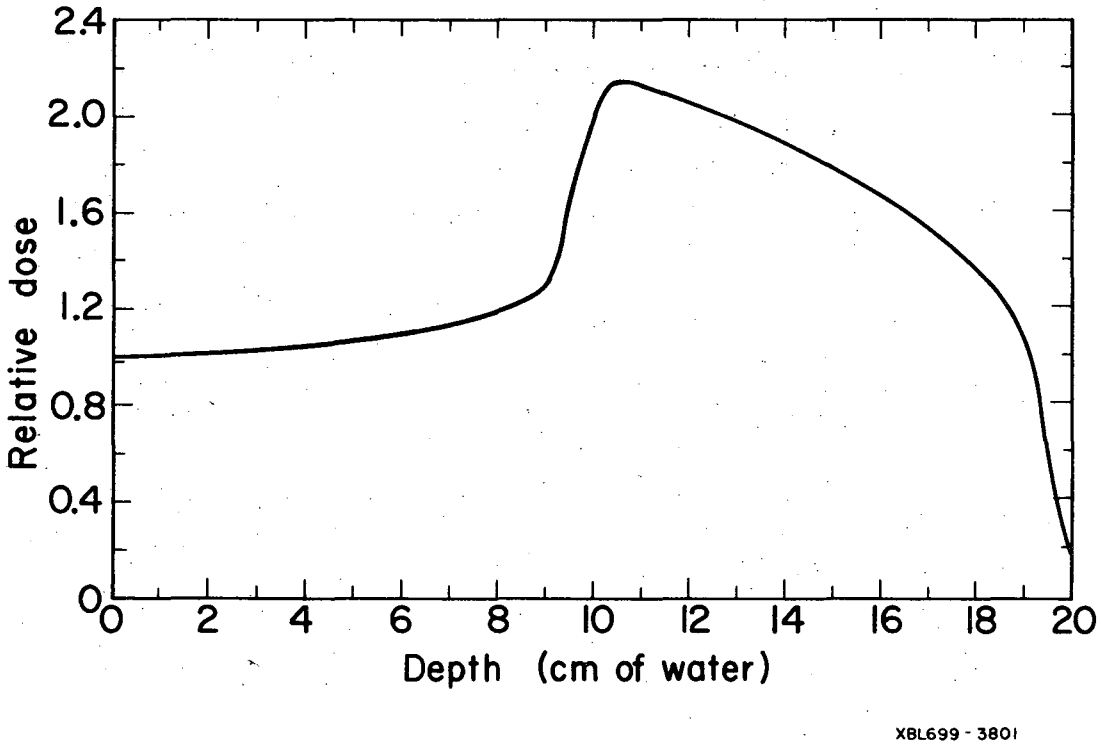
2.4
2.0
1.6
1.2
0.8
0.4
0
Relative dose
0
2
4
6
8
10
12
14
16
18
20
Depth (cm of water)
XBL699-3801

Fig. 8

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