Title

A MEASUREMENT OF THE AVERAGE ENERGY REQUIRED TO CREATE AN ION PAIR IN NITROGEN BY 250 MeV/amu C|+ IONS

Permalink

https://escholarship.org/uc/item/5g6420pc

Author

Stephens, Lloyd D.

Publication Date

1975-04-01

Submitted to Physics in
Medicine and Biology

LBL-4218
Preprint c.

A MEASUREMENT OF THE AVERAGE ENERGY REQUIRED TO CREATE AN ION PAIR IN NITROGEN BY 250 MeV/amu C^{6+} IONS

Lloyd D. Stephens, Ralph H. Thomas, and Lola S. Kelly

April 16, 175

Prepared for the U.S. Energy Research and
Development Administration under Contract W-7405-ENG-48

A MEASUREMENT OF THE AVERAGE ENERGY REQUIRED TO CREATE AN ION PAIR IN NITROGEN BY 250 MeV/amu C^{6+} IONS*

Lloyd D. Stephens, B.S.
Ralph H. Thomas, Ph.D., F. Inst. P, C.H.P.
Health Physics Department
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

and

Lola S. Kelly, Ph.D.
Biomedical Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

April 16, 1975

Abstract

A measurement of the average energy required to create an ion pair in nitrogen by 250 MeV/amu C^{6+} ions is described. A value of 36.6±0.7 eV was obtained.

---

*Work done under the auspices of the U. S. Energy Research and Development Administration.

Introduction

The Bevalac facility of the Lawrence Berkeley Laboratory provides heavy ions as massive as argon up to energies in excess of 2 GeV/amu (Grunder 1974). Because energetic heavy ion beams make possible the irradiation of small mammals (and other biological specimens of moderately large volume) at constant high linear energy transfer (LET), there is great interest in the application of heavy ions to fundamental research in radiobiology and to applied research directed toward their practical application in medicine (Tobias et al. 1972). As an example of the practical application of heavy ions to radiobiological studies, Patrick et al. (1974) have described the design of an experiment to study hematological effects and the incidence of cancer in mice irradiated by fully-stripped C^{6+} ions of energy 250 MeV/amu. Kelly (1975) has reported preliminary results of this experiment.

With this increasing application of high-energy heavy ions in radiobiology, there is a corresponding need to develop reliable techniques of dosimetry. Patrick et al. (1975 a,b) have reported the use of ^{7}LiF thermoluminescent dosimeters for the absolute dosimetry of heavy ions. This paper reports preliminary measurements of "W"--the average energy required to create an ion pair--in nitrogen, which will facilitate the use of nitrogen-filled ionization chambers for absolute dosimetry.

Previous Determinations of W

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

Measurement of W in Nitrogen for 250-MeV/amu C^{6+} Ions

The charge, Q, collected from the passage of N ions between the plates of a parallel-plate ionization chamber placed normal to a heavy-ion beam is given by

$$Q = \frac{10^6 N \ \rho\, s\, e\, (dE/dx)}{W}, \tag{1}$$

where ρ is the gas density (g cm^{-3}),

s is the plate separation (cm),

e is the electronic charge (coulomb), and

(dE/dx) is the specific energy loss of the ions in the gas within the chamber (MeV g^{-1} cm^2),

with Q measured in coulomb and W in eV. Rearranging Eqn.1 it follows that

$$W = 10^6 \rho\ s\ e\ (dE/dx) \frac{N}{Q}, \tag{2}$$

where ρ, N, and Q are parameters that may be determined experimentally.

In the measurement reported here, a parallel-plate ionization chamber filled with nitrogen at ambient temperature and pressure was used. The chamber was designed to have a minimum wall thickness of ~ 0.047 g cm^{-2} in the carbon-ion beam path and was constructed with a central collecting electrode of circular cross section (2-cm diam.) surrounded by several annular electrodes (see Fig. 1) (Howard 1974).

Throughout the measurements reported here, charge was collected from the largest annulus (8-cm i.d.; 10-cm o.d.) and was measured with a Thomlinson electrometer. The charge collected was presented digitally. The spacing between the collector electrodes, s, was 1 cm. The chamber was placed normal to a beam of fully-stripped C^{6+} ions of energy 252 MeV/amu from the Bevatron. Beam transport focusing elements were adjusted to produce as large a beam spot as feasible, with small divergence at the ionization chamber. Figure 2 shows a typical example of the spatial distribution of beam intensity measured with X-ray film. The beam intensity was not uniform or symmetrical about the beam axis. Consequently, the carbon-ion fluence at any point in the radiation fields used in these measurements was a function of distance from the beam axis, r, and of polar angle, θ, about the beam axis. Figure 3 shows the variation of carbon-ion fluence with polar angle, θ, measured for two of the experimental runs reported here. The carbon-ion fluences shown in these figures were determined using ^{7}LiF thermoluminescent dosimeters (Harshaw TLD 700 "chips": 1/8 in.×1/8 in.×0.035 in.).

In the determination of W reported here, it was necessary to determine the parameters $N\{r_1,r_2\}$ and $Q\{r_1,r_2\}$,

where

$$W = 10^6 \ \rho \ s \ e \ dE/dx \cdot \frac{N\{r_1, r_2\}}{Q\{r_1, r_2\}} , \qquad (2a)$$

and $Q\{r_1, r_2\}$ was the charge collected on the annular electrode (inner radius r_1, outer radius r_2) and $N\{r_1,r_2\}$ was the corresponding number of carbon ions traversing the chamber defined by

$$N\{r_1, r_2\} = \int_{r_1}^{r_2} \int_0^{2\pi} \frac{\partial^2 N}{\partial r \partial \theta} \cdot dr \, d\theta \qquad (3)$$

where $\frac{\partial^2 N}{\partial r \partial \theta}$ is the number of ions between r and r + dr, and between polar angles θ and $\theta + d\theta$.

At a fixed radius, r, the average fluence $\hat{\phi}(r)$ is given by

$$\hat{\phi}(r) = \frac{1}{2\pi} \int_0^{2\pi} \phi_r(\theta)\, d\theta \qquad (4)$$

where $\hat{\phi}_r(\theta)$ is the ion fluence at (r, θ).

The average fluence, $\hat{\phi}(r)$, was experimentally determined as a function of r by rotating dosimeters about the beam axis. Figure 4 shows the response of ^{7}LiF thermoluminescent dosimeters as a function of distance from the beam axis for three radiation fields used in these measurements. In all cases the $\hat{\phi}(r)$ is adequately represented by a Gaussian distribution:

$$\hat{\phi}(r) = \phi_0 \, e^{-r^2/2\sigma^2} , \qquad (5)$$

as may be seen by inspecting Fig. 4.

This empirically determined form for $\hat{\phi}(r)$ greatly simplifies the evaluation of $N\{r_1,r_2\}$, which is then given by

$$N\{r_1,r_2\} = 2\pi\sigma^2 \phi \cdot \left\{ e^{-r_1^2/2\sigma^2} - e^{-r_2^2/2\sigma^2} \right\} \qquad (6)$$

The parameter σ was determined, as already described, by rotating dosimeters about the beam axis. Radiation fields having values of σ of 4.85, 4.33, and 5.90 cm were used in three independent sets of measurements (see Fig. 4). It is both mathematically and experimentally convenient to determine the average ion fluence at the mid-radius, r_m, of the annular ionization chamber:

$$r_m = (r_1+r_2)/2 . \qquad (7)$$

Then combining equations (6) and (7) we obtain

$$N\{r_1,r_2\} = 2\pi\sigma^2\ \phi(r_m)\left\{\frac{e^{-r_1^2/\sigma^2} - e^{-r_2^2/\sigma^2}}{e^{-\left(\frac{r_1+r_2}{2}\right)^2/\sigma^2}}\right\} \tag{8}$$

With $r_1 = 4.0$, $r_2 = 5.0$ and $\frac{r_1+r_2}{2} = 4.5$ cm, the term

$$\frac{\sigma^2\left\{e^{-r_1^2/\sigma^2} - e^{-r_2^2/\sigma^2}\right\}}{e^{-\left(\frac{r_1+r_2}{2}\right)^2/2\sigma^2}}\ ,$$

is not strongly dependent upon the value of σ for the irradiation fields used in our measurement, and has the value 4.48. Using this value, combining equations (2a) and (8) and substituting the values:

$S = 1$ cm

$e = 1.602 \times 10^{-19}$ coulomb

$\left(\frac{dE}{dx}\right)_{N_2} = 125$ MeV $g^{-1}cm^2$ (Steward 1969)

we obtain

$$W = 5.63_7 \times 10^{-10}\ \frac{\rho\ \hat{\phi}(4.5)}{Q\{4,5\}}\ \text{eV}\ . \tag{9}$$

W may therefore be determined by measurements of the density of the nitrogen filling the chamber, ρ, the carbon-ion fluence averaged around the perimeter of a circle of radius 4.5 cm, $\hat{\phi}(4.5)$, and the corresponding charge collected by the annular chamber, Q{4,5}.

The density of nitrogen in the chamber was calculated from measurement of the ambient temperature and barometer pressure.

It was convenient to determine the ion fluence with ^{7}LiF thermoluminescent dosimeters that had been calibrated using nuclear emulsions. If g is the thermoluminescent dosimeter response per unit fluence, Eq. (9) then becomes

$$W = \frac{5.63_7 \times 10^{-10}}{g} \cdot \frac{\rho\,\hat{\tau}(4.5)}{Q\{4,5\}}\,, \tag{10}$$

where $\hat{\tau}$ is the corresponding average thermoluminescent dosimeter response at 4.5 cm from the beam axis.

The value of g was determined by exposing thermoluminescent dosimeters simultaneously with Kodak NTA nuclear emulsion (Patrick _et_ _al_. 1975b). The incident carbon-ion fluence was determined by optical scanning of the processed emulsion, more than 3000 tracks being counted in each emulsion. Table 1 summarizes the experimental data.

The mean value of g obtained was 7.59×10^{-6} TLU ions^{-1} cm^2. Substituting into eq. (10) we obtain finally:

$$W = 7.42_7 \times 10^{-5} \cdot \frac{e\ \hat{\tau}(4.5)}{Q\{4,5\}}. \tag{10}$$

Five independent determinations of W were made in three different beam conditions. Table 2 summarizes the experimental data.

Investigation of possible sources of statistical error shows that the density of nitrogen in the chamber may be determined to better than ±1% (standard deviation). The charge collected on the chamber electrodes may be measured to better than ±1%, and the incident heavy-ion fluence was measured to an accuracy of about ±4% for each exposure (see Table 1). Statistical fluctuations in the values of W of ± 4.2% (standard deviation) are therefore to be expected and in close agreement with the value of ±3.7% obtained from the values of treated as separate measurements (see Table 2).

Absolute sources of error in the value of W quoted, include uncertainty in the value of plate separation, S, of ~ 0.2 mm(±2%) and absolute errors in emulsion scanning, which are believed to be less than ±5%. Known absolute errors, therefore, amount to less than ±5.3%.

Conclusions

A value of 36.6±0.7 eV for the average energy required to create ion pairs in nitrogen by 250 MeV/amu C^{6+} ions was obtained. Systematic errors may lead to an absolute error of about ±5.3% or less.

The value of W should be dependent upon linear energy transfer, charge state, and velocities of the charged particle. The higher density of energy deposited adjacent to the particle trajectory by heavy ions, compared to lighter ions, leads to greater recombination of ion pairs and hence to higher W values. Comparison of our value of W with other values in the literature may not, therefore, be significant. The value of 36.6 eV reported here is comparable with those of 36.6 eV and 36.4 eV reported by Myers (1968) for protons and alpha particles. The value of 38.6 eV reported by Varma et al. (1975) was obtained using 35 MeV O^{6+} ions, which have an LET of ~ 785 keV/μ, compared to the value of 12.5 keV/μ for the 250 MeV/amu C^{6+} ions used in our measurements. The influence of the parameters discussed at the beginning of this paragraph on W values, therefore, seems to be small in the range of LET and for the ion species so far investigated.

Acknowledgments

We would like to thank J. T. Lyman and G. M. Howard for providing the ionization chamber data; Olga Fekula, Mary Long, and S. B. Thomas for scanning the nuclear emulsions. A Chatterjee gave useful advice during the writing of this paper.

This work was done under the auspices of the U. S. Energy Resources Development Administration.

REFERENCES

GRUNDER, H. (ed.), 1973 Heavy Ion Facilities at Lawrence Berkeley Laboratory Lawrence Berkeley Laboratory Report LBL-2090, October

HOWARD, G. M., Lawrence Berkeley Laboratory, private communication.

KELLY, L. S., LAPLANT, P., and THOMAS, R. H., 1975, Leukemogenic Effect of Heavy Ions (Carbon Ion Beam 250 MeV/amu) in RF Mice. Paper read at Radiation Research Society Annual Meeting, Miami Beach, Florida, 11-15 May.

MYERS, T. 1968, "Ionization Chambers," Chapter 7 in Radiation Dosimetry, ed. F. H. Attix and W. C. Roesch. (New York Academic Press), Vol. 1.

PATRICK, J. W., STEPHENS, L. D., THOMAS, R. H., and KELLY, L. S., The Design of an Experiment to Study Carcinogenesis and Hematological Effects in Mice Irradiated by Heavy Ions. Radiat. Res. in press.

PATRICK, J. W., STEPHENS, L. D., THOMAS, R. H., and KELLY, L. S. 1975a, The Efficiency of ^{7}LiF Thermoluminescent Dosimeters for Measuring 250 MeV/amu C^{6+} ions. Health Physics, <u>28</u>, 615.

PATRICK, J. W., STEPHENS, L. D., THOMAS, R. H., and KELLY, L.S., 1975b, The Efficiency of ^{7}LiF Thermoluminescent Dosimeters to High LET Particles, Relative to ^{60}Co γ-Rays. Health Physics, in press.

TOBIAS, C. A., LYMAN, J. T., and LAWRENCE, J. H., 1972, Some Considerations of Physical and Biological Factors in Radiotherapy with High LET Radiations Including Heavy Particles, Pi Mesons and Fast Neutrons, in <u>Prog. in Atomic Medicine: Recent Advances in Nuclear Medicine</u>, ed. J. H. Lawrence (Grune and Stratton Inc., New York) Vol. 3, p.167.

VARMA, M. N., BAUM, J. W., and KEUHNER, A. V., Experimental Determination of W for Oxygen Ions in Nitrogen, Brookhaven National Laboratory Report BNL 19686, January 1975. (Submitted to Phys. Med. and Biol.)

Table 1. Calibration of ^{7}LiF Thermoluminescent Dosimeters

Exposure #	Thermoluminescent dosimeter reading (arbitrary units - TLU)		Incident ion fluence (ions cm^{-2})	Dosimeter sensitivity (g) (TLU ions^{-1}cm^2)
1	0.784) 0.772)	0.778	1.01×10^5(±2%)	7.70×10^{-6}
2	0.934) 0.965)	0.950	1.32×10^5(±2%)	7.20×10^{-6}
3	2.22) 2.12)	2.17	2.76×10^5(±2%)	7.86×10^{-6}
				Mean: $(7.59\pm0.17)\times10^{-6}$ TLU ions^{-1}cm^2.

Table 2. Summary of Determinations of W for 250 MeV/amu C^{6+} ions in nitrogen

Run #	σ (cm)	ρ (gm cm^{-3})	Exposure #	$\hat{\tau}(4.5)$ (TLU)	Q(4,5) (coulomb)	$\hat{\tau}(4.5)/Q(4,5)$ (TLU/coulomb)	W (eV)
1	4.85	1.21×10^{-3}		*	*	*	35.3†
2	4.33	1.21×10^{-3}	(i)	73.4	1.764×10^{-7}	4.16×10^{8}	37.4
			(ii)	72.8	1.709×10^{-7}	4.260×10^{8}	38.3
3	5.90	1.19×10^{-3}	(i)	132.7	3.380×10^{-7}	3.925×10^{8}	34.7
			(ii)	717	1.706×10^{-6}	4.203×10^{8}	37.1
						Mean: 36.6±0.7 eV	

---

*Does not apply.

†Value of W calculated from data presented in Patrick *et al*. 1974.

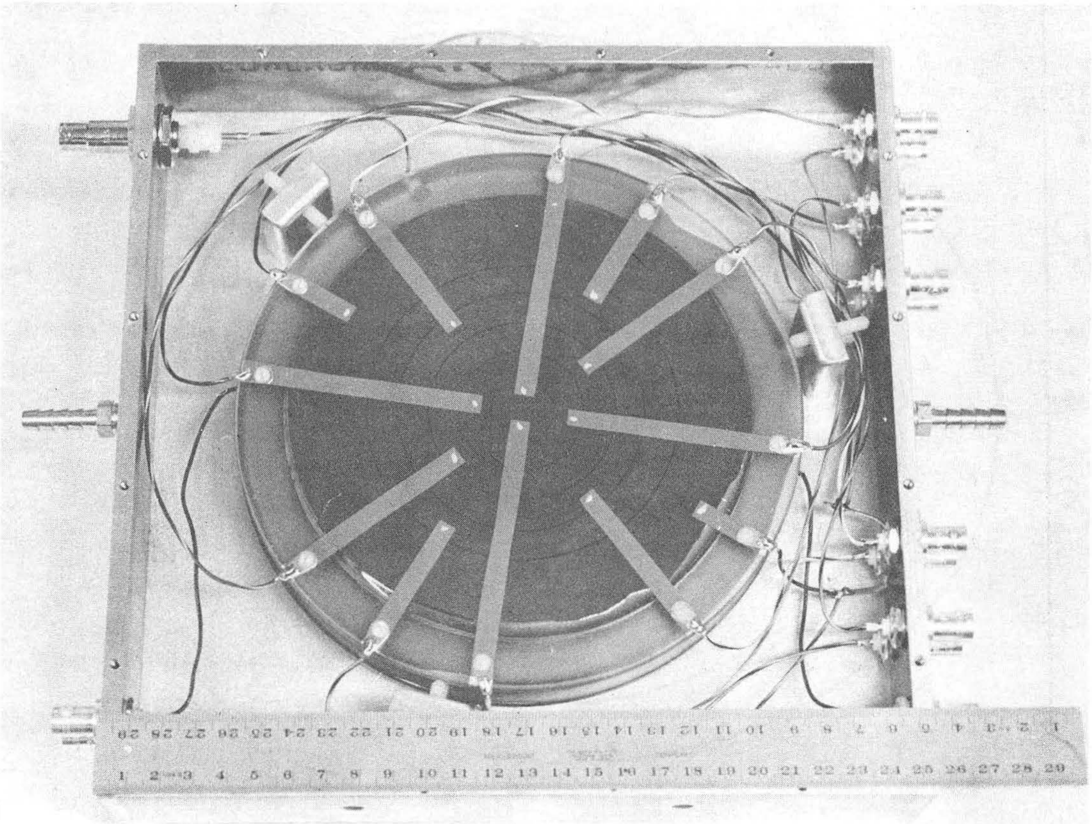
FIGURE CAPTIONS

Fig. 1. Photograph of annular ionization chamber used. The outer ring was used in these measurements.

Fig. 2. Typical spatial distribution of carbon-ion beam used in other measurements as determined using X-ray film. Similar data were obtained using thermoluminescent dosimeters.

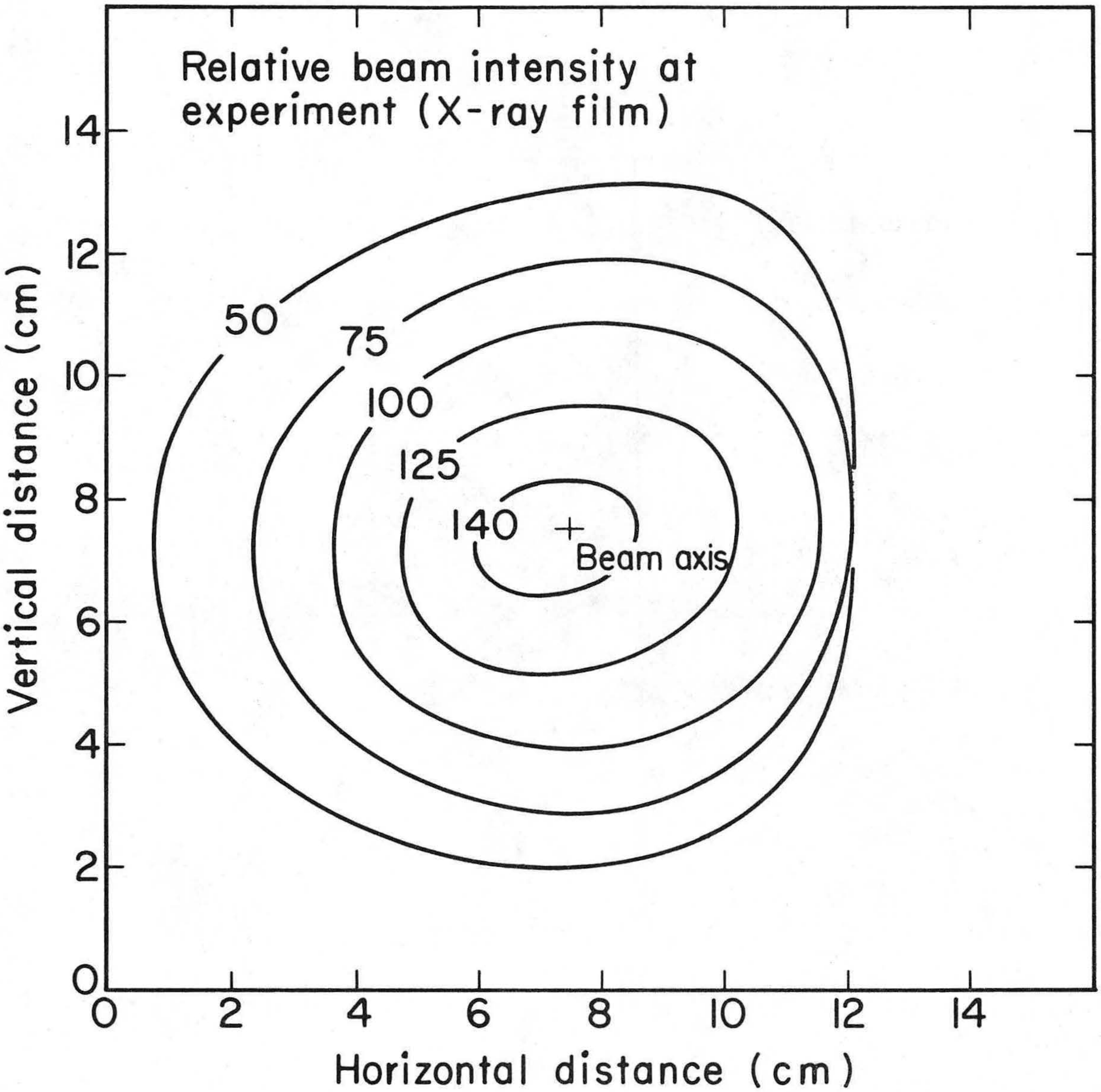
Fig. 3. Variations of carbon-ion fluence, a distance 4.5 cm from the beam axis, as a function of polar angle for two of the measurements reported.

Fig. 4. The average carbon-ion fluence, $\hat{\phi}(r)$ as a function of distance, r, from the beam axis for the three measurements reported. The solid curves show the Gaussian distributions that best fit the experimental data.



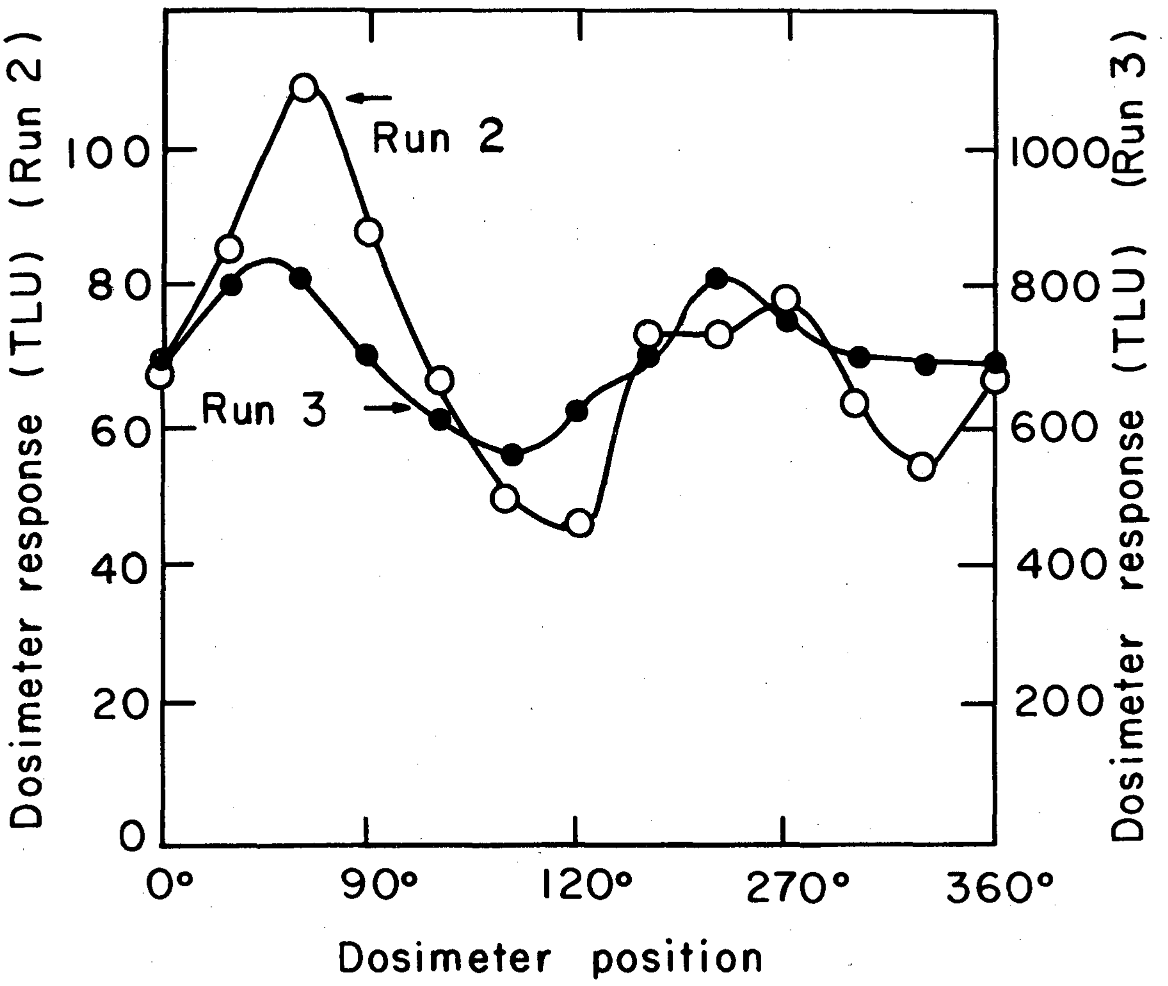
XBB 7210-5162

Fig. 1



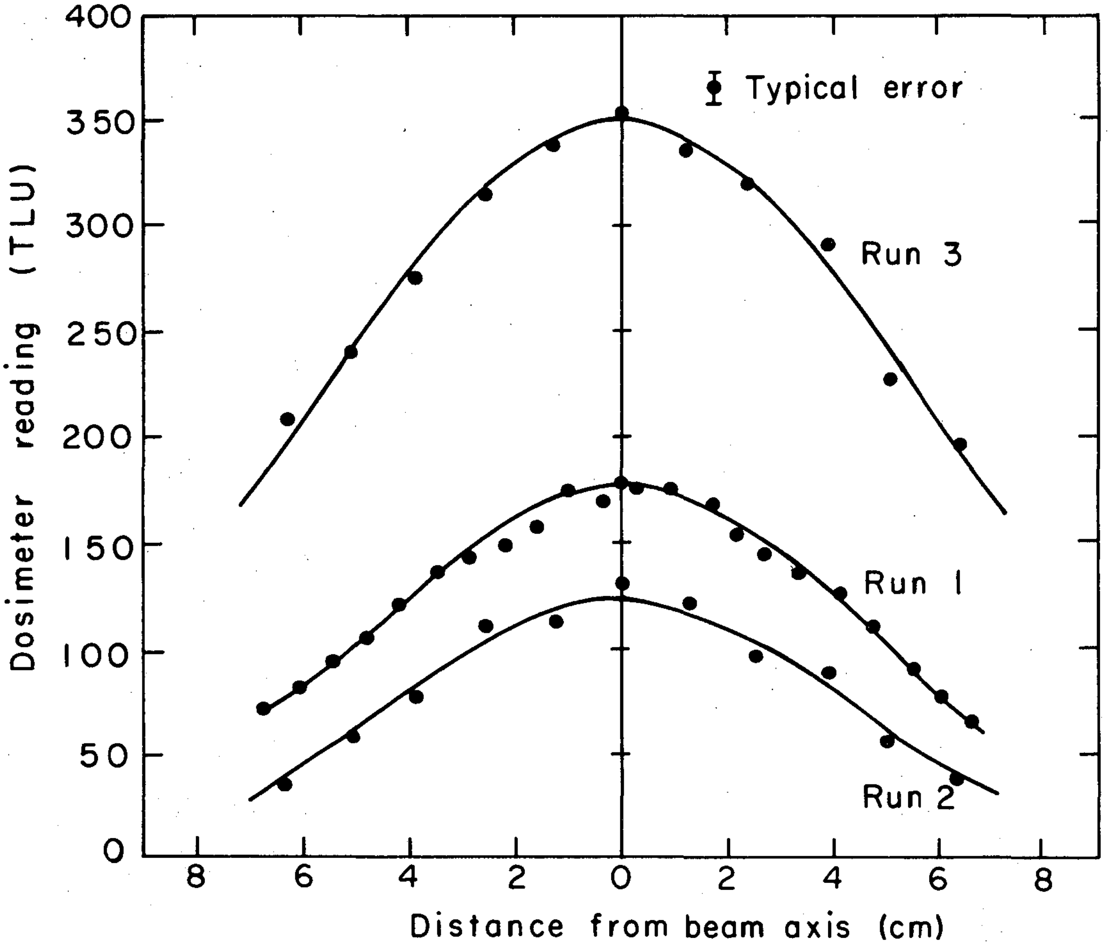
XBL7211-4366B

Fig. 2



XBL751-2099

Fig. 3



XBL758-3770

Fig. 4

TECHNICAL INFORMATION DIVISION
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720