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# AN INTERCOMPARISON OF DOSIMETRY TECHNIQUES IN RADIATION FIELDS AT TWO HIGH-ENERGY ACCELERATORS

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"Publish and be damned" - attributed to
Arthur Wellesley, Duke of Wellington 1769-1852

## ABSTRACT

A comparison of radiation intensity measurements outside the shielding of the Bevatron and the 20 GeV Electron Linear Accelerator at Stanford is described. Measurements were made using several different techniques by workers from Brookhaven National Laboratory, Lawrence Berkeley Laboratory, and the Stanford Linear Accelerator Center. The measurements indicate large discrepancies (factors of two or more) between different techniques of measurement and illustrate the need for improvement in high-energy accelerator dosimetric techniques.

## 1. INTRODUCTION

The radiation environments of particle accelerators which operate in the GeV region are extremely varied and depend on the primary particle accelerated and on the degree to which the electromagnetic and hadronic cascades are developed in the accelerator structure and shielding. A large variety of particles may be produced with energies extending up to the maximum energy of the primary beam particle. In many cases the pulsed nature of the radiation field may produce additional difficulties.

A comprehensive program of health physics at high-energy accelerators requires an understanding in some detail of the production and transmission through shielding of accelerator-produced radiation. (Pa73, Ri73) For such investigations, radiation detectors designed for nuclear physics research can provide the flux and spectral data necessary for many aspects of health physics work, such as shielding evaluation and design, background reduction in experimental counting areas, etc. In addition, such data may be interpreted in terms of dose-equivalent for radiation protection purposes. (Gi68, Rou69, Ic73). Initial measurements in an unknown environment often require a wide variety of instruments and detailed study of the operating conditions under which changes may occur. Afterwards, the use of more limited and less cumbersome instruments may be acceptable with some degree of interpretation of the readings based on prior knowledge of the field. The use of instruments calibrated to read directly in terms of dose-equivalent is of considerable value in providing essentially instantaneous information for health protection purposes.

Measurements were made with a Brookhaven National Laboratory (BNL) instrument which has been designed to measure absorbed dose and dose equivalent directly in mixed radiation fields. (Ku72a) Concurrently, data were obtained using radiation detectors regularly employed at both the Lawrence Berkeley Laboratory (LBL) and Stanford Linear Accelerator Center (SLAC) in the distinctly different but well understood radiation environments which exist at the SLAC 20 GeV electron linac and at the LBL 6 GeV proton synchrotron. Dose rates differ by more than an order of magnitude, being higher at LBL. Beam duty factors also differ considerably, being about $3\times10^{-4}$ at SLAC and about 0.1 at LBL. This paper describes the characteristics of the instruments which were used, along with the measurements and their intercomparison.

## 2. EXPERIMENTAL CONDITIONS

### Stanford Linear Accelerator Center

Radiation outside the end station wall is produced by electrons which scatter in a thin target and which subsequently interact in the aluminum transport pipe. Only a small fraction of the total beam is involved. For these measurements, 19.5 GeV electrons were scattered from a 0.03 radiation length hydrogen target. Rep Rate was 210 pps with a pulse width of 1.5 μsec. Peak Beam current was about 20 mA. Measurements were made at a production angle of about 120° from the transport pipe through 2 feet of concrete.

### Lawrence Berkeley Laboratory

5.4 GeV protons were incident on a septum magnet which divided the beam more or less equally between two channels with a resultant beam loss of approximately $10^{10}$ protons per pulse on the septum. Pulse repetition rate was 10 ppm with a pulse width of about 1 sec. Radiation measurements were made outside the shielding and on the roof above and downstream of the septum magnet. Shielding consisted of 4 feet of ordinary concrete on top of 8 inches of steel.

## 3. INSTRUMENTATION

3.1. Stanford Linear Accelerator Center Health Physics Group. The ionization due to photons and charged particles was measured with a large volume aluminum-walled, nitrogen-filled ionization chamber designed for environmental studies. (Wa74) The fluence of neutrons from about 20 keV to about 20 MeV was measured with a moderated $BF_3$ counter. (6 cm thick paraffin moderator, cadmium covered.) In addition, thermal neutrons were measured with a bare $BF_3$ counter at both locations but found to represent such a small fraction of the total neutron dose equivalent that they could be ignored. The measured neutron fluence is converted to dose equivalent by the use of recommended fluence to dose equivalent conversion factors.(Ic73) The total dose equivalent, H, may then be written:

$$H = Q_\gamma D_\gamma + Q_c D_c + K g_N \Phi_N \qquad (1)$$

| | | |
|---|---|---|
| where | $D_\gamma$, $D_c$ | are the absorbed doses produced by photons and charged particles respectively. |
| | $Q_\gamma$, $Q_c$ | are the respective quality factors. |
| | $\Phi_N$ | is the neutron fluence measured with a moderated $BF_3$ counter. |
| | $g_N$ | is the fluence to dose equivalent conversion factor. |
| | K | is a correction factor that takes account of the fact that the neutron detector does not measure over the entire neutron energy spectrum. |

Since $Q_\gamma = 1$ and the charged-particle contribution to the absorbed dose outside the shielding of high-energy accelerators is very small, we may write equation (1) as:

$$H = Q_\gamma D_\gamma + K g_N \phi_N . \qquad (1a)$$

The neutron dose equivalent, $H_N$, was also approximately determined by using an Andersson-Braun "rem-meter" (An63,An64) for comparison with other data. By combining this measurement with that of the neutron fluence with a moderated $BF_3$ counter, some information of the average neutron energy and quality factor in the sensitivity range of the detectors was deduced.

From equation (1a) we see that:

$$H_N = K\, g_N\, \phi_N . \qquad (2)$$

Thus, if $H_N$ and $\phi_N$ over the entire neutron spectum are measured:

$$g_N = H_N/\phi_N . \qquad (2a)$$

If $g_N$ is determined, it follows that the effective neutron energy and quality factor, $<Q_N>$, may be determined by inspection of tables (e.g. in ICRP publication 21).

A few words of caution should be given about this simple method of determining the neutron quality factor. Firstly, the response functions of moderated thermal neutron detectors are subject to reported uncertainties over the energy intervals of the detectors. This may be seen from inspection of Fig. 1 which shows the relative responses of moderated $BF_3$ counters and moderated indium foil detectors with neutron energy as reported by various authors. Figure 2 shows the energy response functions of the

Andersson-Braun counter as reported by different authors. (La70) It is clear that there is considerable uncertainty in the reported response functions of both detectors.

Secondly, the response of both detectors falls as neutron energy increases above 10 MeV. If a sizeable fraction of the neutron dose equivalent lies above this energy region, both detectors will under-respond resulting in an average neutron energy that is too low, and a neutron QF that is too high.

Thirdly, the average quality factor is not generally a parameter that is strongly dependent upon average neutron energy.

The average quality factor for the radiation field, $< Q >$, is now defined to be (remembering that $Q_\gamma = Q_c = 1$):

$$< Q > = \frac{(D_\gamma + D_c) + H_N}{(D_\gamma + D_c) + H_N / < Q_N >} \tag{3}$$

where $(D_\gamma + D_c)$ is determined by the nitrogen filled chamber
$H_N$ is determined by the Andersson-Braun counter
$< Q_N >$ is determined as described.

Values of these parameters measured at SLAC and LBL are given in Section 4.

### 3.2. Brookhaven National Laboratory Universal Dose Equivalent Instrument

Until recently, no universal rem-meter had been developed, although instruments were available responding over a limited energy region to photons and neutrons. Kuehner et al. (Ku72a,Ku72b) describe a portable instrument which can measure absorbed dose and dose-equivalent directly in mixed radiation fields. This instrument has already been successfully used in radiation surveys at the Brookhaven National Laboratory Medical Research Reactor, and in measurements of the intensity of galactic cosmic radiation at altitudes between 10,000 and 60,000 feet (Ku72a)

The Brookhaven instrument is a Rossi-type LET spectrometer (Ros55) with a modified electrode system designed by Benjamin et al. (Be64) and is used as a portable mixed radiation, dose-equivalent meter. The detector consists of a 0.6 cm thick spherical shell, some 20 cm in diameter, constructed of A-150 Shonka conducting plastic. The spectrometer gas filling consists of the usual "tissue equivalent" mixture of 66% methane, 3% nitrogen, and 31% carbon dioxide at a pressure of 10 torr. Under these conditions, the detector simulates a tissue sphere approximately 3 microns in diameter.

An ionizing event in the detector produces a current pulse which is converted to a voltage pulse proportional to the initial event and then is modified by two special biased amplifier systems (Ba67) to produce an output which is approximately proportional to dose-equivalent rate. This electronic conversion obviates the need for laborious data reduction of the event-size spectra to yield the dose-equivalent, and makes possible the construction of a portable instrument for routine application. Because both the observed dose rate and the dose-equivalent rate are recorded, the quality factor can also be determined.

### 3.3 Lawrence Berkeley Laboratory Health Physics Department

Table 1 summarizes the characteristics of the detectors used by the LBL Health Physics Department. Of these detectors, four were used in the determination of neutron spectra:

a. moderated $BF_3$ proportional counter
b. aluminum activation detectors
c. bismuth fission chamber
d. carbon activation.

At the Stanford Linear Accelerator Center high photon dose rates prevented the acquisition of reliable data with the proton recoil counter. Carbon activation detectors were not used at SLAC because the short half life of $^{11}C$ (20.4 min) did not permit transportation to LBL for measurements.

The method used to determine accelerator-produced spectra from detector data stems from the work of Smith. (Sm65) Routti (Rou69) wrote the program LOUHI which calculates the incident neutron spectrum from the observed detector counts and the known response functions of the detectors. LOUHI has three important constraints which require the solution to be positive, zero beyond a given maximum energy, and smoothly varying for cases where radiation has penetrated thick shields. The extent to which sharp structure is damped can be varied. Figure 3 shows the response functions which were used. Factors for conversion of neutron fluence to dose equivalent were taken from an analytical expression of the form:

$$g(E) = k\,E^{-x} \tag{4}$$

$g(E)$ = flux density to dose rate conversion factor expressed in $cm^{-2}$ $sec^{-1}/mrem\ hr^{-1}$, and

$E$ = neutron energy in MeV

$k,x$ = parameters whose values change over different energy ranges as shown in Table 2.

With the values of k and x given in Table 2, this analytical expression gives good agreement with the conversion factors given in ICRP Publication 21.

## 4. EXPERIMENTAL DATA OBTAINED AT SLAC AND LBL

Figure 4 shows the differential neutron spectrum calculated by LOUHI from measurements made by the LBL Health Physics Group. From these spectra both the integral fluence and dose equivalent curves have been calculated (Figs. 5 through 8). The horizontal error bars reflect the widths of the energy bins used in LOUHI. Each vertical error bar represents one standard deviation in the sum of the number of counts from all detectors within that energy bin. Because of the high dose rate over the septum magnet at LBL, the statistical counting errors for most points were less than 1% for energies less than 270 MeV, and so were not plotted.

Table 3 summarizes the results of the dose-equivalent rate comparisons. Although the total dose equivalent rates measured by the three participating groups at SLAC are in good agreement, there are significant differences in the neutron and photon dose equivalent rates determined by the SLAC and LBL groups. This may partly be explained by fluctuations in dose equivalent rate during the measurements. Measurements of neutron dose equivalent rate by the LBL group, measurements with the BNL Dose equivalent Instrument, and measurements of photon dose equivalent rate by the SLAC group were integrated over several hours. Neutron measurements by the SLAC group and photon dose measurements by the LBL group were made at intervals during this period. The higher photon dose equivalent rate reported by the LBL group compared to the SLAC group may be due to the sensitivity of the LBL chamber to fast neutrons.

The method used to determine quality factors by the SLAC group (see Table 3) has been described (Section 3.1). The LBL group determined neutron effective quality factors in two ways. The first, and more accurate, method was to determine the effective quality factor over the entire spectrum (as determined by LOUHI) by weighting each energy interval according to the neutron flux density in that interval. The unweighted quality factor appropriate to each energy interval was determined from ICRP Publication 21 (Ic73) In the second, less accurate method, the dose equivalent rate and neutron flux density (both calculations by LOUHI) were divided to determine the neutron flux density equivalent to a dose equivalent rate of 1 millirem/hr. From the flux density to dose equivalent conversion factors given in ICRP Publication 21, an effective energy and quality factor was then determined. It can be seen from Table 3 that there is poor agreement between the two methods. The second method agrees with the SLAC $BF_3$-rem derived quality factor, which is to be expected.

Measurements with the Andersson-Braun counter cannot be reliable in neutron spectra which extend over a wide energy range. Inspection of Fig. 2 shows a significant over-response in the energy region below ~ 100 keV -- an energy region that contains 60% of the neutrons at SLAC and 15% of the neutrons at LBL. At the high-energy end of the spectrum ( > few MeV) the response of the Andersson-Braun counter is rapidly falling -- at LBL 65% of the neutrons lie above 20 MeV. This drop in sensitivity can amount to significant underestimations in dose equivalent. For example, at SLAC, where half of the total dose is delivered by photons, ignoring the high-energy component of the neutron dose equivalent would result in an underestimate of 30% in the total dose equivalent. And, at the Bevatron, where the photon contribution to the total dose equivalent is only 6%, the underestimate would amount to 65% of the total dose equivalent.

One can estimate the reading to be expected from an Andersson-Braun counter in a known spectrum. This has been done using the LOUHI spectra (shown in Fig. 4) and the average response functions of Fig. 2. It was estimated that the Andersson-Braun counter should read 18 mrem/hr at LBL -- which is the measured value reported by the SLAC group in Table 3. The underestimate of dose equivalent by the Andersson-Braun counter was therefore nearly a factor of three in the LBL radiation environment.

Unfortunately, similar estimates in the SLAC neutron spectrum do not produce so clear a picture. The estimated reading expected from the Andersson-Braun counter is 0.2 mrem/hr, compared with an observed 0.7 mrem/hr. Such a high reading cannot be attributed to neutrons in the energy region below 100 keV. Measurements made at SLAC are clearly in serious disagreement.

## 5. CONCLUSIONS

These measurements do not permit a sanguine view of our present ability to determine dose equivalent in mixed radiation fields. At the Stanford Linear Accelerator Center comparison of the total dose equivalent estimated by our three groups would suggest an agreement more illusory than real. At LBL even this crumb of hope is denied us! It is clear that much work is needed before we can be confident of dosimetry high-energy accelerators. Much work lies ahead both in experimental technique and definition of parameters used to define radiation environments.

Höfert, (Ho75) on the other hand, has reported considerably greater success in an intercomparison at the CERN PS with such diverse instruments as the BNL rem-meter, the CERN recombination chamber, and a set of detectors called "Cerberus" (a T E ion chamber, a $CO_2$ ion chamber, a $BF_3$ ion chamber with an Andersson-Braun moderator, and $^{11}C$ detectors).

Distenfeld and Markoe, (Di75) however, when they compared quality factors inferred from measurements at the Brookhaven AGS using the BNL columnar recombination chamber and a Rossi LET spectrometer, found differences comparable to or larger than those reported in our study.

Intercomparisons, such as those described here, are essential if progress is to be achieved. It is only when several alternative techniques of measurement can produce consistent data that we may have confidence in our results.

Table 1. Characteristics of the Detectors Used by the Lawrence Berkeley Laboratory Health Physics Group

| Detector | Reaction | Half-life | Energy range MeV | Response to unit flux* |
|---|---|---|---|---|
| Moderated $BF_3$ | $^{10}B(n_{th},\alpha)^7Li$ | -- | 0.02-20 | 400 cpm<br>(6 cm mod.) |
| Aluminum | $^{27}Al(n,\alpha)^{24}Na$ | 15 h | > 6 | 100 cpm<br>(4500 g) |
| Carbon (polyethylene disc) | $^{12}C(n,2n)^{11}C$ | 20.4 min | > 20 | 16 cpm<br>(780 g) |
| Bismuth fission counter | $^{209}Bi(n,f)$ fragments | -- | > 50 | 1.05 cpm<br>(60g, 220 MeV) |
| Polyethylene-lined proportional counter | proton recoil | -- | 0.05-20 | 1 count = 15 MeV/cm$^2$ |
| Moderated and bare indium foils | $^{115}In(n_{th},\bar{\beta})^{116}In$ | 54 min | 0.02-20 | 10 cpm |
| Ion Chamber | charge collection | -- | > 0.02 | -- |

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*For calibration details see Gi68.

Table 2. Parameters for Neutron Fluence to Dose Equivalent Conversion (Eq. 4) (Ri74)

| Energy range (MeV) | k | x |
|---|---|---|
| $2.5\times10^{-8} \leq E \leq 10^{-6}$ | 117.6 | 0.0453 |
| $10^{-6} < E \leq 10^{-2}$ | 316 | -0.0262 |
| $10^{-2} < E \leq 1$ | 8.5 | 0.75 |
| $1 < E \leq 10^{2}$ | 8 | 0.0774 |
| $10^{2} < E \leq 5\times10^{2}$ | 22.7 | 0.29 |
| $5\times10^{2} < E$ | 42 | 0.425 |

N.B. The number of significant figures given are provided only for purposes of computation and are not indicative of absolute accuracy of the conversion factors.

Table 3

| Group | Neutron Quality Factor $\langle Q_N \rangle$ | Total Quality Factor $\langle Q \rangle$ | Photon Dose-Rate, $(\dot{H}_C+\dot{H}_\gamma)$ (mrem/hr) | Neutron Dose Equivalent Rate $(\dot{H}_N)$ (mrem/hr) | Total Dose Equivalent Rate $(\dot{H})$ (mrem/hr) |
|---|---|---|---|---|---|
| | | | **SLAC SITE** | | |
| BNL | | 2.5 | | | 1.2 |
| LBL | 4.8*/10† | 1.6*/1.8† | 0.51 | 0.49 | 1.0 |
| SLAC | 11 | 2.7 | 0.31 | 0.70 | 1.0 |
| | | | **LBL SITE** | | |
| BNL | | 4.2 | | | 30 |
| LBL | 5.9*/7-11† | 4.6*/6-11 | 3.0 | 48.0 | 51 |
| SLAC | 11 | 4.7 | 2.8 | 18.3 | 21 |

*Best Estimate )
) See text - Section 4
†Rough Estimate)

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*This work was done with support from the U. S. Energy Research and Development Administration.

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## FIGURE CAPTIONS

Fig. 1. Response functions of various detector/moderator configurations as a function of energy.

Fig. 2. The response of an Andersson-Braun rem meter as a function of energy, reported by Andersson and Larson.

Fig. 3. Response functions of several of the detectors used in this experiment.

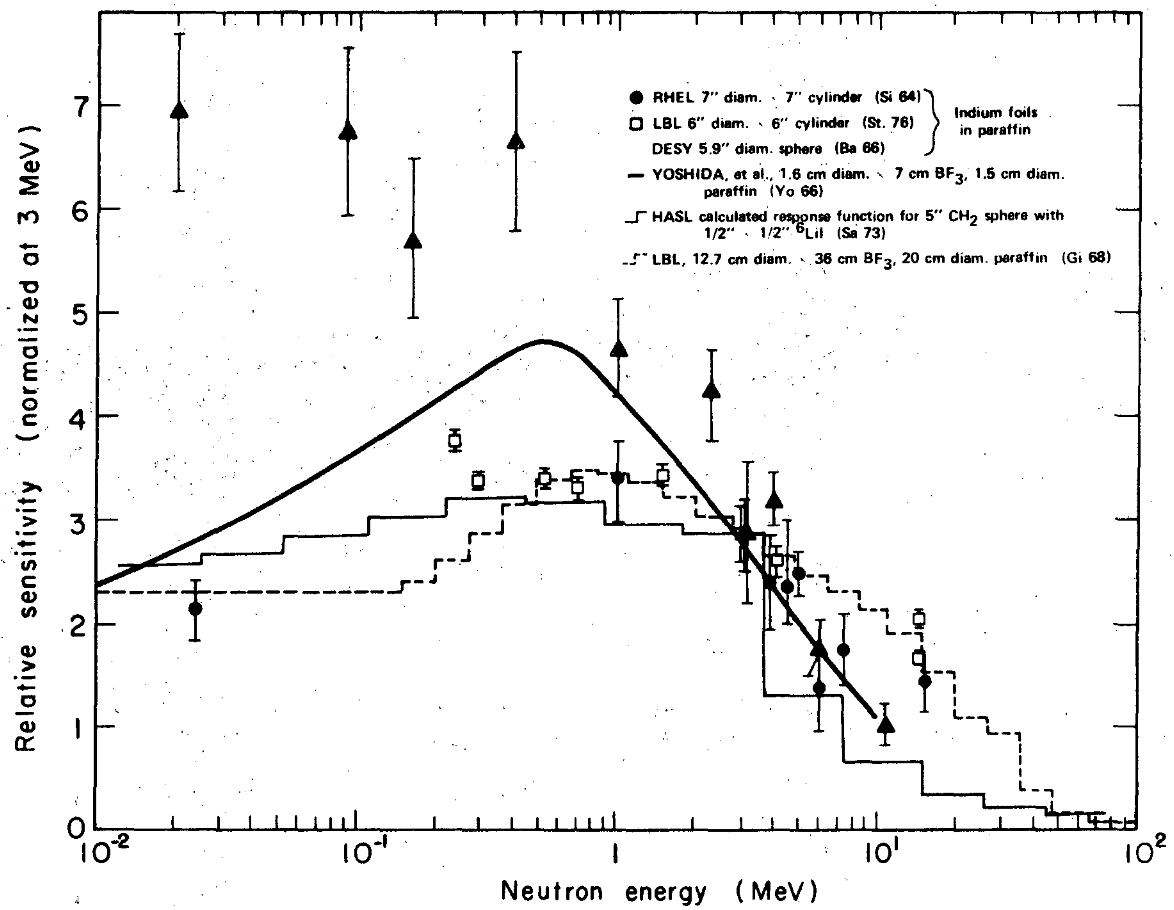
Fig. 4. Differential neutron spectra at LBL and SLAC calculated by LOUHI.

Fig. 5. Integral neutron fluence spectrum (LBL).

Fig. 6. Integral neutron fluence spectrum (SLAC).

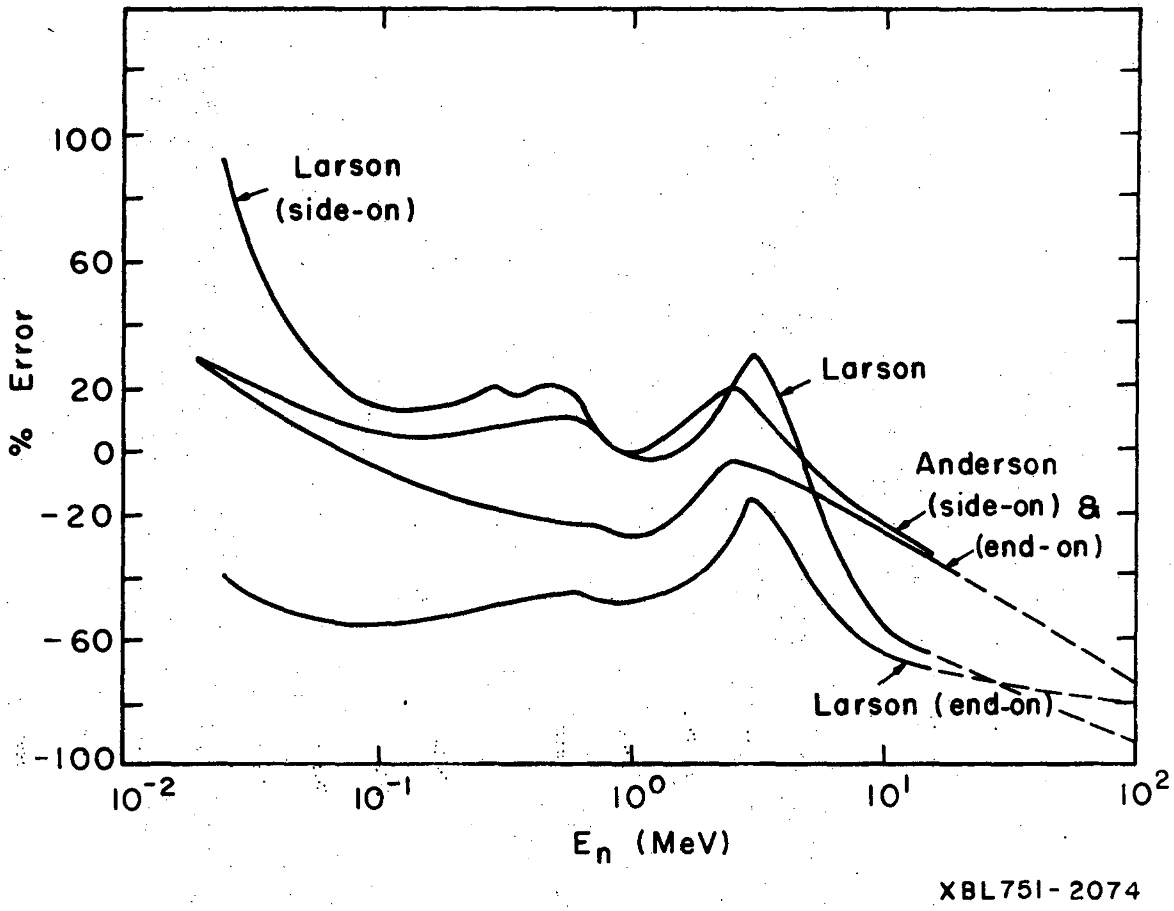
Fig. 7. Integral dose equivalent spectrum (LBL).

Fig. 8. Integral dose equivalent spectrum (SLAC).



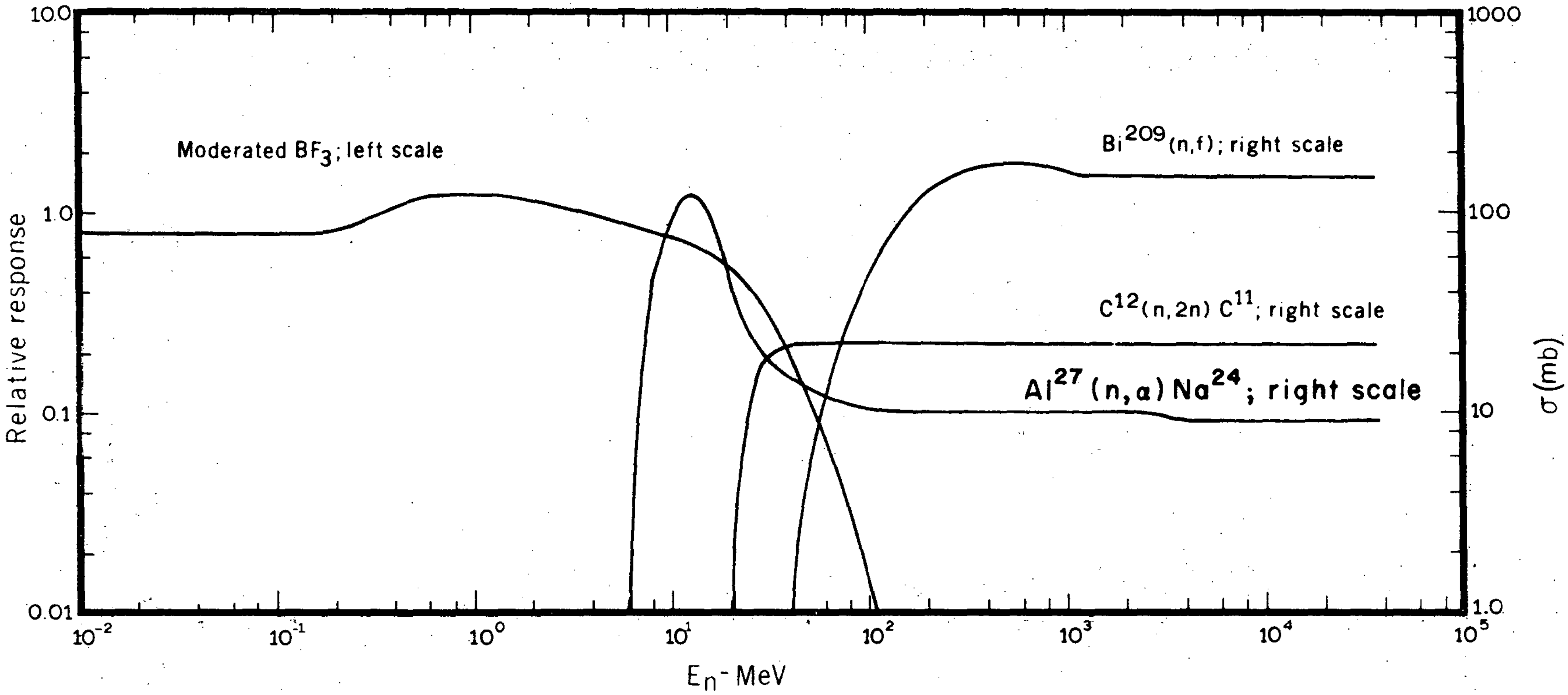
XBL 769-3955

Fig. 1



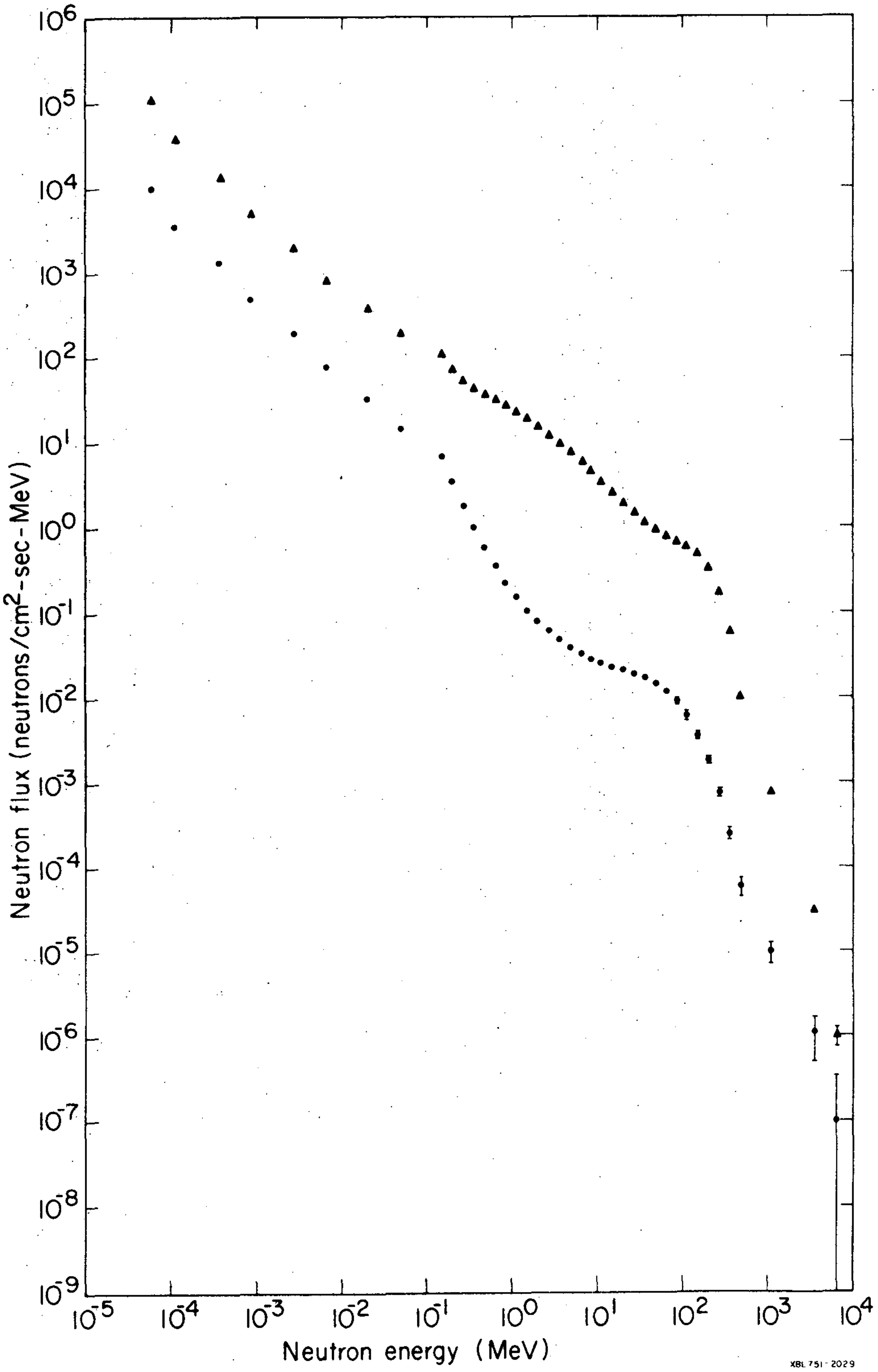
100
60
20
0
-20
-60
-100
% Error
10^-2
10^-1
10^0
10^1
10^2
E_n (MeV)
Larson (side-on)
Larson
Anderson (side-on) & (end-on)
Larson (end-on)
XBL751-2074

Fig. 2



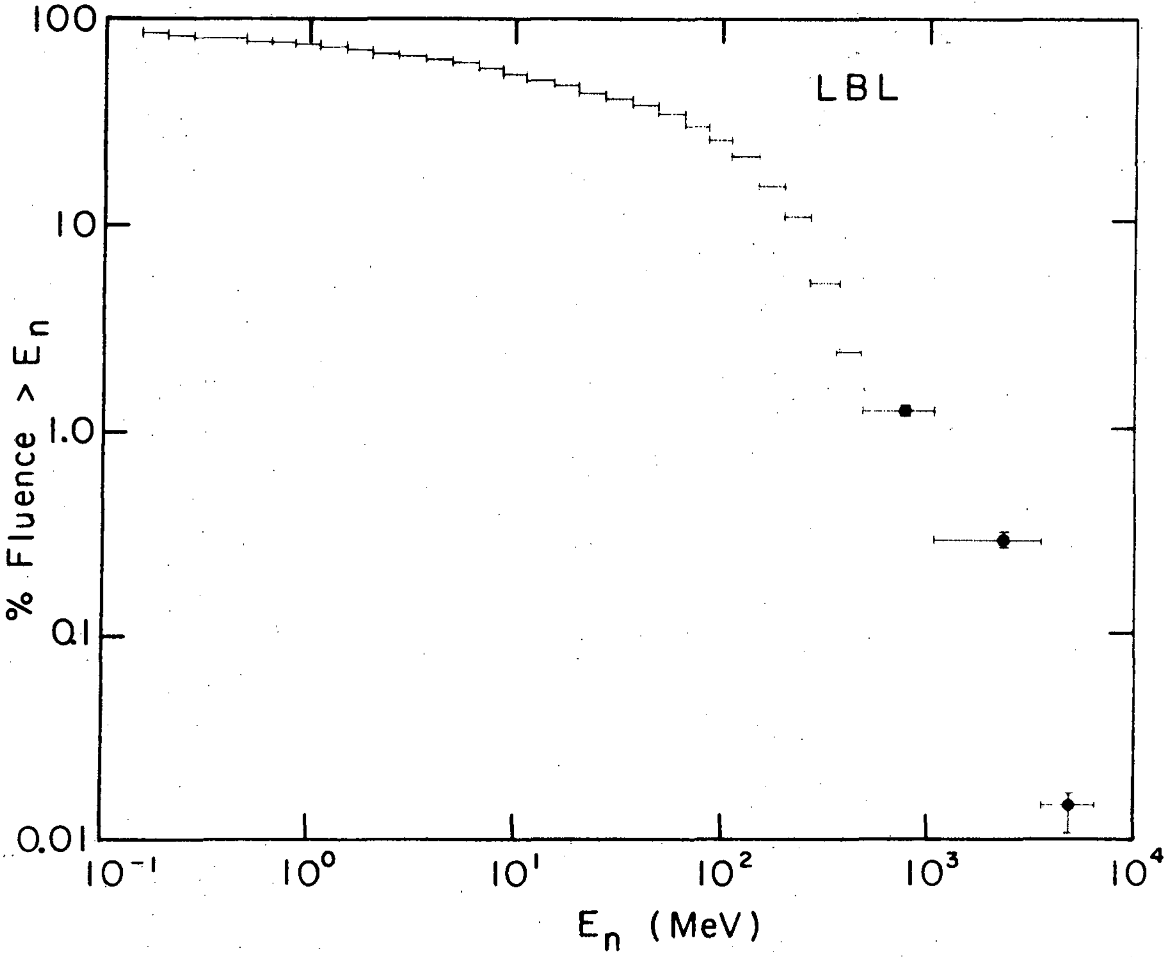
XBL 682 4491

Fig. 3



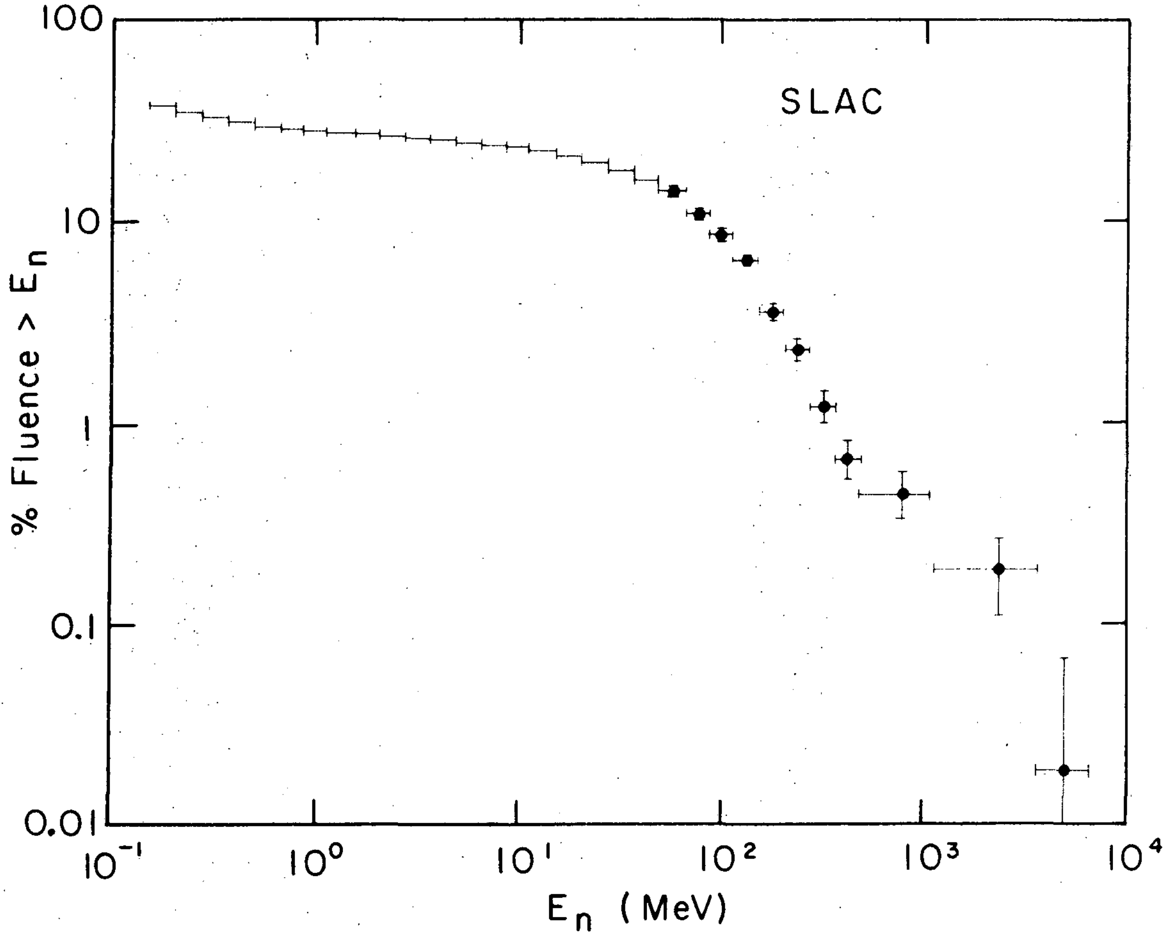
XBL 751-2029

Fig. 4



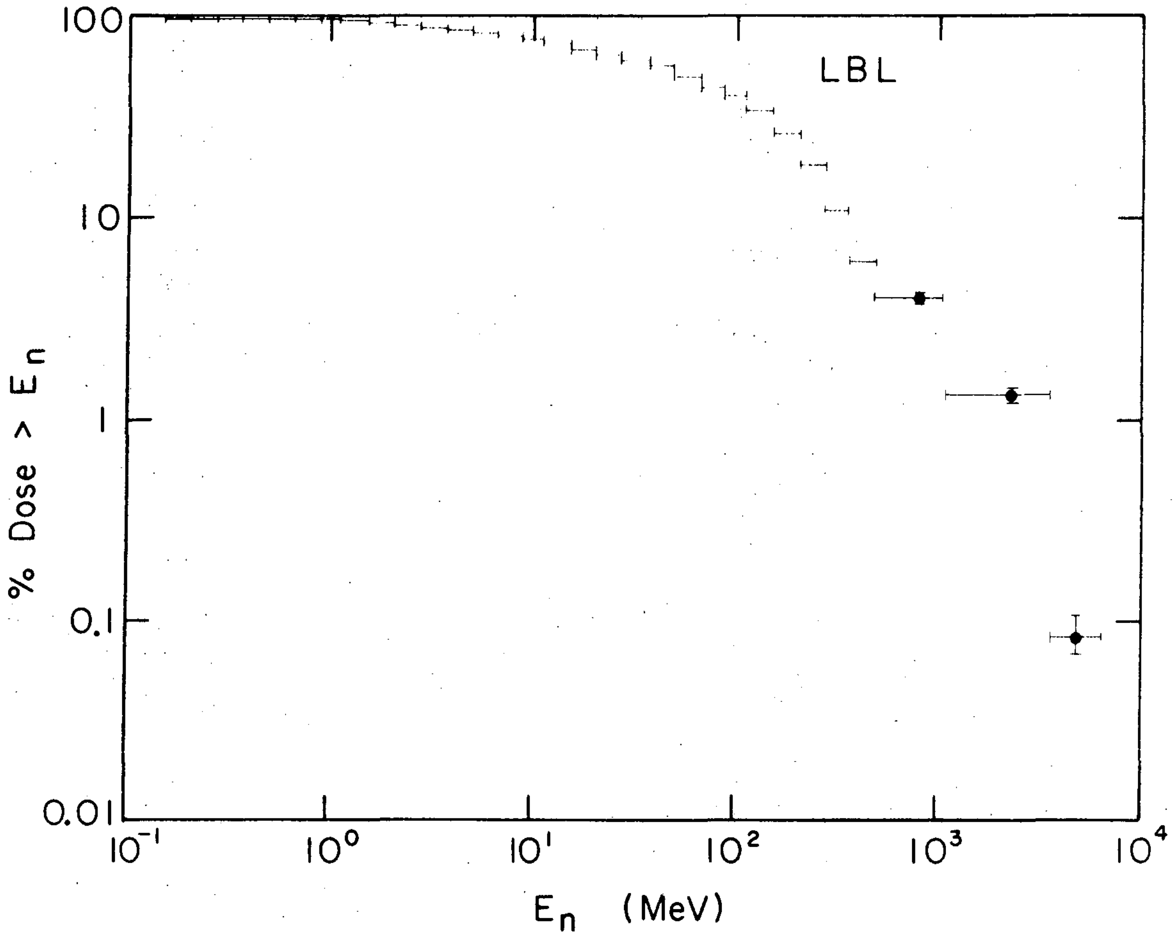
XBL751-2071

Fig. 5



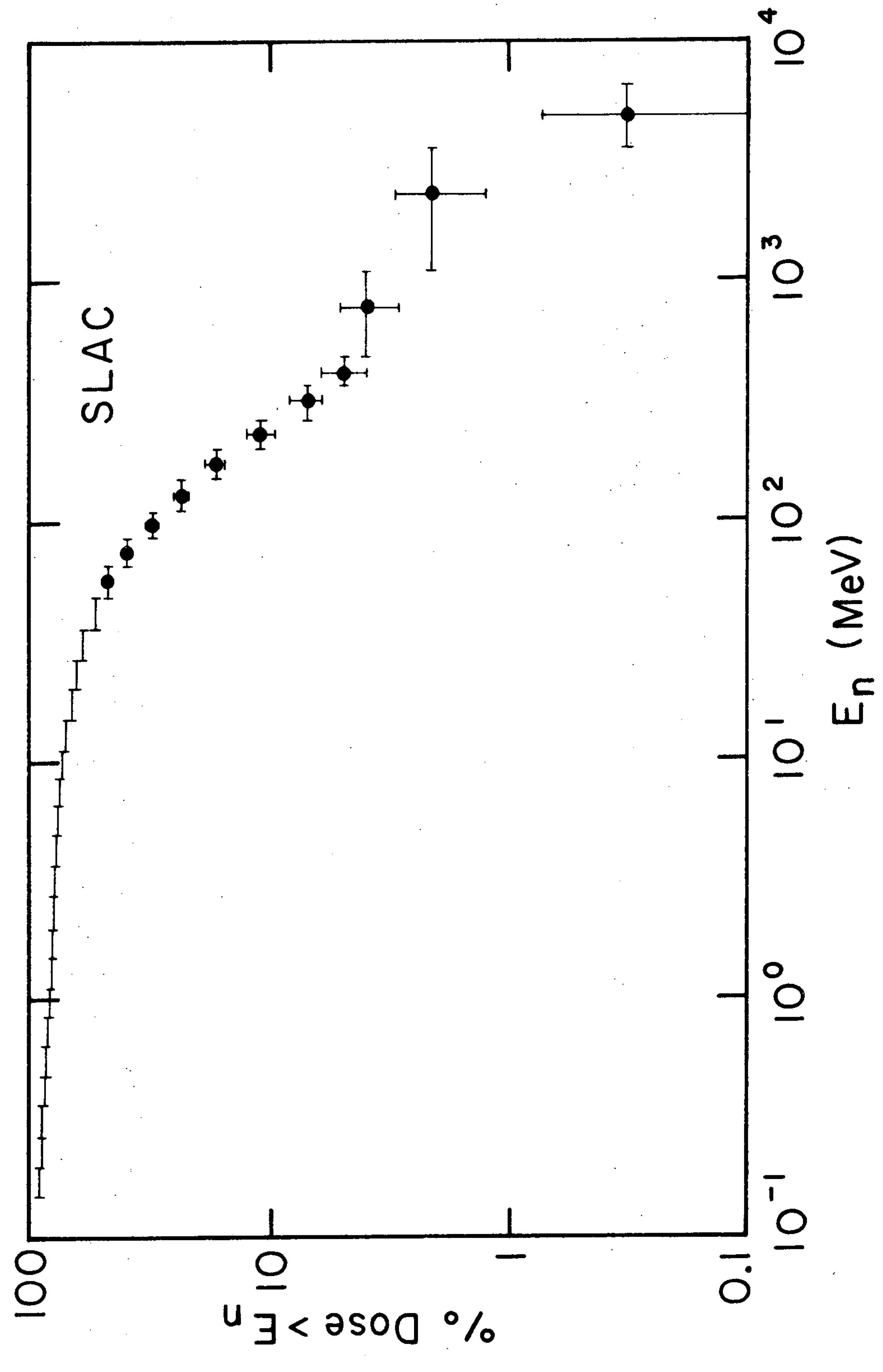
XBL 751-2072

Fig. 6



XBL751-2070

Fig. 7



XBL751-2073

Fig. 8

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