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INTRODUCTION

The characterization of radiation fields is important to many applications. For example, in operational health physics, the choice of instrumentation for monitoring and of a personnel dosimeter for use by radiation workers depend on both the type and spectral characteristics of the radiation. Furthermore, the spectral distribution of the fluence affects radiation damage estimates for materials for new or replacement equipment within the radiation environment. At the same time, knowledge of the character of the radiation fields at a high-energy accelerator leads to a better theoretical understanding of its nature, and is important to the specification of civil construction requirements for future upgrades of the accelerator.

At Fermilab as at many high-energy accelerators neutrons dominate the radiation fields outside of beam pipes within enclosures. In a continuing effort[1] to characterize as completely as possible the fields at various locations around the site, we have measured the neutron spectrum within the DO collision hall. Both the fluence and dose-equivalent energy distributions are summarized in this note.

EXPERIMENTAL PROCEDURE

The measurements were performed on the catwalk along the TEVATRON accelerator beam pipe in the DO collision hall. The main ring passes above the TEVATRON; since it consists largely of magnets with iron yokes, it is expected to have a significant effect on the characteristics of the neutron field at this location. The DO detector is not completed, and so is not in place in the hall. The results presented here are not therefore indicative of the field characteristics expected during normal experimental runs when the detector itself will perturb the pre-existing field properties.

The neutron spectrum was determined from measurements by use of a Bonner multisphere spectrometer.[2] This is a low resolution broad-range system that consists, in this case, of thermoluminescent detectors (TLD's) placed at the centers of polyethylene moderating spheres of diameters 2, 3, 5, 8, 10, 12, and 18 inches, and one with no moderation (bare detector). The TLD packets contained four chips each of ^{6}LiF (~95.6% ^{6}Li) and ^{7}LiF, so called TLD 600/700 pairs. Both members of the pair respond almost equally to photons and charged particles while the TLD 600 chip is much more sensitive (through the ^{6}Li (n,α) ^{3}H reaction) than is the TLD 700 to thermal neutrons, produced as the result of moderation of the incident spectrum within the spheres. The neutron response of the TLD 600 was obtained by subtracting the photon/charged particle contribution given by the response of the TLD 700. Both sets of TLDs were calibrated individually for photon response by use of a ^{137}Cs radioactive source, and the TLD 600s for neutrons by use of a PuBe source. Standard Fermilab TLD readout techniques* were employed.

The seven spherical plus one bare detectors were spaced along the TEVATRON beam line spanning a distance of about 20 feet, centered on the DO interaction region, and about 2 feet from the beam line center. See Fig. 1. Tissue equivalent ion chambers (CHIPMUNKS) and pin-diode neutron dosimeters[3] placed at both ends of the detector array were utilized to check for flux nonuniformities as a function of longitudinal distance along the beam line. The ratio of the responses of these upstream and downstream detectors were used to correct the raw sphere data, based on an assumed linear variation of the flux with detector position.

The measurements were performed during accelerator running conditions in which many different operations were in progress. These included rapid-cycle

*This method uses a 15 minute 100°C pre-anneal cycle, and a 15 minute 400°C post-readout annealing cycle.

acceleration of the beam in the Main Ring to 120 GeV for antiproton production, flat top coasting beam in the TEVATRON for colliding beam physics, accelerator study periods, reverse injection of antiprotons, etc. The results reported here represent, therefore, the average spectrum that arises from the varied operations that take place during collider mode running within the collision hall.

ANALYSIS

Measured sphere responses as a function of sphere size, normalized so that their sum is unity, are shown in Fig. 2 for two independent sets of D0 measurements. The results here are based on use of pin-diode dosimeter correction factors, although results based on the CHIPMUNK responses are similar. The solid curve represents a fit to the 1st run data based on the BUNKI calculation. (See discussion below.)

The determination of neutron fluence as a function of energy, the neutron spectrum, from such measured responses involves an unfolding problem that has been discussed previously by many authors,[4] and will not be detailed here. In the present work, the range from thermal energies up to a few hundred MeV is divided into thirty-one energy bins so that with 8 detectors the multisphere unfolding problem requires the solution of eight equations in thirty-one unknowns. The underdetermined nature of this problem can lead to more than one solution spectrum that describes the data equally well, and the sometimes mathematically ill-conditioned nature allows small uncertainties in the data to translate into large uncertainties in the unfolded spectrum.

We have used three different computer programs that employ different unfolding techniques to gain some confidence in the reasonableness of the solutions. They are BUNKI,[5] which utilizes the SPUNIT[6] interactive recursion procedure, and allows a choice of starting spectra; LOUHI,[7] a constrained least-squares method with user controlled constraint conditions; and SWIFT,[8] based on a Monte Carlo method with <u>no</u> a priori assumptions as to the character of the spectrum. In all cases the response functions of Sanna[9] calculated for 4 mm by 4 mm ^{6}LiI scintillators were used as a reasonable approximation to the ^{6}LiF TLD 600 chip responses. Analysis using BUNKI with a set of response functions calculated more recently by Hertel, et al.,[10] give results very similar to those presented here.

RESULTS

The unfolded spectra from the three programs are shown in Figs. 3 and 4. Two sets of independent runs were made. In the first, data were accumulated for about 5.8 rads as indicated by the CHIPMUNK tissue-equivalent ion chamber, or 3 rads, neutrons only, as obtained from the change in resistance of the pin-diode detector. The second run was longer; about 14 rads were accumulated by the CHIPMUNK and about 10 rads from the pin-diode. The energy scale on these figures is logarithmic and, since the ordinate is flux per unit logarithmic energy interval, the area under the curves for each energy bin is proportional to the neutron fluence within that bin.

The observed spectra are qualitatively similar for the three unfolding codes. Each reveals a peak (or "accumulation" of neutrons) near thermal energies, one at energies between 0.1 and 0.5 MeV, and a rise in the fluence at very high energies (>50-100 MeV). It should be noted that even the 18 inch Bonner sphere has a fairly poor sensitivity to neutrons with energy beyond ~20 MeV. Thus, while the results suggest the existence of higher energy particles, a more quantitative measure of the flux above this energy must await measurements with an improved detector. Also, sphere response functions are set equal to zero beyond 400 MeV in all of the unfolding programs; this accounts for the observed spectra apparently going to zero at the highest energy.

Some of the properties of the spectra based on the different unfolding codes are summarized in Tables 1 and 2, which give the relative neutron fluence and dose-equivalent in rather broad energy bands. The results for BUNKI and LOUHI represent averages for the two independent runs since agreement from run to run for each program separately was good. For SWIFT, on the other hand, the results for the two runs are shown separately; particularly at the highest two energy bands the numbers do not agree too well from run to run. Further, the relative values in these highest two bins are lower than the results from BUNKI and LOUHI. This is reflected in the 50%

larger value for the quality factor from the SWIFT calculation shown in the last line of Table 2. Moderately low values of the quality factor (QF~4) in accelerator-generated fields usually indicates that a large fraction of the dose-equivalent arises from high-energy particles.

Even though specific features may vary, some general conclusions about the neutron radiation field in the D0 collision hall can be made. It is interesting to note, for example, that while less than 20% of the neutron fluence lies at energies above 2 MeV, some 60-70% of the total dose-equivalent arises from such neutrons. More quantitatively, from calculations of the neutron spectrum as a cumulative percentage of fluence, the median energy - the energy determined from the 50% value - is about 0.15 MeV. For cumulative dose-equivalent, on the other hand, the same 50% value is over 100 MeV (based on LOUHI).

The existence of high-energy neutrons (>25 MeV) was not observed in previous measurements[11] within the accelerator enclosure (at the A17 and A48 straight sections), although both a thermal component and a peak near a few hundred keV were seen. In those measurements, however, data were collected only during "quiet" periods of coasting beam operation, and the spectrometer was located against the tunnel wall 2 meters away from the beam line. The observation of high-energy neutrons is expected to be enhanced at a location very close to the beam line.

The peak observed at neutron energies between 0.1 and 2 MeV, which represents some 30-40% of the total neutron fluence is reminiscent of the spectrum of leakage neutrons associated with a large iron electromagnet.[12] It is not unreasonable at the location of the present measurements on the catwalk at the TEVATRON beam line, to observe a similar leakage spectrum due to beam losses in the nearby main ring. The hadronic cascade initiated by the primary protons produces neutrons within the iron yokes of the beam line magnets which, after slowing down to energies below 1 MeV, readily escape from the iron because of the small inelastic cross sections, and are detected in the spectrometer.

As seen in Table 1, some 30-35% of the fluence arises from neutrons between 1.5 eV and thermal energies. These particles - originally prompt reaction products of the hadronic cascades and evaporation neutrons from excited nuclei - are those that have been moderated through scattering in the concrete walls and other material in the collision hall.

Table 1 Percent fluence in specific energy bins for spectra unfolded with three computer programs.

Energy	BUNKI (SPUNIT)	LOUHI	SWIFT Run 1	SWIFT Run 2
<1.5 eV	37.5	36	33.5	27
0.0015-110 keV	1	21.5	25	22
0.11-1.9 MeV	42	23	28	34.5
1.9-25 MeV	0	1	4	11
>25 MeV	19.5	18.5	9.5	5.5

Table 2 Percent dose equivalent in specific energy bins and quality factor for spectra unfolded with three computer programs.

Energy	BUNKI (SPUNIT)	LOUHI	SWIFT Run 1	SWIFT Run 2
<1.5 eV	2.5	2.5	3	2
0.0015-110 keV	0.1	7.5	5	1
0.11-1.9 MeV	27	22	24	38
1.9-25 MeV	0	1	16	41
>25 MeV	70	67	51	18
Quality Factor	4.2	4.3	6.3	6.4

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FIGURE CAPTIONS

1. Location of the detectors in the D0 collision hall, plan view. The main ring (not shown) is at an elevation of about 6' above the TEVATRON beam line.

2. Detector response as a function of sphere diameter normalized so that their sum is unity. The measured results are for the two independent runs. The solid curve is the fit to the Run 1 responses based on the BUNKI unfolding code.

3. The best-fit spectra for Run 1 from BUNKI, LOUHI and SWIFT (lower curve) unfolding codes plotted as fluence per unit logarithmic energy interval.

4. The best-fit spectra for Run 2 from BUNKI, LOUHI and SWIFT (lower curve) unfolding codes plotted as fluence per unit logarithmic energy interval.

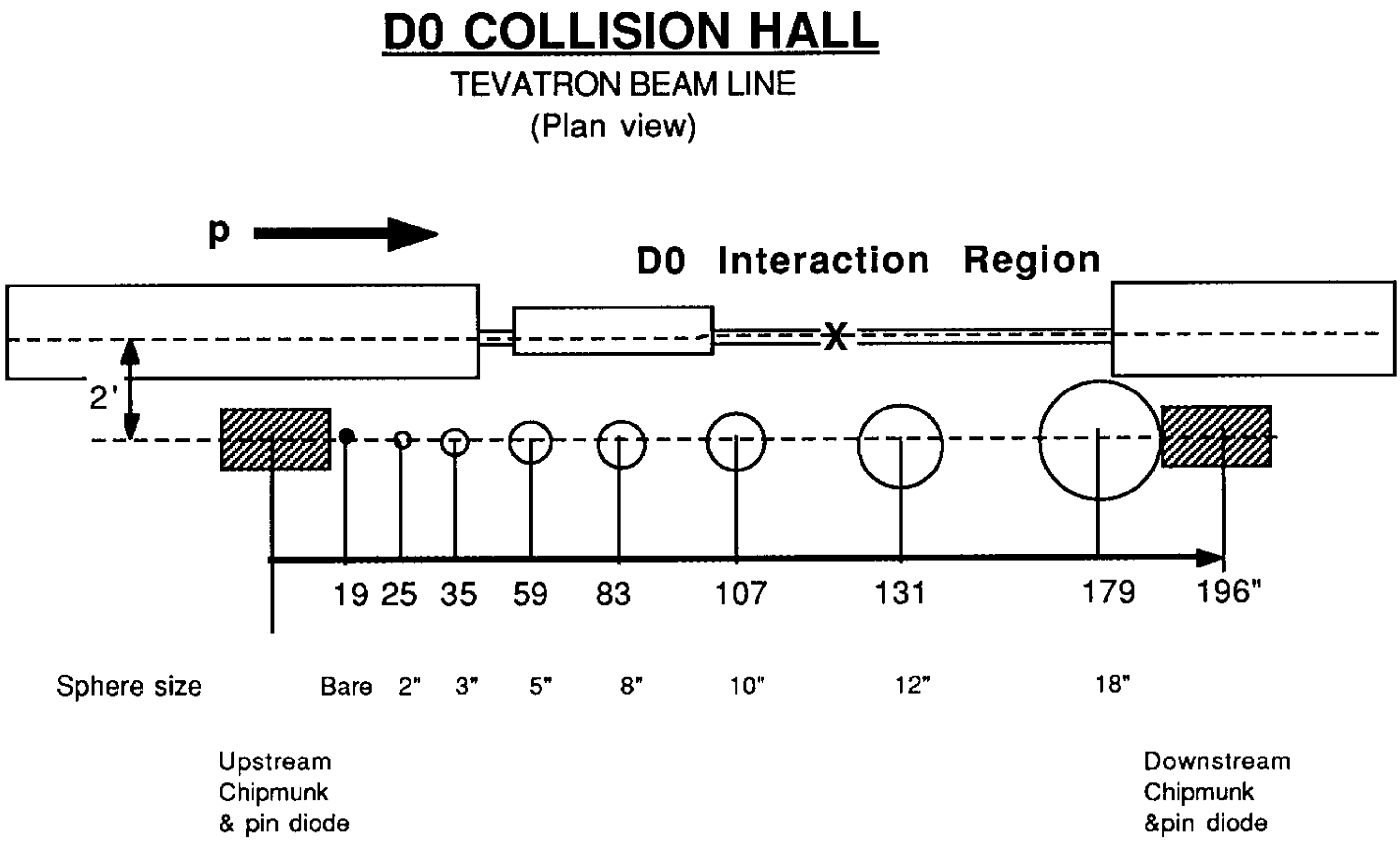

D0 COLLISION HALL
TEVATRON BEAM LINE
(Plan view)
p
D0 Interaction Region
2'
19 25 35 59 83 107 131 179 196"
Sphere size
Bare 2" 3" 5" 8" 10" 12" 18"
Upstream
Chipmunk
& pin diode
Downstream
Chipmunk
&pin diode

Figure 1

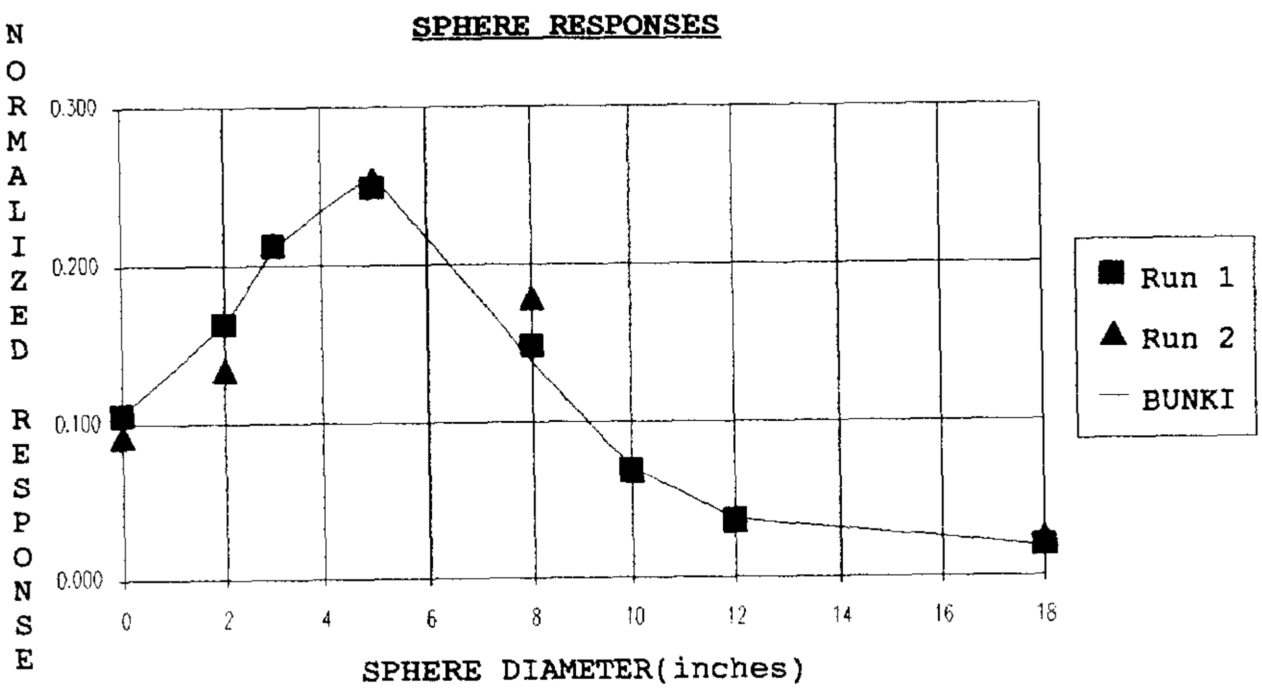
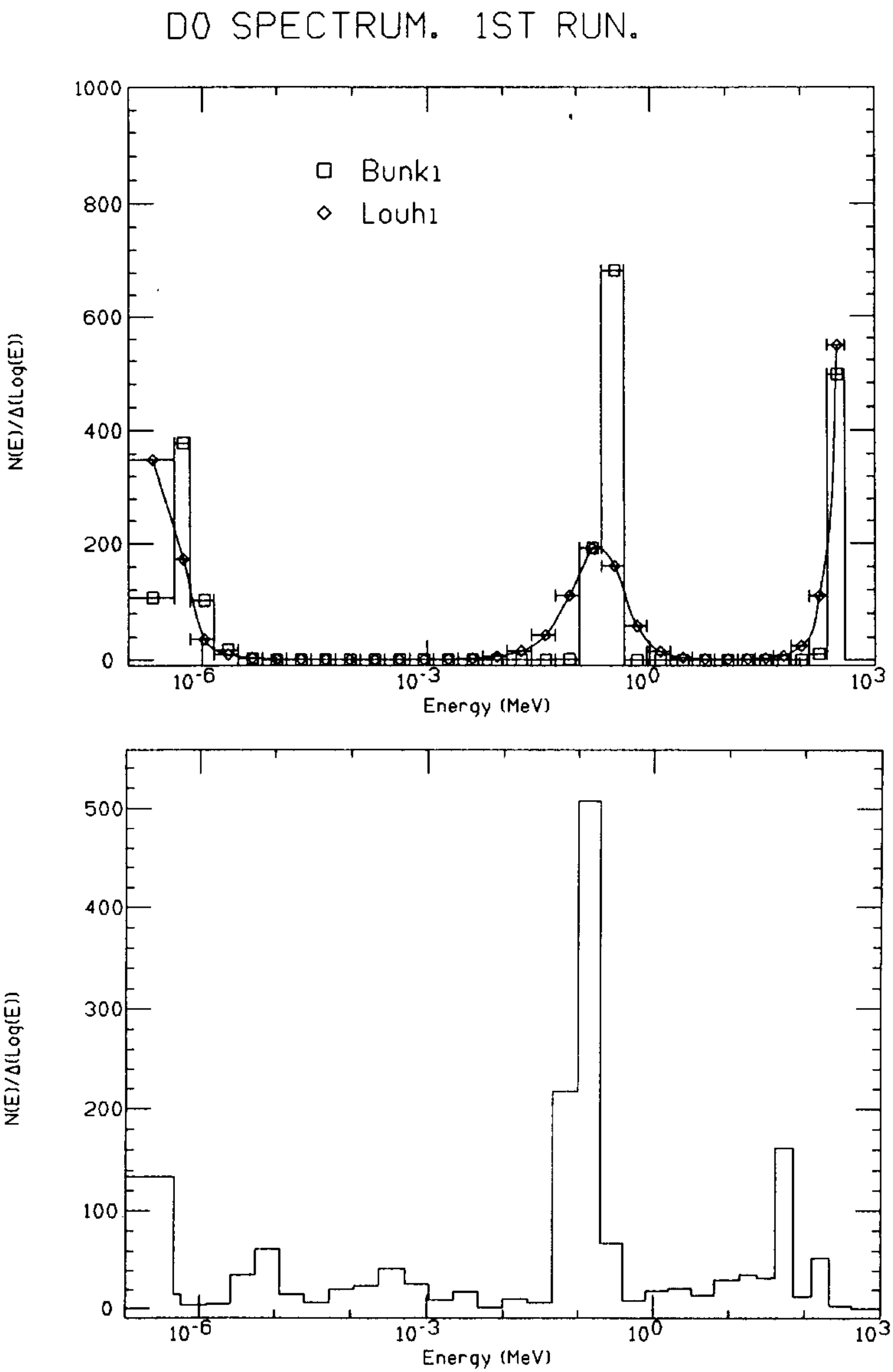

SPHERE RESPONSES
NORMALIZED RESPONSE
0.300
0.200
0.100
0.000
0
2
4
6
8
10
12
14
16
18
SPHERE DIAMETER(inches)
Run 1
Run 2
BUNKI

Figure 2



DO SPECTRUM. 1ST RUN.
Bunki
Louhi
1000
800
600
400
200
0
N(E)/Δ(Log(E))
10-6
10-3
100
103
Energy (MeV)
500
400
300
200
100
0
N(E)/Δ(Log(E))
10-6
10-3
100
103
Energy (MeV)

Figure 3

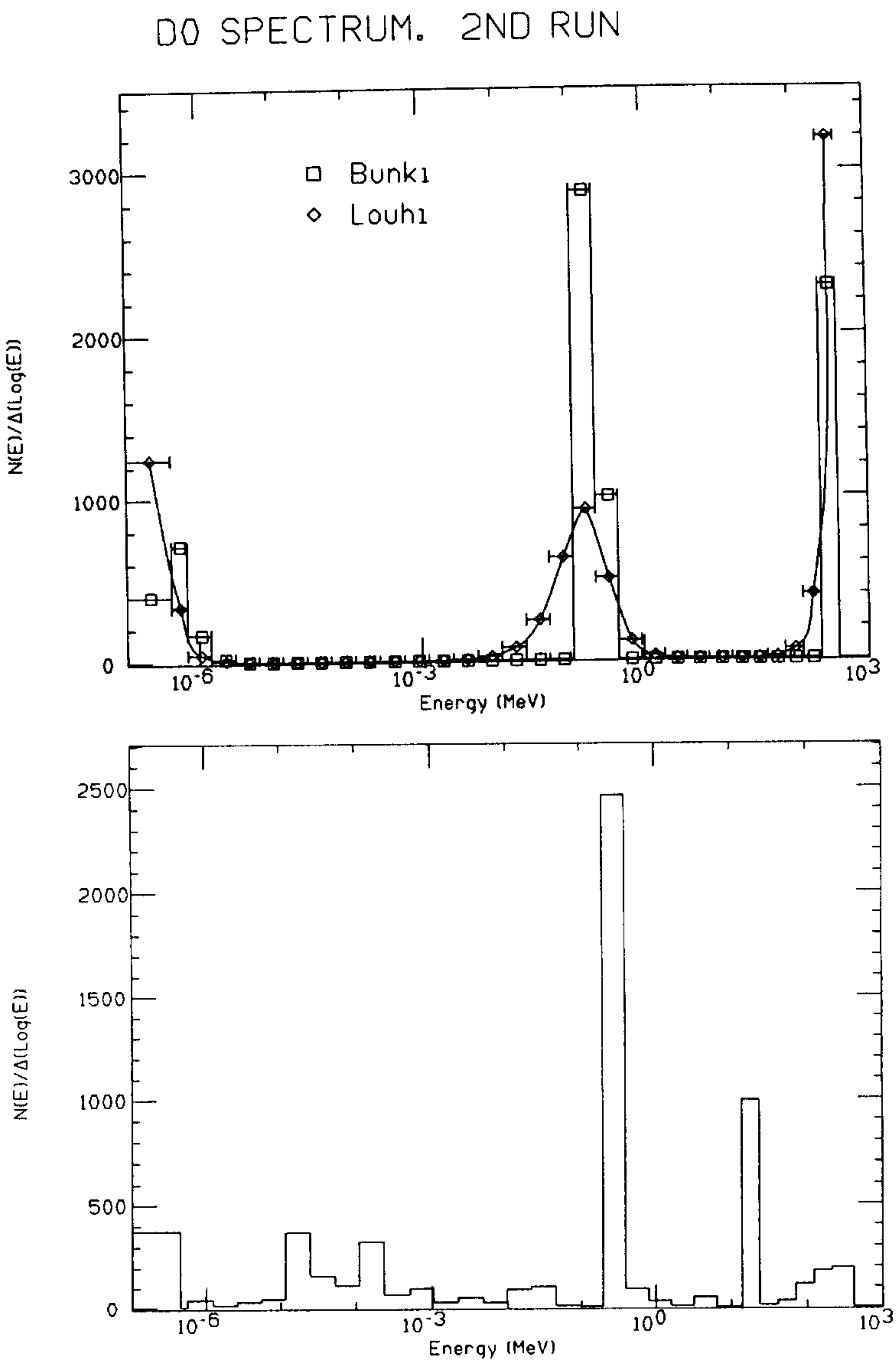

DO SPECTRUM. 2ND RUN
Bunki
Louhi
N(E)/Δ(Log(E))
Energy (MeV)
N(E)/Δ(Log(E))
Energy (MeV)

Figure 4