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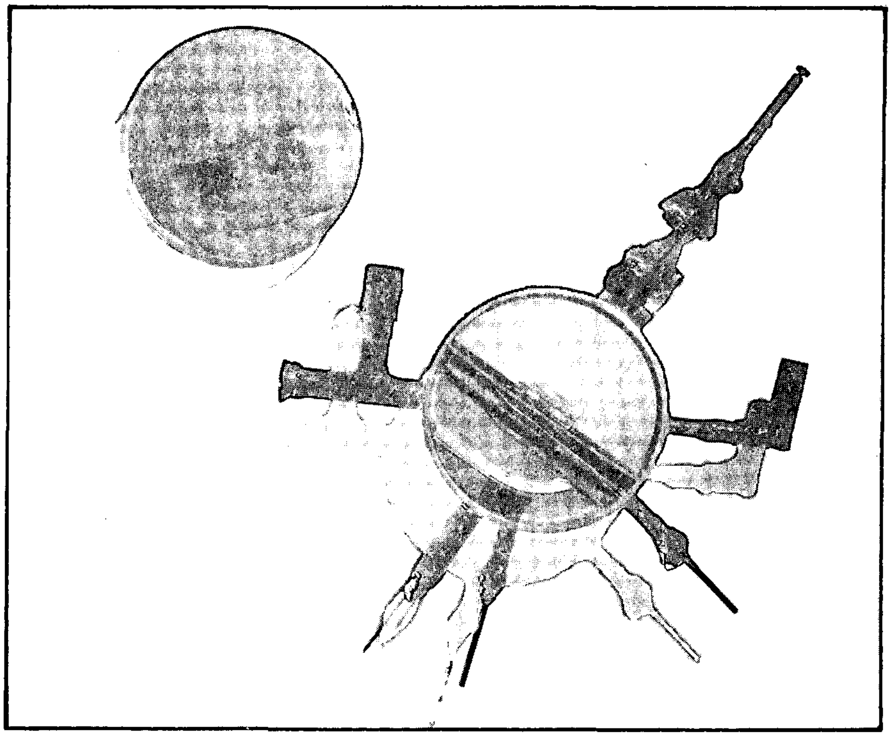

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Review of Measurement at Accelerators and Application to Dosimetry Calibration

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ABSTRACT

Multisphere spectrometers have been used widely to determine neutron spectra and other related quantities from various radiation sources. At Lawrence Berkeley Laboratory (LBL), the multisphere spectrometer has taken measurements at different LBL accelerator facilities (the SuperHILAC, the BEVALAC, and the 88"-Cyclotron) as well as for measurements in the tunnel of the Tevatron at Fermilab. Spectra were unfolded with a LOUHI code using Sanna's response function, which gave satisfactory results. The neutron-scattering effect is important for the Bonner detectors, which will be discussed briefly.

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1. Introduction

The multisphere spectrometer at Lawrence Berkeley Laboratory (LBL) has been used frequently to determine neutron spectra and other related quantities from various radiation sources. It has been employed to take measurements at different LBL accelerator facilities (the SuperHILAC, the BEVALAC, and the 88"-Cyclotron). It has also been used in the tunnel of the Tevatron at Fermilab. This paper summarizes the procedures, methods, and results of these experiments with the multisphere spectrometer, and shows the diversity of its applications and significance. The spectra are unfolded with a LOUHI code using Sanna's response function, which produces satisfactory results comparable to those obtained with other codes. The neutron-scattering effect is important for the Bonner detectors. This scattering effect will also be discussed briefly.

2. Preparation and Arrangement of the Spectrometer

The LBL multisphere spectrometer is a set of eight Bonner detectors, consisting of ^{6}LiI(Eu) crystals as scintillators surrounded by spherical polyethylene moderators. The moderators range in diameter from 0 (bare) to 45.72 cm, as follows (diameters in inches): bare, 2", 3", 5", 8", 10", 12", and 18". The detectors are coupled to a 4096-channel multichannel analyzer (MCA), through light-pipes, photomultipliers, and preamplifiers. Before measurement begins, it is important to follow certain procedures to ensure the proper operation of the spectrometer. These procedures are described below.

2.1 Preliminary Preparation

Before the beginning of a series of experiments, the following procedures are taken.

(1) The multisphere spectrometer should be calibrated with a standard neutron point source. Eight detectors are set up in a circle of at least 2 m radius, with the centers of the scintillators at least 1.5 m above the floor. At the center of the circle, the standard neutron source is placed on a styrofoam post at the same height as the scintillators. The detectors are tested first with 5-in spheres covering all the scintillators. The purpose of this test is to set the regions of interest and to adjust the preamplifiers of each individual detector, if necessary. The numbers of counts should be within 10% of each other, so that these values can be used as reference values later. Then tests are carried out with spheres of different sizes attached to the proper detectors for the measurement of neutron spectra. These measurements should be identical, or very close, to the spectrum of the standard neutron source. The neutron source used at LBL is ^{238}PuBe ($\xi = 8.59 \times 10^7$ ns^{-1}, ±2.3%). The calibration should be done in an area with ample space, where neutron scattering is not significant.

The resulting spectrum from the calibration should be compared with spectra obtained previously from the same source. An example is shown in Fig. 1, where the peaks of the spectra are in the same energy bin, and the tails of the high-energy region almost coincide. The calibration is then considered acceptable.

(2) In the test area where the experiments are to be carried out, the neutron fluence should be mapped out with suitable detectors, such as BF_3 proportional tubes, in order to get a general idea of the flux distribution within the area.

(3) If the purpose of the experiments is calibration of neutron dosimetry, an Andersson-Braun remmeter must be placed near the anthropomorphic phantom to measure neutron dose equivalents.

2.2 Arrangement of the Spectrometer

The method and set-up of the Bonner detectors depend very much on the purpose of the experiment, as well as on the geometry of the testing area. They could be arranged in series, in an array, in pairs, or one by one, according to the requirement of the experiments, which will be described later.

3. Unfolding Code for the Spectrometer

The data obtained from the multisphere spectrometer are unfolded with a LOUHI code using Sanna's response functions for the spheres, which produces satisfactory results comparable to those obtained with other codes such as BUNKI and SWIFT. LOUHI is a constrained least-squares method that allows user-controlled constraint conditions (Rou80); BUNKI uses the SPUNIT iterative recursion procedure, along with an algorithm that allows a choice of different starting solutions (Lo84, Br84); and SWIFT is based on a Monte Carlo method that allows a broad sampling of possible neutron spectra with no *a priori* assumptions about their character, apart from non-negativity (OBr81, Cha83, OBr83). In general, the fit to measured neutron counting rates is of comparable quality for the three unfolding codes, as will be described in the following sections.

With the unfolding of the LOUHI code, the calculated results presented useful information about the neutron spectrum: neutron average energy, absorbed dose, dose equivalent, and fluence, all given in total amounts or as a function of energy bin.

4. Description of the Experiments

4.1 Tevatron Experiments at Fermilab

Set-up

For the Tevatron experiment (McC86), the object was to determine the neutron spectrum, fluence distribution, and rates. Bonner detectors were arranged in series along the wall of the tunnel. In addition, two moderated BF_3 gas proportional counters were set at the up-stream side and down-stream side along with the series of the Bonner spheres; a parallel-plate thorium fission counter and a similar bismuth fission counter were positioned near the 25.4-cm (10") and 30.48-cm (12") spheres, to obtain additional fluence and spectral information. Two extra Bonner detectors surrounded by a 12.7-cm (5") diameter sphere were used as a beam loss monitor. The setup is shown in Fig. 2. All detectors were at the same elevation as the Tevatron ring, as shown in Fig.3.

Results

The neutron spectra derived from three unfolding codes (LOUHI, BUNKI, and SWIFT) for a 800-GeV low-beta coasting beam run are compared in Fig. 4. The results are quite similar, except that SWIFT tends to predict higher, narrower peaks at the same location than do the other programs. Although the shapes may vary, the areas under the respective curves do not differ significantly. In Table 1, the calculated values of total neutron fluence from these three codes are compared for several runs. The results are in very good agreement.

4.2 SuperHILAC Experiments at LBL

Set-up

The object of the SuperHILAC experiment (Gr87) was to determine a relatively soft neutron spectrum and relatively uniform ambient dose equivalents inside a workplace. The experiment was carried out in an empty room that overlooks one of the superHILAC beam stops. A beam of argon ions at 8.5 MeV per nucleon was targeted on a beamstop at about six meters distance from a phantom placed near the center of the room, with an average beam intensity of 3.5×10^{11} ions per second. The Bonner detectors were set up in an array (Fig. 5) along the back wall of the room. A standard moderated BF_3 for fluence measurements and a Andersson-Braun counter for the measurement of dose equivalent were stationed on the table near the phantom. Another BF_3 counter, placed under the table, served to monitor beam-intensity changes for data-normalization purposes. The Bonner detectors with large spheres were located near the edges of the room so that the low-energy scattered fluence would matter the least. Initially the room was mapped for uniformity of flux density and dose equivalent rate by means of a BF_3 counter and a Andersson-Braun counter, respectively. Fluence values obtained from the mapping, along with the counts from the BF_3 monitor under the table, were used to normalize all detector counts to the position of the phantom for the dosimetry run. The anthropomorphic phantom bore four NTA and four CR-39 personal dosimeters, and it was rotated during a ten hour-irradiation.

Results

Measurements with Bonner spheres were made during a dedicated two-hour run at relatively low intensity. The spectrum was unfolded with the LOUHI code, which also calculated the dose equivalent per unit fluence. The cumulative fluence, as well as the cumulative dose equivalent as a function of neutron energy, are shown in Fig. 6. The dose equivalent calculated from LOUHI, and the responses of both CR and NTA film, were appropriately within the error limits for this study, as shown in Table 2.

4.3 BEVALAC Experiments at LBL

Set-up

The object of the BEVALAC experiment (Gr88) was twofold: (1) to characterize the complex radiation field outside the shielding of the Biomedical facility, and (2) to evaluate a variety of detectors in such a field. In this experiment, neon ions at 580 MeV·A were stopped in a 30.5-cm polyethylene cube at the patient isocenter. Detectors were placed on the opposite side of an 0.91-m-thick concrete wall at about 90° to the beam direction. Two locations were of particular interest regarding calibration of the dosimeter, locations A and B shown in Fig. 7. Bonner detectors were set up in pairs at the locations of interest, with each detector of the pair at each position for one particle-beam run. Thus all eight detectors took measurements at each of the two positions of interest. This experimental arrangement provides an opportunity to study dosimeter response in a field containing significant fluences of both high-energy neutrons and protons. The dosimeters under investigation were CR, bubble detector BD-100, NTA film, and an integrating Andersson-Braun remmeter.

Results

The neutron spectra from the Bonner-sphere measurements at locations A and B were quite similar, as shown by the typical plots in Figs. 8 and 9, for a diffferential spectrum and a cumulative dose equivalent as a function of energy, respectively. There are two peaks at about 0.1 and 10 MeV in the spectrum, which are attributed to evaporation neutrons and to the transmission of higher-energy neutrons through the thin shield. The minimum proton energy needed to traverse the concrete shield is about 650 MeV, but values as high as 2.9 GeV are kinematically possible at 90° for Ne-C interactions. The charged-particle field observed can therefore be tentatively ascribed in part to protons from the target that are transported directly through the shield.

A comparison of dosimeter responses with the neutron dose equivalent H_{ref} obtained from the unfolding of the Bonner spheres is given in Table 3. Except for the NTA film, all the dosimeters, as well as the remmeter, under-respond by approximately 30–50%. The NTA film dosimeter greatly overestimates the dose equivalent, because it registers incident charged particles, both protons and neutrons, with ≈100% efficiency.

4.4 88"-Cyclotron Experiments at LBL

Set-up

The experiment in the 88"-Cyclotron was designed to measure dose equivalents at a location of constant distance, from a target that was struck by a charged particle beam to generate monoenergetic neutrons, of energy 20, 30, 40, and 50 MeV in four steps. Bonner detectors had to be set up one after the other at the same location for each run. The purpose of this experiment was for dosimetry calibration.

Results

In this experiment only seven detectors were used for the measurements. The largest sphere (45.72 cm) was not used. It was replaced by a 12.7-cm sphere that served as a reference unit at a fixed location throughout the measurement. To generate neutrons of about 20 MeV, a proton beam of about 23 MeV was used to strike a lithium target. The Bonner detector was set 7 m from the target, aligned with the beam line, with the centers of the scintillator at the same height as the beam. The beam was switched on and off for each measurement of one detector. The neutron spectrum is shown in Fig. 10, where the curve is a normalized spectrum, after correction with the reference detector.

The neutron beam was supposed to have a monoenergy of 20 MeV. Instead, there are three peaks on the spectrum, one of which is located near 20 MeV. The middle peak at 0.1 MeV was attributed to evaporation neutron. The unfolded results from the LOUHI code show that the average energy is 2.4 MeV, and the total dose equivalent rate is 4.39 μSv h^{-1}. The experiment is not yet concluded, and will be continued at a subsequent time.

5. Discussion and Conclusion

The multisphere spectrometer at Lawrence Berkeley Laboratory has been found to be a very useful instrument for measurement of the neutron spectrum, with a very broad energy range, from 0.025 eV to several GeV. By using the LOUHI code, the calculated results present useful information about the neutron spectrum: neutron average energy, absorbed dose, dose equivalent, and fluence, all given in total amounts or as a function of energy bin. The unfolded fluence spectrum from LOUHI was compared with those obtained with other codes, such as BUNKI or SWIFT. They were found to be very similar. In the measurement of dose equivalent for the calibration of the dosimeter, values obtained from LOUHI always compared well to those from conventional dosimeters (CR-39) or others.

The neutron-scattering effect is important for the Bonner detectors. If the multisphere spectrometer is employed to calibrate a point neutron source that will be used later as a substandard neutron source for calibration of other nuclear instruments, the resulting fluence of the point source may include a certain amount due to scattering neutrons. Therefore, the fluence value of the point source would not be useful if the calibration of the nuclear instrument is not carried out at the same spot.

In conclusion, the multisphere spectrometer is a powerful instrument that has made many contributions to the field of nuclear science. It deserves more attention for the new kind of moderating material as well as for other sizes of spheres, and needs further development in the extension of high energy range and comparision with other kinds of neutron spectrometer in the near future.

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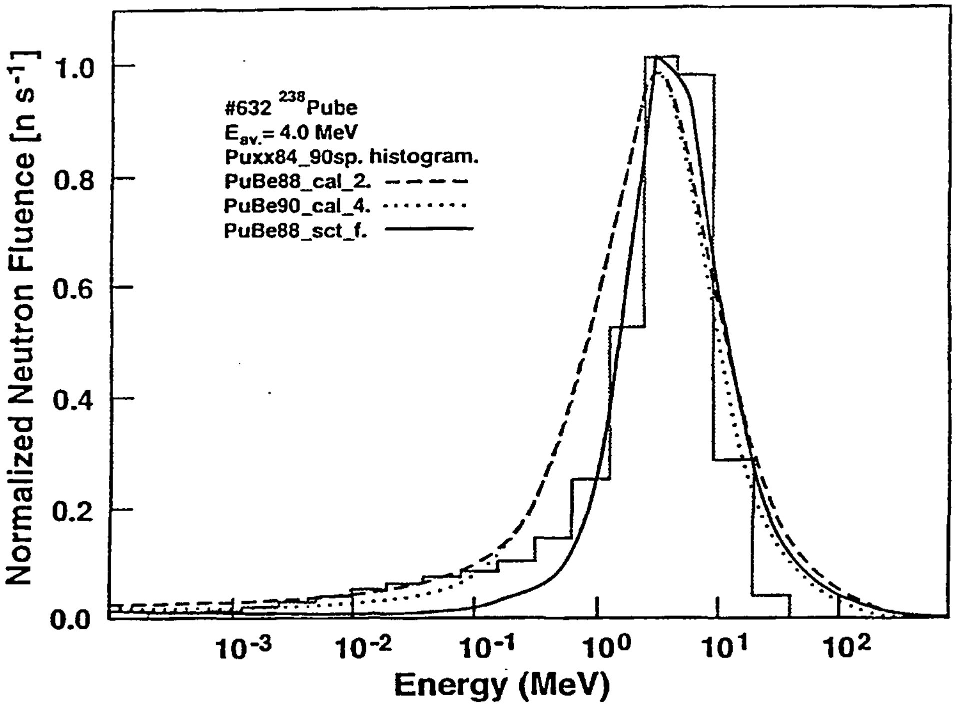

Fig. 1 Comparison of PuBe Spectra

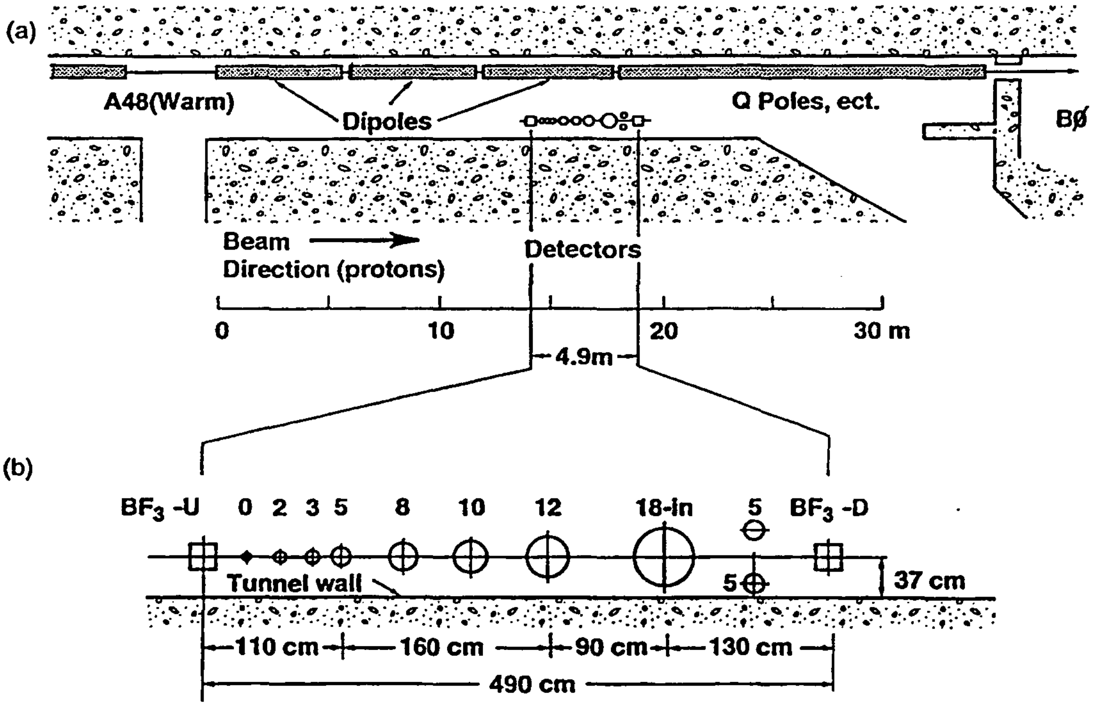

Fig. 2 Plan view of experimental setup in the tunnel. Beam direction (for protons) was left to right. (a) overall view; (b) detail of detector geometry. Solid circles: LiI (Eu) detectors; squares: moderated BF counters. Numbers indicate the polyethylene sphere diameter in inches. Th and Bi fission counters were positioned near the 10" and 12" spheres.

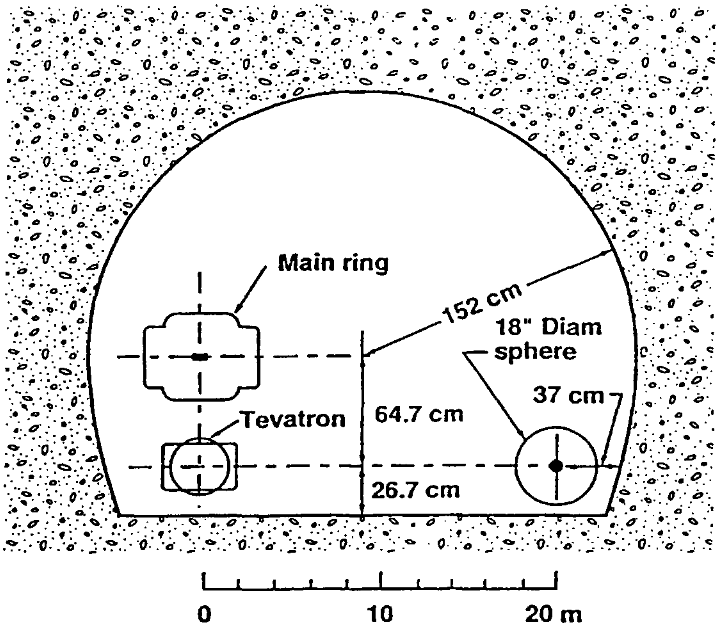

Fig. 3 Tunnel cross section showing relationship of detectors to Tevatron and MR.

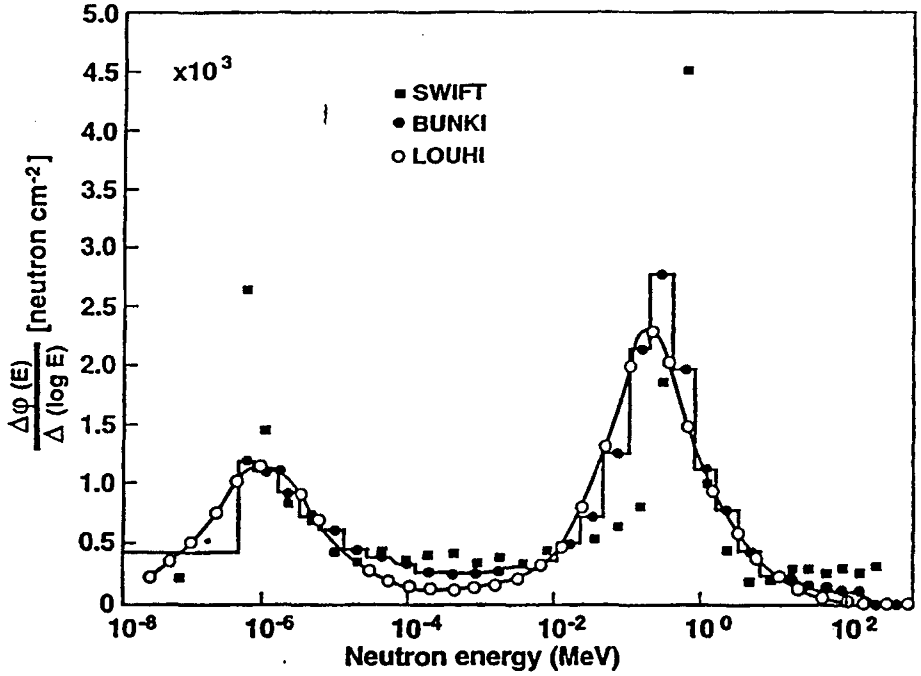

Fig. 4 Comparison of spectra derived from three unfolding codes, BUNKI, LOUHI and SWIFT, for Tevatron 800-GeV coasting bean.

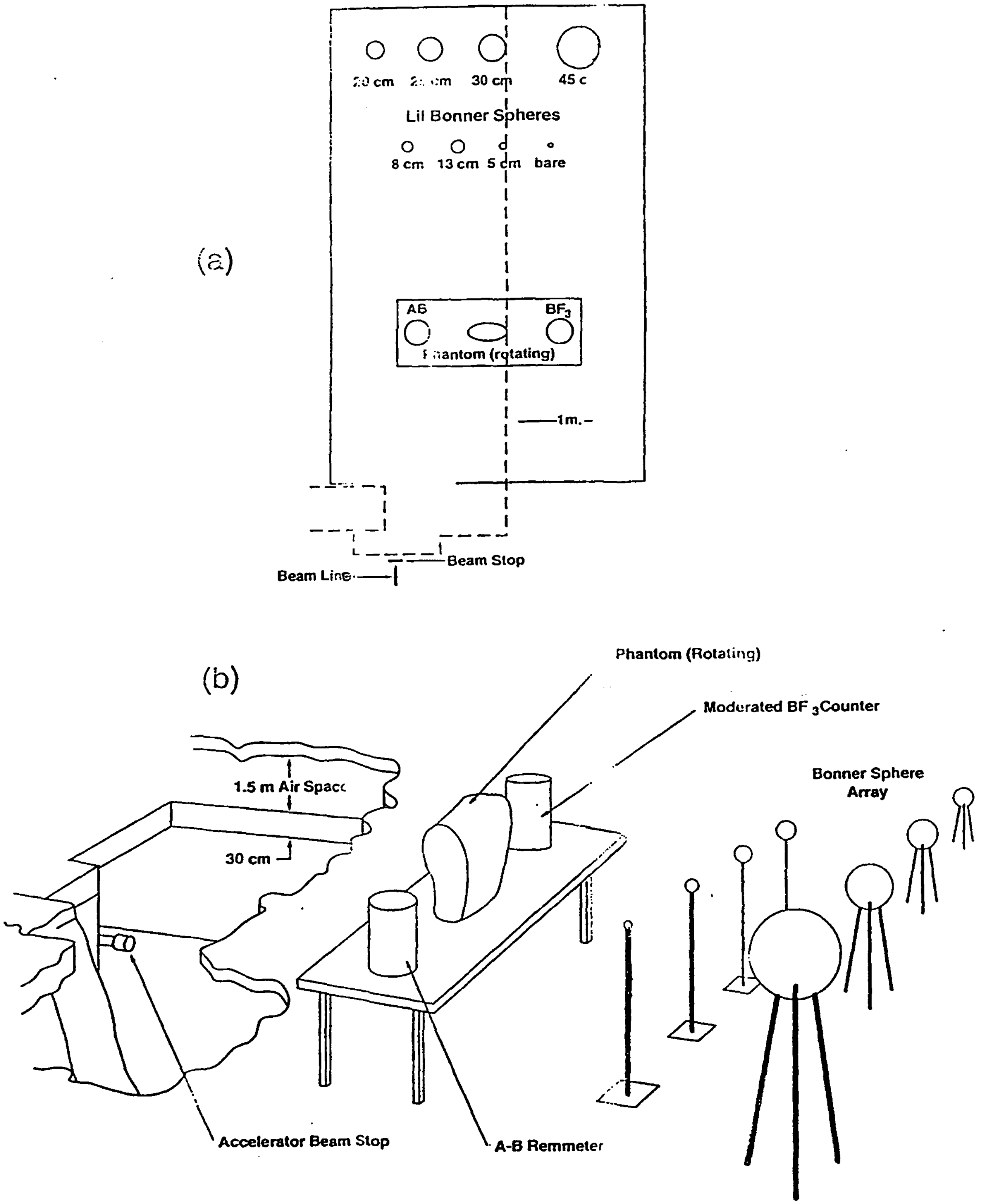

Fig. 5 Bonner detector setup for the SuperHILAC experiment
(a) Plan view and (b) 3-D view

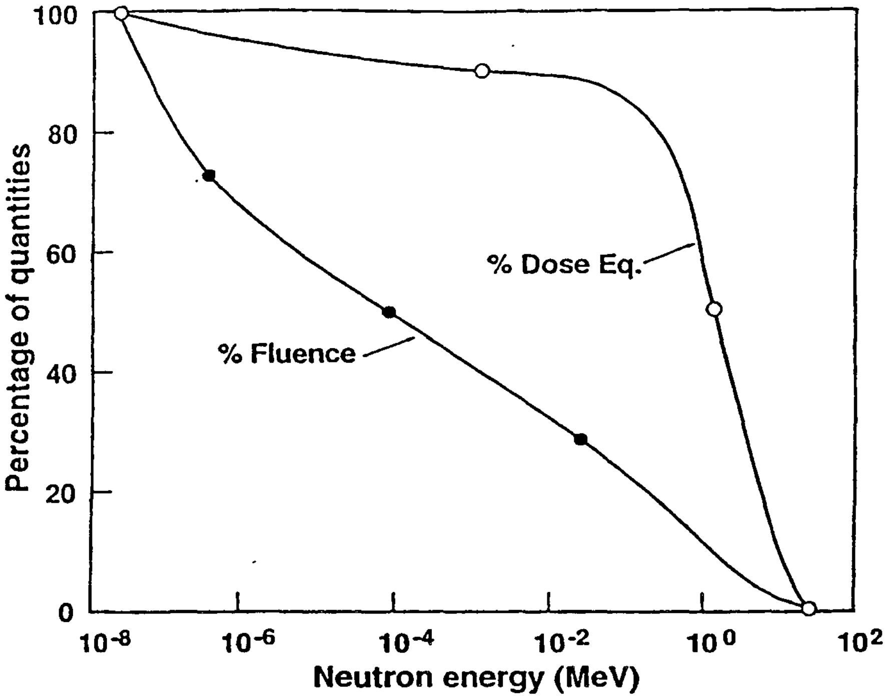

Fig. 6 Cumulative neutron fluence and dose equivalent calculated from LOUHI.

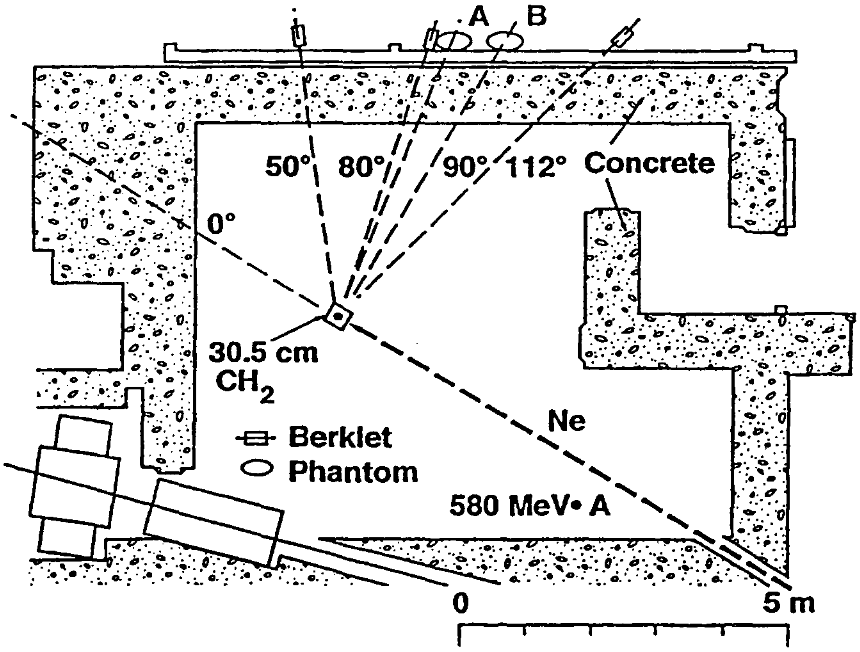

Fig. 7 Setup of Bonner Spheres at locations A and B in pairs for BEVALAC experiment.

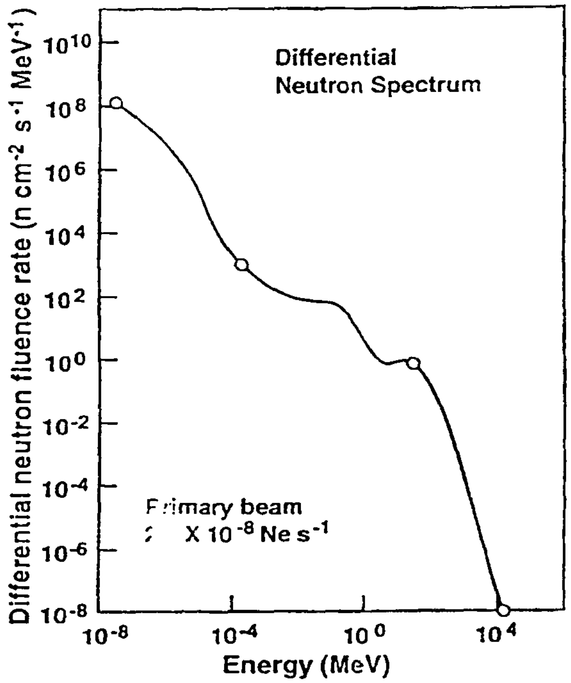

Fig. 8 The differential neutron spectrum as a function of energy (BEVALAC).

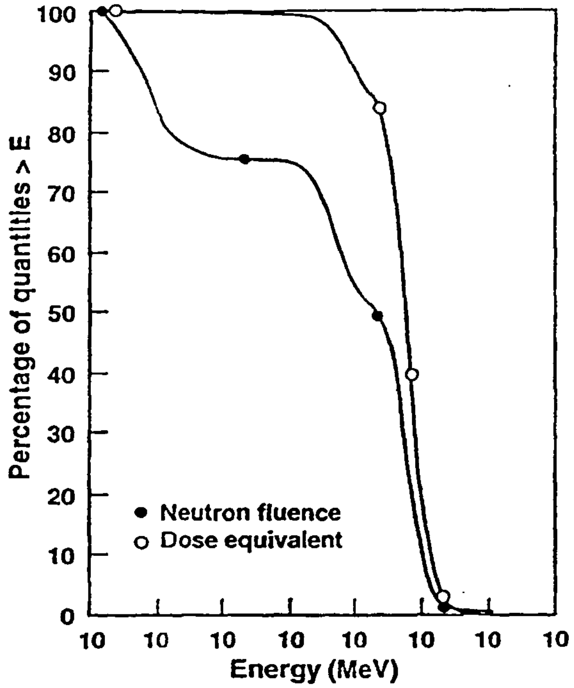

Fig. 9 The cumulative neutron fluence and dose equivalent as - functions of energy.

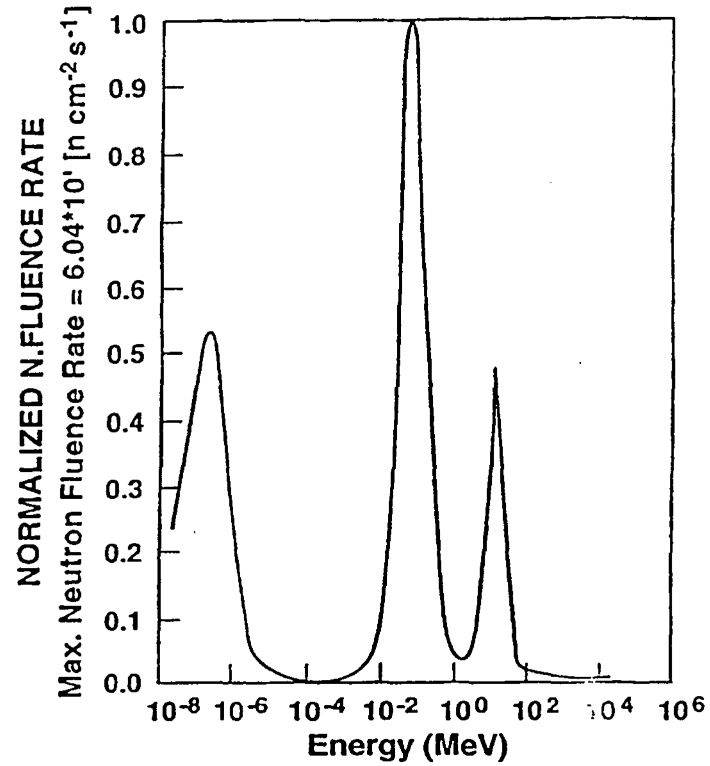

Fig. 10 The normalized neutron spectrum. (88" cyclotron)

Gate on Time (sec)	Beam Intensity (protons)	Total Neutron Fluence (10^3 neuts cm^{-2})			Average Fluence Rate (cm^{-2}s^{-1})
		BUNKI	LOUHI	SWIFT	
1160	8X10^{10}	2.98	2.97	2.87	2.53
1055	2X10^{10}	6.84	6.80	6.85	6.47
1218	1.4X10^{10}	5.35	5.35	5.28	4.37
1027	2.5X10^{10}	12.3	12.2	12.1	11.9

Table 1. Comparison of neutron spectra in 800 GeV low-beta Tevatron coasting beam runs.

Measurement Method	H (mSv)	Ratio
Bonner Spheres	1.71	1.0
Andersson Braun Counter	2.51	1.46
NTA film dosemeters	1.28	0.75
CR-39 dosemeters	1.50	0.88

Table 2. Comparison of Dose Equivalents obtained with different Methods.

Table 3. Comparison of dosimeter response to neutron spectrometer H_{ref}.
(Dose equivalent in mSv per 1×10^{13} Ne)

Location	H_{ref}, Neutron Spectrometer	A-B* Rem-meter	CR-39**	BD-100**	NTA Film
A	2.15	1.10	1.37±0.15	1.13±0.12(g) 0.95±0.11(p)	22.7
B	1.22	0.74	0.85±0.17	0.76±0.11(g) 0.85±0.31(p)	—

* Negligible statistical error.
** Uncertainties are standard errors from scanning multiple fields.
(g) Glass BD-100 Bubble Detector (no longer available).
(p) Plastic BD-100 Bubble Detector.

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