NEUTRON SKYSHINE MEASUREMENT AT A K1200 SUPERCONDUCTING HEAVY ION CYCLOTRON USING BUBBLE DOSIMETERS

BHASKAR MUKHERJEE
Safety Division, Australian Nuclear Science and Technology Organisation
PMB 1,Menai, NSW 2234, AUSTRALIA

REGINALD M. RONNINGEN
National Superconducting Cyclotron Laboratory, Michigan State University
East Lansing, MI 48824-1321, USA

PAUL ROSSI
Office of Radiation, Chemical and Biological Safety, Michigan State University
East Lansing, MI 48824-1326, USA

Understanding the characteristics of the neutron skyshine radiation is necessary for an accurate assessment of the environmental dose in the vicinity of the containment of a high-energy particle accelerator. At the National Superconducting Cyclotron Laboratory (NSCL), neutron skyshine was measured, using beams of 140 MeV/nucleon ^{4}He and 80 MeV/nucleon ^{22}Ne ions from the K1200 superconducting cyclotron. After passing through a radioactive-beam production target, the ion beam stopped in a solid aluminium stopping bar inside of a dipole magnet, resulting in the production of high energy fragmentation as well as evaporation neutrons in the NSCL Analysis Hall. The neutron dose equivalent and energy spectrum at the 1.37 m thick concrete roof of the Analysis Hall, directly above the aluminium target bar (reference point), were estimated, using a spherical "rem-counter" and a set of seven Bonner-spheres, respectively. The skyshine dose, from neutrons transmitted through 21.5-cm local iron "shielding" of the dipole magnet and the concrete roof, were evaluated using superheated bubble dosimeters at 50 m, 75 m, 100 m and 115 m from the reference point. The neutron doses beyond the extremity of the NSCL facility were extrapolated from the results of this investigation and were used to predict the exposure to members of the public by considering the operation schedule of the K1200 cyclotron.

1. Introduction

Radiation fields, generated during the operation of a high-energy particle accelerator, may penetrate an inadequately shielded roof of the containment building. Penetrating radiation may be transported to a long distance from its source, after undergoing multiple scattering in the atmosphere. This phenomenon is known as skyshine[1, 2]. The National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University operates two superconducting cyclotrons (K500 and K1200) capable of accelerating ion species ranging from $^{2}H^{1+}$ to ^{238}U. The skyshine produced by the neutrons during K1200 operations, which leaked through 26 cm thick local iron "shielding" of the dipole magnet and the 1.37m thick concrete roof[3], was evaluated using the passive "superheated bubble dosimeters". We have estimated the neutron dose equivalents at 50m, 75m, 100m and 115m from the expected source (reference point) of the skyshine, *i.e.*, the spot at the roof surface directly above the neutron-producing target situated in the NSCL's Analysis Hall (Figure 1). The neutron dose equivalent and spectral distribution at the reference point were evaluated using a spherical neutron "rem-counter" and a set of 7 Bonner spheres respectively. The skyshine data was collected for two primary beams, 140 MeV/nucleon ^{4}He and 80 MeV/nucleon ^{22}Ne. This series of skyshine measurement should serve as the benchmark for operations with the cyclotrons coupled, which commences in 2001[4, 5].

2. Neutronics Calculations

2.1 Neutron Production Cross Section

A copious number of neutrons are emitted when a thick target is bombarded with energetic light mass heavy ions. The differential cross section [$n.cm^{-2}MeV^{-1}sr^{-1}$] of neutron production is represented by the phenomenological model[6] consisting of the "moving thermal source" (evaporation) and "fragmentation" components:

$$(d^2\sigma/dEd\Omega) = A_e\times(E/T_e^2)\times\exp(-E/T_e) + A_f\times(E/T_f^2)\times\exp(-E/T_f) \quad (1)$$

$$\text{with, } A_{e\text{ or }f} = \sigma_{nel\text{ or }f}(\Omega)\times K/4\pi \quad (2)$$

where, Ω = Solid angle in Centre of Mass system [sr]
E = Neutron energy in Centre of Mass system [MeV]
T_e = Nuclear temperature (evaporation) = 2.1 MeV
T_f = Nuclear temperature (fragmentation) = 7.5 MeV
$\sigma_{nel\text{ or }f}(\Omega)$ = Non-elastic cross section [$mb.sr^{-1}$] for the evaporation or fragmentation processes
K = Total number of neutrons produced per non-elastic collision

The low-energy "evaporation" neutrons are character-ised by the isotropic distribution. The high energy "fragmentation" neutrons on the other hand, contribute predominantly in the forward angles less than 45 degrees[7].

2.2 Neutron Skyshine Distribution

During the 1960s and 1970s a substantial number of high-energy particle accelerators were installed in various laboratories in the world. Since then the atmospheric transport and skyshine phenomena of high energy neutrons have been reported by a number of investigators[1, 2, 8]. The fluence (or dose equivalent) of skyshine neutrons at a radial distance > 50 m from the source could be empirically represented as[1]:

$$\phi(r) = (aQ/4\pi r^2)\times(1-\exp(-r/\mu))\times\exp(-r/\lambda) \quad (3)$$

where, a = Empirical build up factor = 2.8

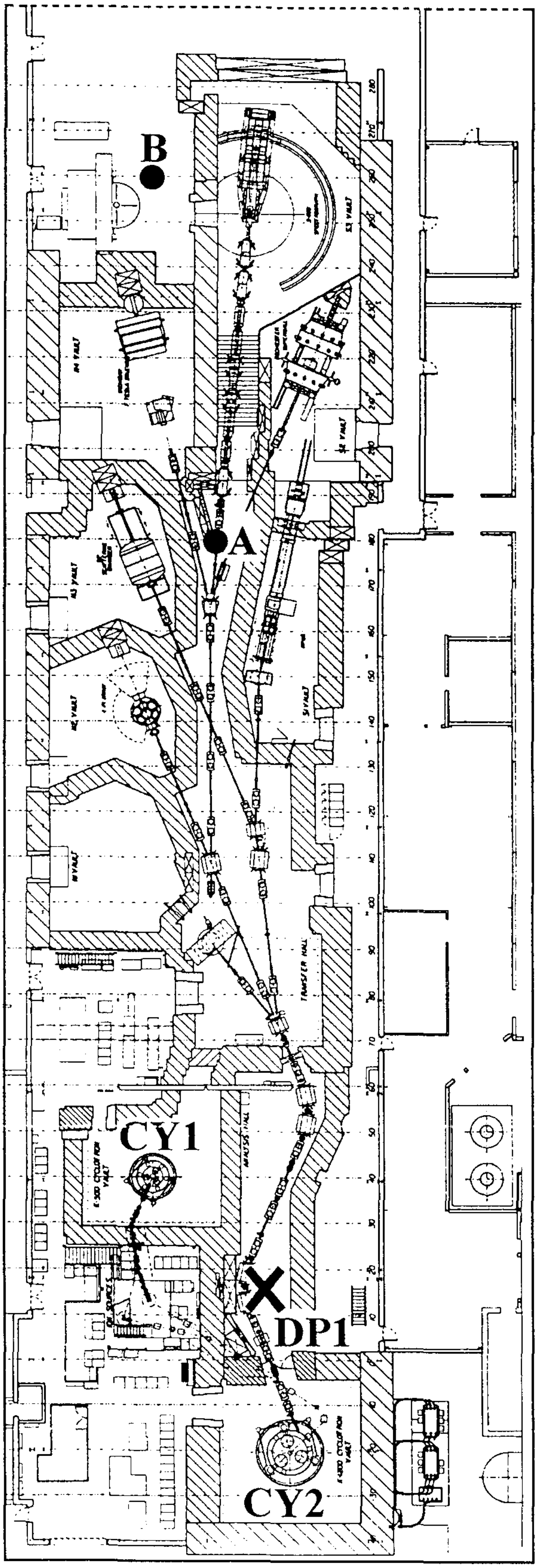

Figure 1: The plan view of the NSCL Facility showing the K500 (CY1) and K1200 (CY2) cyclotrons and associated experimental devices housed in the concrete shielded vaults.

μ = Build up relaxation length in air = 56m
λ = Dose attenuation length in air = 270m for neutrons with the energy < 5 MeV
Q = Neutron source strength [neutrons.s^{-1}] or [μSvh^{-1}]
r = Radial distance from the source, r >50m

3. Materials and Methods

3.1 Neutron Field Characterisation

The neutron energy spectrum at the reference point was assayed with a Bonner Sphere spectrometer based on six polyethylene spheres of 12, 10, 8, 5, 3 and 2 inch diameter, a large polyethylene cylinder (17 inch diameter, 18¼ inch long) which approximates an 18 inch sphere, and a 4mm dia × 4mm ^{6}LiI (Eu) thermal neutron detector (Manufacturer: Ludlum Measurements Inc. USA). The output of the thermal neutron detector was connected to a computerised MCA located at the counting area in the High Bay. A plastic scintillator detector (neutron flux monitor) was securely placed at approximately 2m from the reference point and its anode signal was connected to a Single Channel Analyser (SCA) and a NIM Counter also located in the counting area (Figure 2).

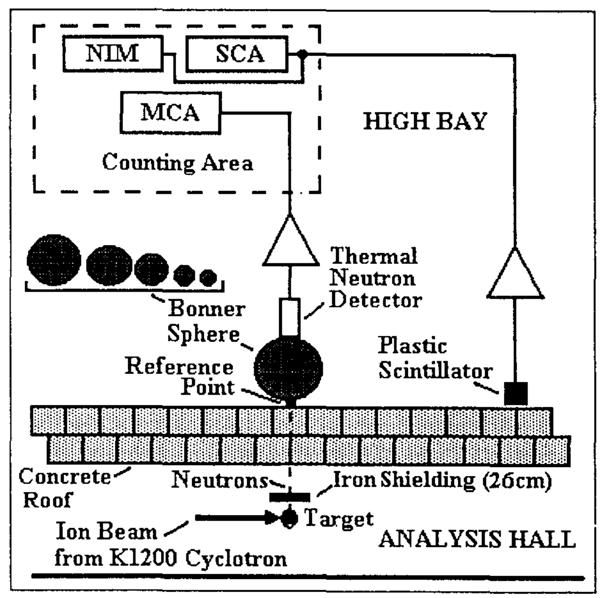

Figure 2: Schematic diagram of the experimental set up at the NSCL High Bay for neutron flux monitoring and spectrometry using a plastic scintillator and a set of polyethylene Bonner spheres respectively.

The count rate for each individual Bonner sphere was normalised to the corresponding count rate of the plastic scintillator and used to unfold the neutron spectrum using the BUNKI neutron spectra unfolding code[9] and shown in Figure 3.

The neutron dose rate at the reference point was evaluated with a 9 inch diameter spherical REM counter (Model: NRD, Manufacturer: Eberline Inc. USA) connected to a NIM counter. For calibration purposes, the REM counter was exposed to a 5 Ci (185 GBq) ^{239}Pu-Be neutron source producing a fluence of 6.95×10^1 [neutrons.cm^{-2}s^{-1}] at a distance of 1m. In total 7227 counts were counted in 15 minutes for an integrated neutron dose equivalent of 27.2 μSv. Therefore, the neutron calibration factor k_n was calculated to be 265.9 [counts.μSv^{-1}].

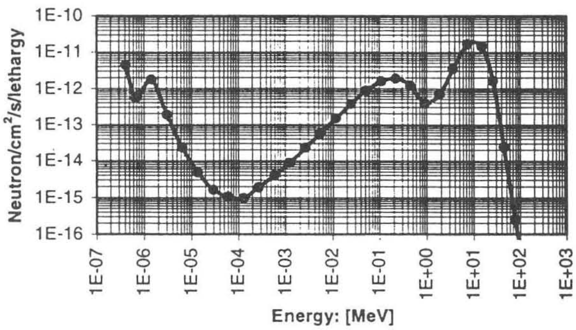

Figure 3: Neutron energy spectrum at the reference point during the bombardment of the aluminium stopping bar with the 140 MeV/nucleon ^4He ions in the Analysis Hall. The average neutron energy was calculated to be 2.5 MeV.

3.2 Skyshine Measurement with Bubble Dosimeter

The bubble dosimeters[10] were used for in-situ neutron dose equivalent assessment along the High Bay. The bubble dosimeters basically consist of a epoxy cylinder (1.7cm diameter × 7cm) filled up with a large number of superheated microscopic droplets dispersed in an elastic hydrocarbon gel. When hit by an energetic neutron the droplets turn into visible bubble trapped in the gel which can be counted[11] by naked eye (Figure 4).

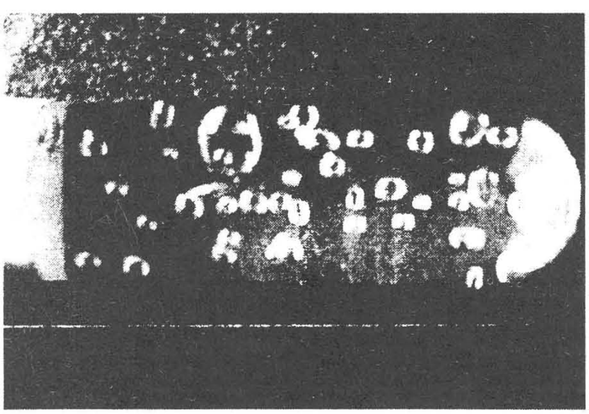

Figure 4: Photograph showing the bubble formation in a BD100R bubble dosimeter after the neutron skyshine exposure at the NSCL High Bay.

Five bubble dosimeters (Model: BD100R, Sensitivity Factor: 4.7 bubbles-μSv^{-1} at 20 °C, Manufacturer: Bubble Technology Industry Canada) were initialised by unscrewing the piston located at the top end of the cylinder. Each then was wrapped in thermal insulation padding and placed in a Styrofoam cup, and then placed at locations A, B, C and D along the High Bay at 50m and 75m, 100m and 115m from the reference point X respectively (Figure 1). All dosimeters were placed at 70 cm from floor level. The positions of dosimeters C and D are not shown. Two dosimeters were placed at position D. The dosimeters were exposed while the target was being bombarded with 140 MeV/n $^4He^{2+}$ ions and in a separate experiment, 80 MeV/n $^{22}Ne^{6+}$ ions. In both cases the integrated neutron dose equivalents at the reference point "X" , the source terms were evaluated from the REM counter totals and neutron calibration factor k_n, and found to be 5486 μSv ($^4He^{2+}$) and 631 μSv ($^{22}Ne^{6+}$) corresponding to 1.46×10^6 and 1.68×10^5 counts respectively. The results are summarised in Table 1. In Figure 5 the neutron skyshine doses are shown as function of distance from the reference point. The photon skyshine contributes only 20% of the total dose therefore been ignored[8].

Table 1: Showing the distance (d) of the BD 100R bubble dosimeter from the reference point, number of bubbles produced after exposure (N_T), number of bubbles without exposure (N_B) and the corresponding neutron skyshine dose equivalent Dn. (*: Source term)

d	140 MeV/n $^4He^{2+}$			80 MeV/n $^{22}Ne^{6+}$		
[m]	N_T	N_B	Dn [μSv]	N_T	N_B	Dn [μSv]
0	---	---	5486*	---	---	631*
50	56	6	11.49	15	4	2.34
75	10	2	1.70	9	3	1.28
100	9	0	1.91	---	---	---
114	5	0	1.06	---	---	---
125	---	---	---	4	0	0.85

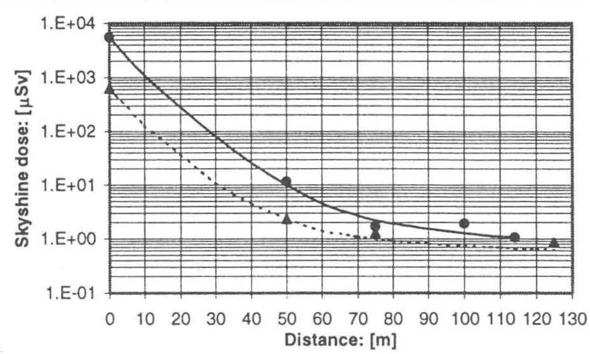

Figure 5: Neutron skyshine dose along the NSCL High bay evaluated with BD 100R bubble dosimeters for 140 MeV/n ^4He (full line) and 80 MeV/n ^{22}Ne (broken line) ion irradiation at the K1200 Cyclotron are shown as functions of the distance from the reference point (Figure 1).

3.3 Prediction of the Boundary Dose Equivalent

The neutron skyshine doses for 140 MeV/nucleon $^4He^{2+}$ and 80 MeV/nucleon $^{22}Ne^{6+}$ ions measured with the BD100R bubble dosimeters (Table 1) were used to predict the annual accumulated (neutron) dose equivalent at the boundary of the NSCL experimental hall, i.e. 125m from the reference point "X" (Figure 1). The accumulated neutron dose equivalent (D_i) for the i^{th} type of ion is derived from the NSCL operation matrix[12] as follows:

$$D_i = T\times k_i\times d_i/t_i \quad (4)$$

where, T = Total cyclotron operation time [hour]

k_i = Beam time allocation factor for i^{th} type of ion [%]

d_i = Dose recorded with BD 100R for i^{th} type of ion

t_i = Exposure time for the i^{th} type of ion [hour]

The total operation time in 1997 is 4764 hours. For Ne like ions ("like" meaning similar in intensity and neutron production), assuming a beam time allocation factor of 44 % and accumulated neutron dose equivalent of 0.85µSv at 125m (extrapolated from Figure 5) in 8 days (192 hours), the annual projected neutron dose equivalent (D_{Ne}) was calculated to be 9.3 µSv. Similarly, for He ions with a beam time allocation factor of 11 % and for the accumulated neutron dose equivalent of 1.0 µSv (extrapolated from Figure 5) in 3 days (72 hours), the annual projected neutron dose equivalent (D_{He}) was calculated to be 7.9µSv. Therefore, the total yearly projected neutron dose equivalent (D_{Ne} + D_{He}) at the boundary of the NSCL experimental hall was estimated to be 17.3 µSv (0.0173 mSv). The remainder of the operation time is devoted to heavier beams, typically at lower beam currents and producing fewer skyshine neutrons. We note for reference, the annual dose equivalent for the members of the public restricted by the US NRC regulation is 1 mSv.

4. Summary and Discussion

The present work demonstrates the method of neutron skyshine dose assessment using superheated bubble dosimeters at a high-energy heavy ion cyclotron facility. The bubble dosimeters are highly sensitive to neutrons of wide energy distributions, thus providing a direct method of skyshine dose evaluation without using the fluence-to-dose conversion factors. The bubble dosimeters are passive devices, sensitive, inexpensive and small. Hence, a large number of such devices could be simultaneously deployed thereby resulting in a substantial reduction of uncertainty in "low level" neutron counting experiments. Evidently, the bubble dosimeters may outperform the conventional Long-counters under many conditions. Long-counters are bulky and are thus certainly less portable, and consume a substantial electric power to drive the detector electronics.

The projected dose assessment, using the He and Ne beam data and extrapolating from a current operation matrix, is well within regulatory mandate. These measurements and dose assessment projection exercise will be most useful for predictions of exposures at the NSCL site boundaries when coupled-cyclotron operation commence.

Acknowledgements

The authors wish to thank the K1200 Cyclotron Operation Department staff. This work was supported by the US National Science Foundation under grant PHY-9528844.

References

[1] J. D. Cossairt et al. *Hlth. Phys.* 48, 175 (1985).

[2] H. W. Patterson and R. H. Thomas in *Accelerator Health Physics* (Academic Press, New York, 1973).

[3] G. I. Britvich et al., *Rev. Sci. Instr.* (submitted).

[4] F. Marti et al. in *Cyclotrons and Their Applications*, ed. J. Cornell (World Scientific, Singapore, 1996).

[5] C. K. Gelbke, *Nucl. Phys. News.* 4, 5 (1994).

[6] T. Nakamura et al., *Nucl. Instr. Meth. Phys. Res A.* 240, 207 (1985).

[7] R. M. Ronningen, NSCL Report MSU-339, East Lansing (1994).

[8] A. Rindi et al., *Particle. Accelerator,* 7, 23 (1975).

[9] K.A. Lowry and T.L. Johnson, U.S. Naval Research Laboratory Report NRL-5430, Wahington D.C. (1984).

[10] H. Ing. et al., *Rad. Meas. 27*, 1 (1997).

[11] F. Vanhavere et al., *Rad. Prot. Dosim,* 65, 425 (1996).

[12] D. Poe, NSCL (private communication).