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ARTICLE

Measurements and simulations of scattered neutrons in a water phantom

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A recoil neutron spectrometer based on NE230 deuterated liquid scintillator (25 mm diameter × 25 mm) has been used to investigate neutron energy spectra of scattered neutrons at positions in and near to the beam axis in a water phantom irradiated by a quasi-monoenergetic 64 MeV neutron beam. An important feature of the spectrometer is that it is able to discriminate against backgrounds that can arise from n-p scattering in the water. Neutron energy spectra are obtained from measurements of pulse height spectra by the NE230 spectrometer using the Bayesian unfolding code MAXED. The experimentally measured energy spectra are compared with spectra calculated by Monte Carlo simulation using the code MCNPX.

Keywords: neutron radiotherapy; energy spectra; area under treatment; scattered and secondary radiation; radiation quality; absorbed dose; radiotherapy; Monte Carlo; unfolding; response matric

1. Introduction

In neutron radiotherapy, detailed knowledge of the energy spectra of neutrons inside and near to the area under treatment by the neutron therapy beam are required to calculate the energy spectra of secondary charged particles, and to characterize the radiation quality and absorbed dose both inside and near to the area under treatment. The latter measurements are of interest because late effects observed after successful treatment of the primary area depend on the dose contributed to neighboring healthy tissue by scattered and secondary radiation. In principle, neutron energy spectra can either be calculated by Monte Carlo Methods or measured experimentally [1].

This paper reports on measurements made of primary and scattered neutrons at positions in and near to the beam axis in a water phantom (simulating human tissue). The neutron spectrometer used is based on a NE230 deuterated liquid scintillator (25 mm diameter × 25 mm) that was developed to measure neutron energy spectra as a function of position in a water phantom irradiated by neutrons of energy up to ~ 64 MeV. More details on the spectrometer can be found in [2]. A deuterated scintillator was used instead of the more widely use natural hydrogen scintillator in order to discriminate against backgrounds that can arise from n-p scattering in the water. Neutron energy spectra were obtained from pulse height spectra measured with the NE230 spectrometer by Bayesian unfolding with the code MAXED [3]. The neutron spectra obtained from the in-phantom measurements are compared with Monte Carlo simulations using the code MCNPX [4] to model the experiments.

2. Experimental procedures

Experiments were conducted at the neutron time-of-flight facility at iThemba LABS in South Africa [5] using a similar beam geometry as described in [6]. Well-collimated neutron beams of energy up to ~ 64 MeV were produced by bombarding either a Li metal target of thickness 1.0 mm, a Be metal target of thickness 10.0 mm or a graphite target of thickness 10.0 mm with a pulsed beam of 66 MeV protons from the iThemba LABS separated sector cyclotron. The beam profile was measured at an angle 0^0 to the proton beam direction at a distance 7.71 m from the target and found to be uniform within 5% over a circular area of diameter 50 mm. A neutron beam monitor (NE213 scintillator) viewed the target through a collimator opening at an angle of 8^0 to the proton beam direction, at a distance 8.05 m from the target. The water phantom consisting of a cubic tank of side 60 cm, made from acrylic sheet of thickness 5 mm was mounted with its centre orientated along the 0^0- neutron beam at a distance of 7.53 m (to the front face of the tank) from the target.

Two types of measurements were completed (a) in-air measurements and (b) in-phantom measurements. For the in-air measurements, data were recorded with either the NE230 spectrometer or a reference detector (NE213 scintillator, 50 mm diameter × 50 mm) placed

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in the 0^0- neutron beam at a distance of 7.71 m from the target. In-air measurements were taken using neutron beams produced by all the three targets, Li, Be and C, respectively. For the in-phantom measurements the NE230 detector assembly was immersed in the water phantom and moved under computer control to positions along and off the beam axis. The in-phantom measurements were taken using the Li target alone.

All of the detectors (NE230, NE213 reference and NE213 monitor) used in the experiments were equipped with Link Systems Model 5010 pulse discriminator units to suppress the detection of gamma rays. Both the NE230 and NE213 scintillators have excellent capabilities for discriminating against gamma rays as well as between protons, deuterons and alphas by means of pulse shape discrimination [3, 7, 8]. The output parameters, pulse height *L*, fast signal *F* and neutron time-of-flight *T* from the Link units were recorded in list mode and then processed off-line. In the case of the NE230 detector, pulse-shape discrimination was used to reject proton events, that is to select only events such as n-d elastic scattering or (n, d) and (n, α) reactions on carbon, in which neutron interactions releases deuteron or heavier particles in the scintillator. This enables discrimination against backgrounds that can arise from n-p scattering in the water. Also the stopping power of the NE230 for deuterons and heavier charged particles is larger than that for protons, excluding protons minimizes problems caused by charged particle escape from the scintillator. Charged particle escape distorts pulse height spectra and results in distortions in the corresponding energy spectra obtained from unfolding [9].

After applying the event selection procedures described above, data were analyzed as follows. All measurements were normalized to the same number of neutrons measured by the beam monitor detector. For the in-air measurements, two-parameter distribution of events as a function of *L* and *T* were obtained. The time-of flight channel *T* was calibrated into incident neutron energy *E*. The *LT*-distributions were used for three purposes: (1) to determine the efficiency of the NE230 detector as a function of incident neutron energy *E;* (2) to form a response matrix of dimensions 43 (*E*) × 104 (*L*) for the NE230 detector; and (3) to validate the unfolding procedure using MAXED. Details can be found in an earlier publication [2].

3. Results and discussion

The results from the tests that were carried out to validate the unfolding procedures used to determine neutron energy spectra from pulse height spectra provide reliable results from the measured data using a response matrix that was determined by experiment. The spectrum of the Li-target measured in-air by time-of- flight was used as the default spectrum in the unfolding code MAXED. **Figure 1** shows comparisons between pulse height spectra measured in the phantom made with the NE230 spectrometer located at different positions along and off the beam axis of the neutron beam. The position is indicated by the depth *d*, measured from the front face of the phantom to the centre of the scintillator and by the lateral distance *l*, from the beam axis (see **Figure 2**).

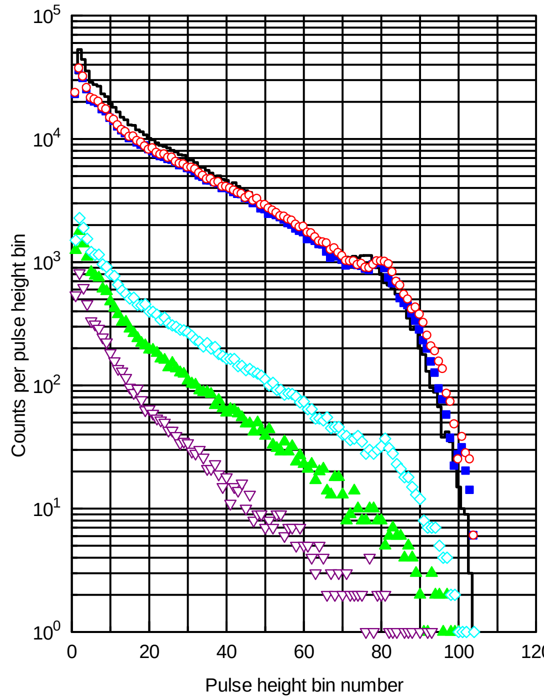

Figure 1. Comparisons of pulse height spectra measured in-air (histogram) and at positions (8 cm, 0 cm) (solid squares); (8 cm, 2 cm) (open circles); (8 cm, 4 cm) (solid up triangles); (8 cm, 7.5 cm) (open down triangles) and (20 cm, 4 cm) (diamonds) in the water phantom.

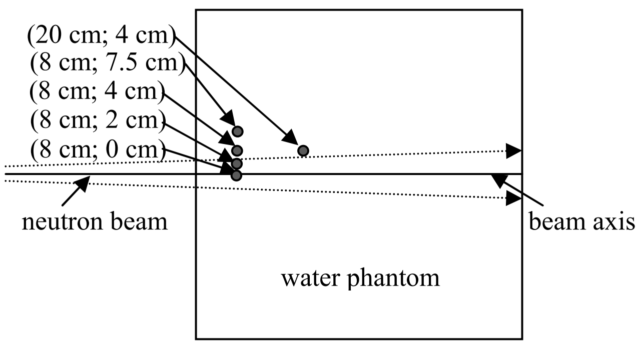

Figure 2. Schematic diagram showing the different positions in the phantom where measurements were made. The area between dotted lines indicates the geometrical path of the beam

Figure 3 shows the neutron energy spectra obtained by unfolding these pulse height spectra using MAXED. The progressive softening of the neutron spectrum at depth 8 cm with increasing lateral distance is evident in these spectra. This is due to the kinematic effect involved, i.e. more lower energy neutrons are scattered out of the beam since the scattering angle of the scattered neutrons increases as their energy decreases. As expected from kinematic considerations, the spectrum measured at position (20 cm, 4 cm) shows a higher proportion of high energy neutrons than for the spectrum measured at (8 cm, 4 cm).

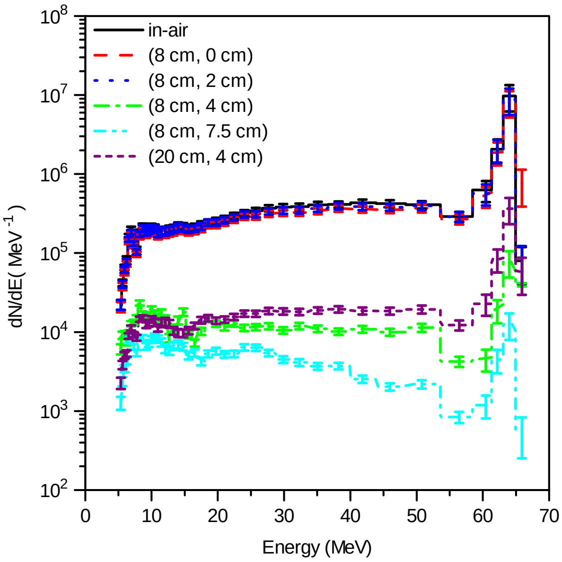

Figure 3. Energy spectra measured at different positions off the beam axis in the phantom compared with the in-air spectrum.

Figures 4(a)-(d) show comparisons between the results of both measured and Monte Carlo simulated spectra off the beam axis. The Monte Carlo simulated spectra were calculated by the code MCNPX, using the spectra of the Li-target measured by time-of-flight in-air as the neutron source spectrum. The first three panels (a)-(c) in Figure 4 show measured spectra (histograms) and calculated spectra (solid circles) at the same depth of 8 cm, while the lateral distances are 2 cm, 4 cm and 7.5 cm, as indicated. Figure 4(a) shows that at the position closest to the beam axis (2 cm) the agreement between the measured and calculated spectra are good. The neutron peak at 64 MeV and the resonance structure around 7.4 MeV are also well reproduced in both the calculated spectrum and measured spectra. However, agreement between the measurements and the calculations becomes progressively poorer further from the beam axis, i.e. the agreement at 7.5 cm is substantially poorer than at 4 cm as can be seen in Figures 4(b)-(c). It is interesting to note, see Figures 4(b) and (d), that at position (20 cm, 4 cm) which is substantially further into the phantom, the measured and calculate spectra are in better agreement than that at (8 cm, 4 cm). The differences between the Monte Carlo results and the measurements can probably be attributed largely to the unfolding procedure insofar as using the Li spectrum measured in-air by time-of-flight as the default spectra in the unfolding. At the positions where agreement is worst the detector is situated out of the path of the neutrons that arise directly from the target. In these cases the neutrons that enter the detector do so after having been scattered. Thus, the spectra are not to have a strong peak around 64 MeV, and using the Li spectrum will produce results that overestimate the strength of the 64 MeV peak. This is in keeping with the fact that the agreement between the calculations and the measurements are better at position (20 cm, 4 cm) than at (8 cm, 4 cm), since the former position lies in a more forward direction that the latter.

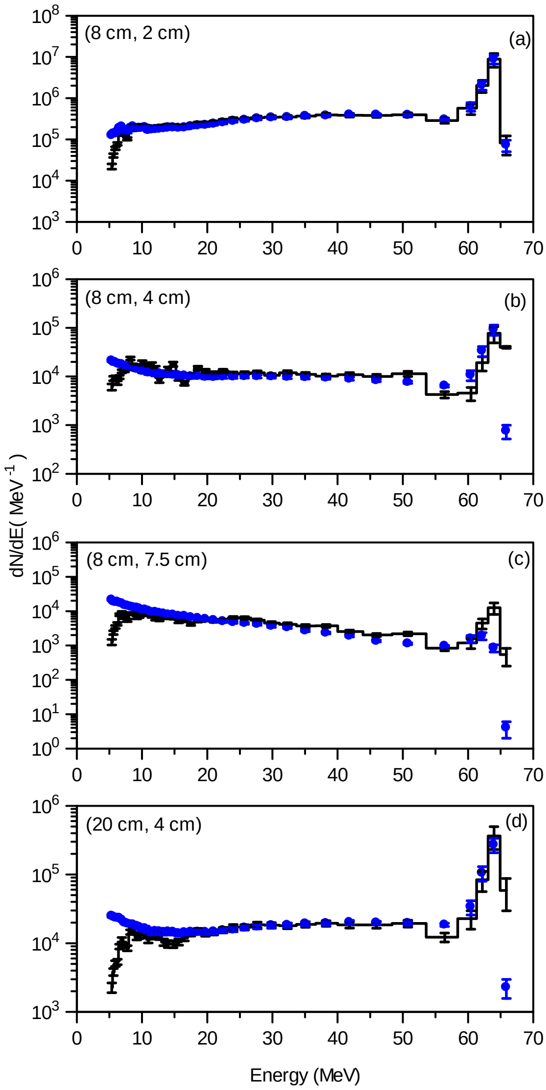

Figure 4. Neutron energy spectra measured (histograms) and calculated via MCNPX (solid circles) at off beam axis positions (8 cm, 2 cm); (8 cm, 4 cm); (8 cm, 7.5 cm) and (20 cm, 4 cm) in the water phantom.

With regard to the poor agreement between the calculations and the measurements around the region of the 7.4 MeV resonances, attributed to resonances of ^{12}C with the 65 cm thick graphite block put in front of the collimator side facing the target, the measured spectrum shows a sharp drop in intensity which is consistent with the electronic threshold of the experiment of about 5 MeV while Monte Carlo calculations indicate that the resonance has faded out. The apparent strength of the resonance in the measured spectra is attributed to an artefact associated with the unfolding procedure in that MAXED applies no smoothing routines and preserves any structure in the prior spectrum that is finer than the energy resolution of the detector [10]. On the other hand, the Monte Carlo calculations are in keeping with the expectation that the resonance structure will fade out due to scattering.

A preliminary investigation was carried out using a flat default spectrum to unfold the data recorded at the positions (8 cm, 4 cm), (8 cm, 7.5 cm) and (20 cm, 4 cm). The results are shown in **Figure 5** in which the dotted line indicates results from the unfolding using the flat default spectrum. It is clear that at the position (8 cm, 4 cm) the results obtained using the flat default spectrum appears to be less in agreement with the MCNPX calculations than the results obtained

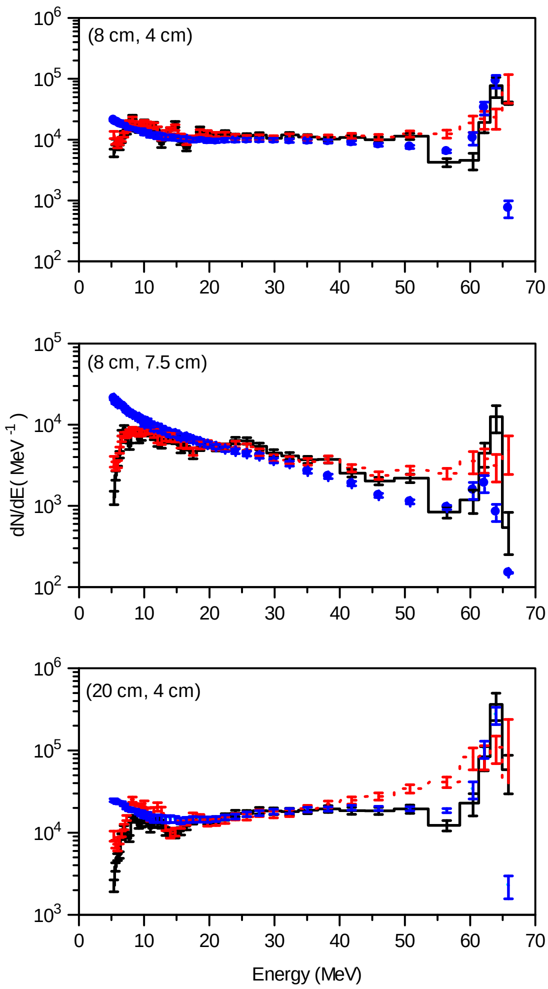

Figure 5. Measured neutron energy spectra obtained using Li default spectrum (histograms), flat default spectrum (dotted line) for unfolding, and MCNPX calculations (solid circles) at off beam axis positions (8 cm, 4 cm), (8 cm, 7.5 cm) and (20 cm, 4 cm) in the phantom.

with the Li default spectrum in between 50 MeV and 60 MeV as well the results deviate systematically from both the Monte Carlo calculations and the results from the Li default spectrum especially around the peak at 64 MeV. For the positions (8 cm, 7.5 cm) and (20 cm, 4 cm) there is also no evidence that a flat default spectrum produces results that are in greater agreement with the Monte Carlo calculations. This points strongly to the possibility that the disagreements at these positions might lie in the choice of the default spectrum used in the unfolding which requires a more detailed investigation.

4. Conclusion

In conclusion, the results demonstrate that a neutron spectrometer based on a deuterated organic liquid scintillator (NE230) for measuring neutron energy spectra of scattered neutrons at positions in and near to the beam axis in a water phantom is viable. The broad trends of the neutron energy spectra that were obtained after unfolding were that the spectrum softens with increasing lateral distance from the beam axis. These results are consistent with other measurements that have been reported [1, 11]. Comparisons with Monte Carlo calculations using MCNPX showed good agreement between the measurements and the calculations for the spectra that were measured at positions not far off the beam axis. However, this agreement between the measurements and the calculations is less further off the beam axis, in particular, those in which the detector was situated out of the path of the neutrons that arise directly from the target. The disagreements at these positions might lie in the choice of the default spectrum used in the unfolding, which will be investigated in detail in future work.

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