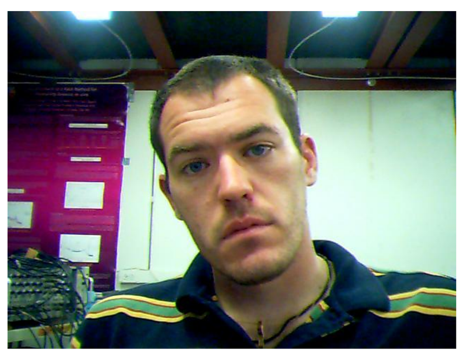
# Neutron Spectrometry and Dosimetry Results at McMaster KN Accelerator Using Bonner Sphere Spectrometer (BSS), Rotational Spectrometer (ROSPEC) and Cylindrical Nested Neutron Spectrometer (NNS)

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## Introduction

The neutron spectrometry measurements took place at the McMaster University KN Van de Graaf Accelerator using BSS **[1]**, NNS **[2]** and ROSPEC **[3]**. The instruments are depicted in Figures 1, 2 and 3 and described in corresponding references. Protons were accelerated onto thin $^{7}$LiF target, inducing the $^{7}$Li(p,n)$^{7}$Be threshold reaction. When protons impinge on a thin Li target it is expected that mono-energetic neutrons are produced. Depending on the target thickness, the energy spread of these neutrons can vary. For this particular case, a thin LiF target with a nominal thickness of 1 μm has been used. In theory, for this target thickness the energy spread of mono-energetic neutrons is approximately 6 keV at 2.3 MeV of proton energy. However, this value is considerably higher because of the resolution of the KN machine. It has been seen that the resolution of this machine is at least $\pm$10 keV **[4]**. Nevertheless, this combined energy spread is significantly smaller than the nominal resolution of all the spectrometric instruments used in this campaign. Therefore, it was expected that the thin target mono-energetic peak feature should appear in a single bin for all BSS, NNS and ROSPEC.

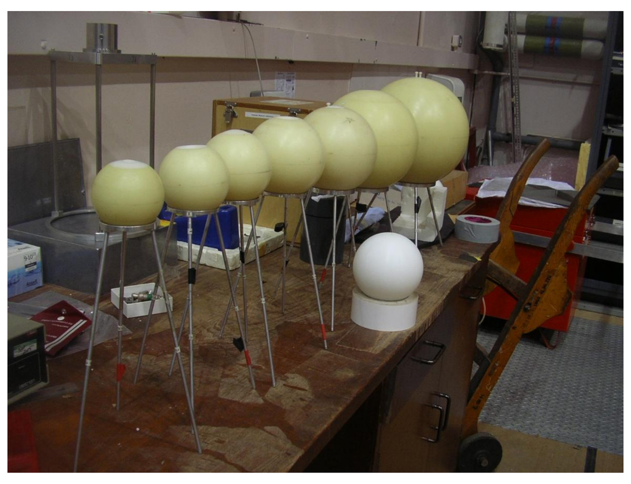

**Figure 1.** Bonner Sphere Spectrometer (**BSS**)

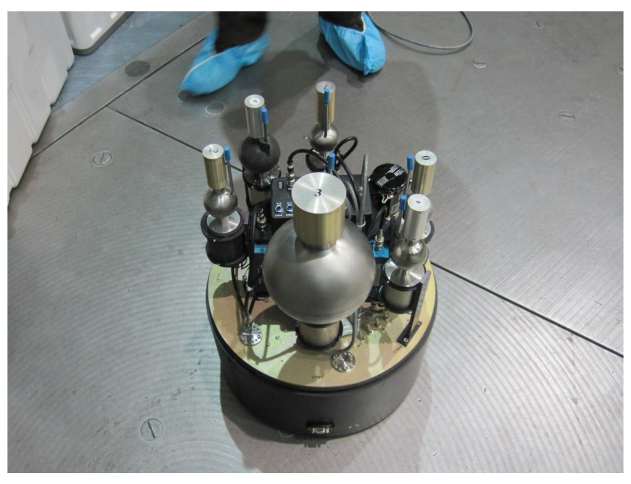

**Figure 2.** Rotational Spectrometer (**ROSPEC**)

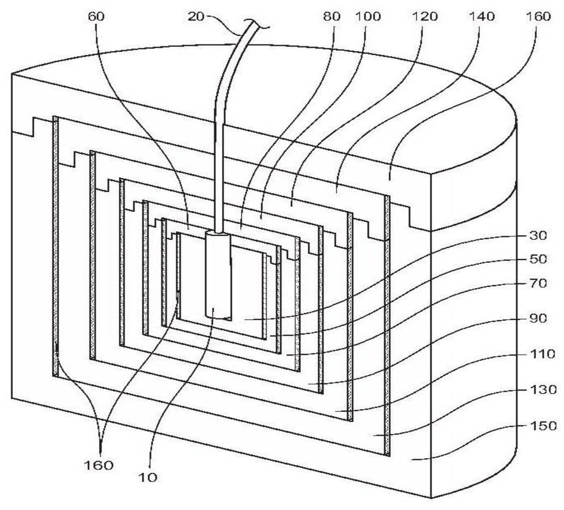



**Figure 3.** Cylindrical Nested Neutron Spectrometer (**NNS**)

## Materials and Methods

The measurements were performed 1 m away from the thin LiF target assembly. The nominal proton incoming energies were: 2.2, 2.3, 2.4 and 2.5 MeV. However, it was calculated elsewhere **[5]** that effective proton energies corresponding to the above mentioned nominal energies are: 2.15, 2.24, 2.34 and 2.44 MeV, respectively.

Finally, neutron energies corresponding to the effective proton energies are: 401, 511, 620 and 720 keV, respectively. The unfolded neutron fluence rates were then folded with different dose conversion coefficients in order to obtain dosimetric information for the characterized fields. The measurements were taken on two occasions: March and August 2011. In March 2011 (designated as measurement 1), NNS and ROSPEC were used at all four effective proton energies. In August 2011 (designated as measurement 2), BSS and ROSPEC were used at all effective proton energies, while NNS measurements were repeated at 2.3 and 2.5 MeV, only. This work contains all measurements.

## Results

The neutron fluence and dosimetry results are given in graphical and tabular forms. The analysis was performed for three energy ranges: thermal to 1 eV; 1 eV to 50 keV; and 50 keV to the end of the neutron spectrum. All the results were normalized to the time integrated proton current on deposited on the target (proton charge in μC).

### ROSPEC Results

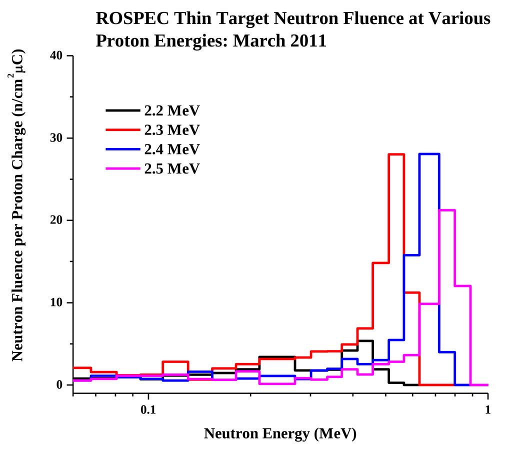



**Figure 4.** ROSPEC neutron spectra obtained in March 2011

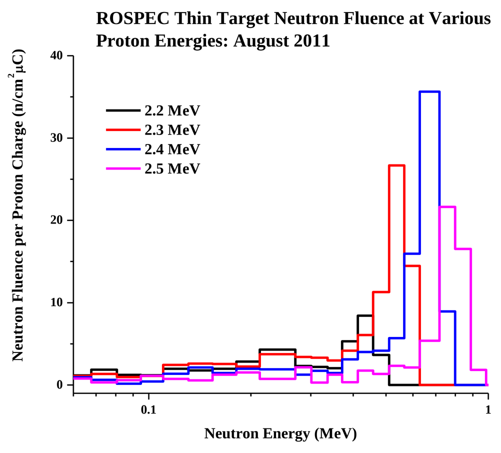



**Figure 5.** ROSPEC neutron spectra obtained in August 2011

| | | 2.2 MeV | | 2.3 MeV | | 2.4 MeV | | 2.5 MeV | |
|---|---|---|---|---|---|---|---|---|---|
| | | ROSPEC 2 | ROSPEC 1 | ROSPEC 2 | ROSPEC 1 | ROSPEC 2 | ROSPEC 1 | ROSPEC 2 | ROSPEC 1 |
| KERMA | Therm-1 eV | 2.31E-08 | 1.95E-08 | 3.49E-08 | 3.24E-08 | 2.64E-08 | 1.92E-08 | 2.06E-08 | 1.69E-08 |
| (mrad/μC) | 1 eV-50 keV | 2.12E-06 | 1.55E-06 | 2.44E-06 | 2.73E-06 | 1.93E-06 | 1.15E-06 | 1.36E-06 | 1.15E-06 |
| | 50 keV-end | 5.04E-05 | 3.56E-05 | 1.31E-04 | 1.37E-04 | 1.54E-04 | 1.22E-04 | 1.15E-04 | 1.14E-04 |
| | **TOTAL** | **5.25E-05** | **3.71E-05** | **1.33E-04** | **1.40E-04** | **1.56E-04** | **1.24E-04** | **1.17E-04** | **1.16E-04** |
| NCRP-38 | Therm-1 eV | 2.09E-06 | 1.76E-06 | 3.15E-06 | 2.93E-06 | 2.39E-06 | 1.74E-06 | 1.86E-06 | 1.53E-06 |
| (mrem/μC) | 1 eV-50 keV | 2.65E-05 | 1.97E-05 | 3.15E-05 | 3.23E-05 | 2.46E-05 | 1.46E-05 | 1.68E-05 | 1.48E-05 |
| | 50 keV-end | 6.76E-04 | 4.79E-04 | 1.97E-03 | 2.05E-03 | 2.45E-03 | 1.95E-03 | 1.86E-03 | 1.84E-03 |
| | **TOTAL** | **7.05E-04** | **5.00E-04** | **2.00E-03** | **2.09E-03** | **2.48E-03** | **1.96E-03** | **1.88E-03** | **1.86E-03** |
| ICRP-74 | Therm-1 eV | 2.06E-06 | 1.74E-06 | 3.11E-06 | 2.89E-06 | 2.36E-06 | 1.71E-06 | 1.84E-06 | 1.51E-06 |
| (mrem/μC) | 1 eV-50 keV | 3.07E-05 | 2.27E-05 | 3.62E-05 | 3.78E-05 | 2.84E-05 | 1.69E-05 | 1.95E-05 | 1.70E-05 |
| | 50 keV-end | 9.07E-04 | 6.43E-04 | 2.51E-03 | 2.62E-03 | 2.98E-03 | 2.37E-03 | 2.19E-03 | 2.18E-03 |
| | **TOTAL** | **9.40E-04** | **6.68E-04** | **2.55E-03** | **2.66E-03** | **3.01E-03** | **2.39E-03** | **2.21E-03** | **2.20E-03** |
| Mean Neutron Energy (keV) | | **205.1** | **201.3** | **338.2** | **342.2** | **462.0** | **473.6** | **543.6** | **531.2** |
| Neutron | Therm-1 eV | 1.8 | 1.6 | 2.8 | 2.6 | 2.1 | 1.5 | 1.6 | 1.4 |
| Fluence | 1 eV-50 keV | 17.9 | 13.4 | 21.7 | 20.8 | 16.8 | 10.1 | 11.2 | 10.2 |
| (n/cm$^2$/μC) | 50 keV-end | 42.3 | 29.7 | 90.6 | 94.8 | 93.0 | 74.6 | 64.7 | 65.8 |
| | **TOTAL** | **62.0** | **44.7** | **115.1** | **118.2** | **112.0** | **86.2** | **77.6** | **77.3** |

**Table 1.** ROSPEC results

### BSS & NNS Results

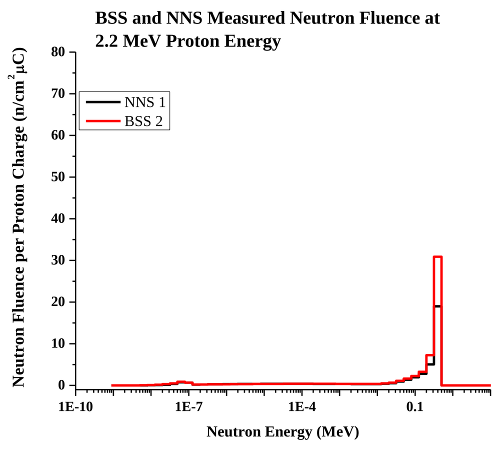



**Figure 7.** BSS & NNS spectra at 2.2 MeV

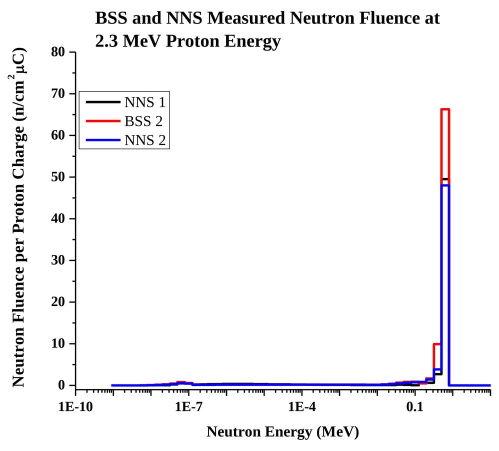



**Figure 8.** BSS & NNS spectra at 2.3 MeV

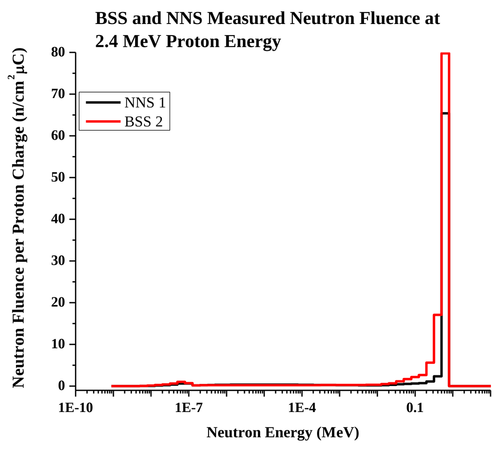



**Figure 9.** BSS & NNS spectra at 2.4 MeV

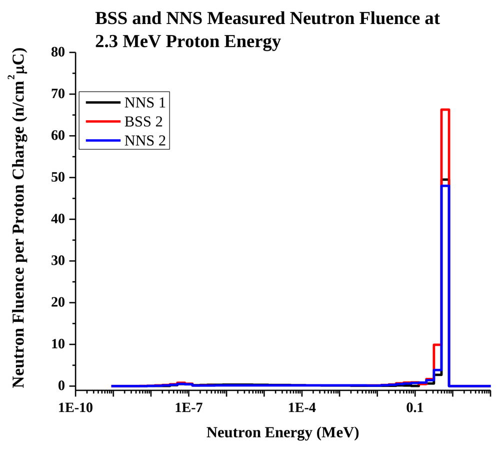



**Figure 10.** BSS & NNS spectra at 2.5 MeV

| | | 2.2 MeV | | 2.3 MeV | | | 2.4 MeV | | 2.5 MeV | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | NNS1 | BSS2 | NNS1 | NNS2 | BSS2 | NNS1 | BSS2 | NNS1 | NNS2 | BSS2 |
| KERMA | Therm-1 eV | 4.17E-08 | 5.50E-08 | 5.73E-08 | 6.33E-08 | 7.99E-08 | 4.33E-08 | 6.24E-08 | 3.29E-08 | 3.37E-08 | 4.80E-08 |
| (mrad/μC) | 1 eV-50 keV | 6.22E-07 | 7.49E-07 | 1.03E-06 | 9.56E-07 | 1.24E-06 | 3.38E-07 | 7.33E-07 | 1.47E-07 | 3.36E-07 | 4.35E-07 |
| | 50 keV-end | 3.72E-05 | 5.76E-05 | 1.10E-04 | 1.37E-04 | 1.79E-04 | 1.25E-04 | 1.80E-04 | 9.51E-05 | 9.59E-05 | 1.38E-04 |
| | **TOTAL** | **3.79E-05** | **5.84E-05** | **1.11E-04** | **1.38E-04** | **1.81E-04** | **1.25E-04** | **1.81E-04** | **9.53E-05** | **9.62E-05** | **1.39E-04** |
| NCRP-38 | Therm-1 eV | 3.69E-06 | 4.39E-06 | 4.51E-06 | 4.94E-06 | 5.82E-06 | 3.77E-06 | 4.64E-06 | 3.26E-06 | 2.70E-06 | 3.63E-06 |
| (mrem/μC) | 1 eV-50 keV | 1.30E-05 | 1.40E-05 | 1.71E-05 | 1.62E-05 | 1.87E-05 | 9.59E-06 | 1.14E-05 | 6.24E-06 | 6.73E-06 | 7.51E-06 |
| | 50 keV-end | 5.27E-04 | 8.23E-04 | 1.69E-03 | 2.14E-03 | 2.78E-03 | 2.03E-03 | 2.87E-03 | 1.55E-03 | 1.55E-03 | 2.23E-03 |
| | **TOTAL** | **5.44E-04** | **8.42E-04** | **1.71E-03** | **2.16E-03** | **2.80E-03** | **2.04E-03** | **2.89E-03** | **1.56E-03** | **1.56E-03** | **2.24E-03** |
| ICRP-74 | Therm-1 eV | 4.28E-06 | 5.00E-06 | 5.12E-06 | 5.61E-06 | 6.52E-06 | 4.33E-06 | 5.23E-06 | 3.81E-06 | 3.08E-06 | 4.11E-06 |
| (mrem/μC) | 1 eV-50 keV | 1.22E-05 | 1.33E-05 | 1.65E-05 | 1.55E-05 | 1.82E-05 | 8.83E-06 | 1.11E-05 | 5.71E-06 | 6.36E-06 | 7.23E-06 |
| | 50 keV-end | 7.04E-04 | 1.10E-03 | 2.10E-03 | 2.63E-03 | 3.44E-03 | 2.43E-03 | 3.49E-03 | 1.85E-03 | 1.86E-03 | 2.68E-03 |
| | **TOTAL** | **7.21E-04** | **1.11E-03** | **2.13E-03** | **2.65E-03** | **3.46E-03** | **2.44E-03** | **3.51E-03** | **1.86E-03** | **1.87E-03** | **2.70E-03** |
| Mean Neutron Energy (keV) | TOTAL | **223.7** | **253.3** | **371.8** | **419.4** | **413.2** | **523.5** | **490.1** | **529.2** | **515.7** | **523.0** |
| Neutron | Therm-1 eV | 3.5 | 4.2 | 4.3 | 4.7 | 5.6 | 3.5 | 4.4 | 3.0 | 2.6 | 3.5 |
| Fluence | 1 eV-50 keV | 9.4 | 9.9 | 11.7 | 11.1 | 12.3 | 7.2 | 7.6 | 4.9 | 4.8 | 5.2 |
| (n/cm$^2$/μC) | 50 keV-end | 30.2 | 45.4 | 75.3 | 88.3 | 118.2 | 70.8 | 109.1 | 53.6 | 55.6 | 80.2 |
| | **TOTAL** | **43.1** | **59.5** | **91.3** | **104.1** | **136.1** | **81.6** | **121.2** | **61.5** | **62.9** | **88.9** |

**Table 2.** BSS and NNS results

## Discussion

ROSPEC results are separated from BSS and NNS results because of the markedly different energy binning. Compared to BSS and NNS, ROSPEC has significantly better energy resolution, especially beyond 50 keV. However, direct comparison of all three instruments can be done using appropriate values in Tables 1 and 2. Furthermore, comparison of the repeated ROSPEC measurements can be done by considering values from Table 1. Likewise, comparison of the repeated NNS measurements at 2.3 and 2.5 MeV can be done by considering values from Table 2.

Observing Table 1, we can see almost perfect agreement in ROSPEC measurements in two cases: at 2.3 and 2.5 MeV, while slightly different results were seen at 2.2 and 2.4 MeV. This suggests a problem of non constant neutron yield per proton charge collected on LiF target. Obviously, this problem occurred at 2.2 and 2.4 MeV, but not at 2.3 and 2.5 MeV. The same problem is additionally confirmed by NNS system. From Table 2, we see a perfect agreement between repeated measurements at 2.5 MeV, while there's a ~15% discrepancy at 2.3 MeV. In both ROSPEC and NNS case, the higher neutron yield per time integrated proton current has been seen in August 2011 measurements. The neutron yield is a chronic problem of this particular KN accelerator and it has been confirmed on several occasions. One of the immediate remedies to this problem will be a presence of a fixed neutron monitor, which will be the measure of the neutron yield change, and can also be used as an overall normalization tool.

On the other hand, when comparing different instruments, we see a very good agreement between NNS and ROSPEC results. However, we also observe slightly higher numbers obtained by the BSS system. This trend is evident for every proton energy. This is due to the fact that the BSS system over-responds, i.e. its response functions values are smaller than they should be, and appropriate corrections have to be applied. The over-response of the AECL BSS system has been confirmed on many occasions.

## Conclusion

The results obtained in this neutron metrology campaign are reasonable and in a good agreement. The source of discrepancies between the BSS and the other two instruments were identified as over-responding of the BSS system. The other source of discrepancies within the same instruments, corresponding to repeated measurements has been identified as a non-constant neutron yield per collected proton charge. Both issues will be resolved, as outlined in the previous section.

## References


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