Evaluation of Compton Camera Imaging during Boron Neutron Capture Therapy

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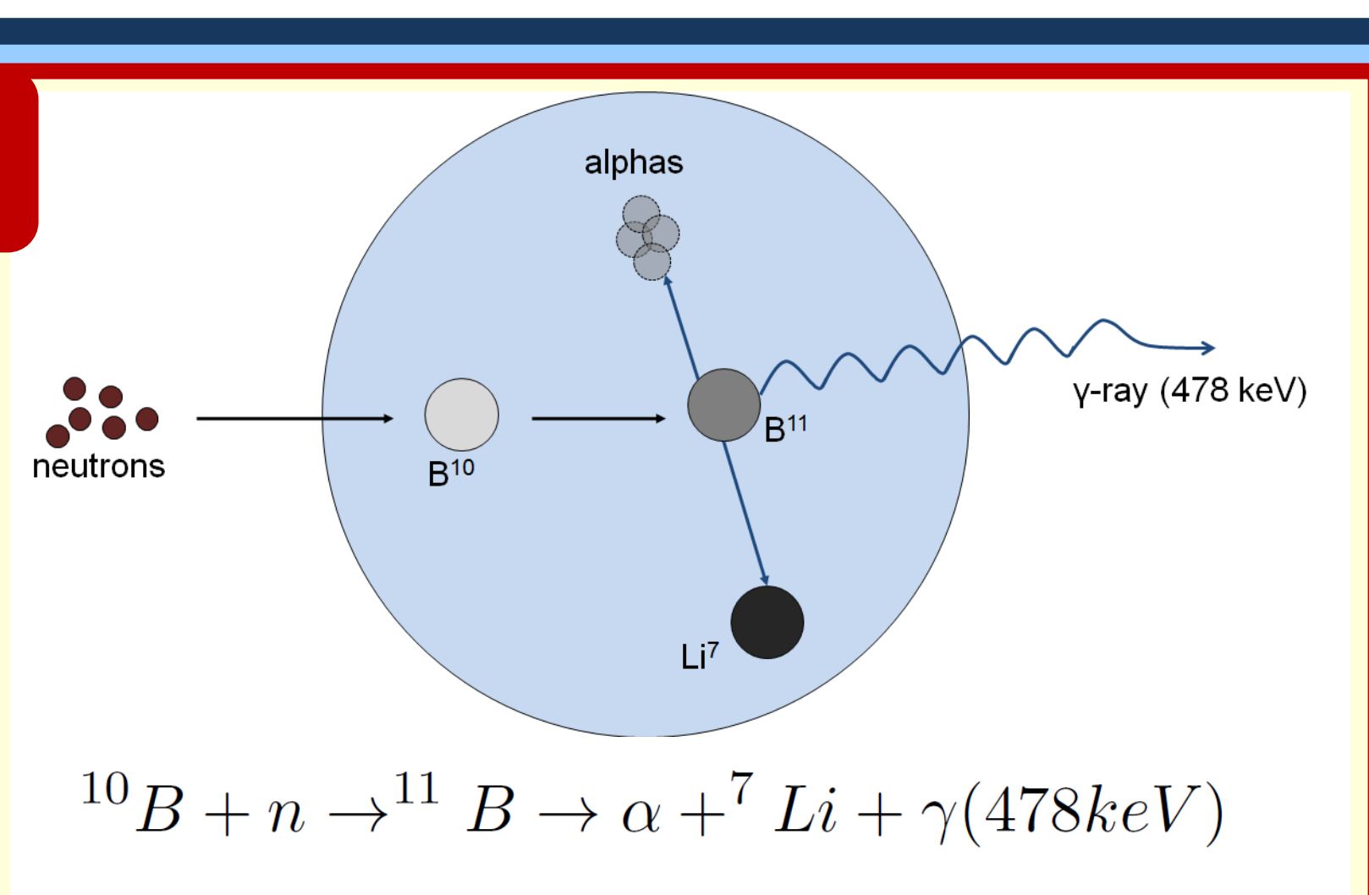
Abstract

Boron Neutron Capture Therapy (BNCT) is an advanced dual approach to treating cancer in humans. In BNCT a non-toxic boron-containing compound is intravenously injected into the patient and accumulates in the tumour to be treated. A beam of low-energy neutrons is then directed at the tumour containing the boron compound. In the tumour, the boron (^{10}B) atoms capture the neutrons and split into two new atoms. This releases locally high energy that kills the tumour cell and is usually accompanied by the release of γ-rays. This project evaluated the feasibility of using a Compton camera detector system to analyse this γ-radiation to produce an image of the region being treated. It has been shown that spectroscopy of ^{10}B is possible, but the image reconstruction is not efficient for small volumes in the short time period required for clinical treatment. The simulations have to be experimentally validated and further Monte-Carlo simulations would be recommended.

Boron Neutron Capture Thearpy

In BNCT, the patient is given an intravenous injection of a boron-containing chemical, that preferentially binds to tumour cells. The typical concentration of ^{10}B is about 15 µg/g in blood/brain and 52.5 µg/g in a tumor. After the injection, the patient is exposed to a thermal neutron beam. The ^{10}B captures the neutrons and splits into an alpha particle and a lithium-7 nucleus, releasing a ***478 keV*** γ-ray. The two new atoms cause damage to the tumour, while healthy tissue is largely spared.



$$^{10}B + n \rightarrow ^{11}B \rightarrow \alpha + ^{7}Li + \gamma(478keV)$$

Figure 1: The process during BNCT.

Radiation Interaction

The three main interaction mechanisms of radiation with matter are *photoelectric absorption*, *Compton scattering* and *pair production*.

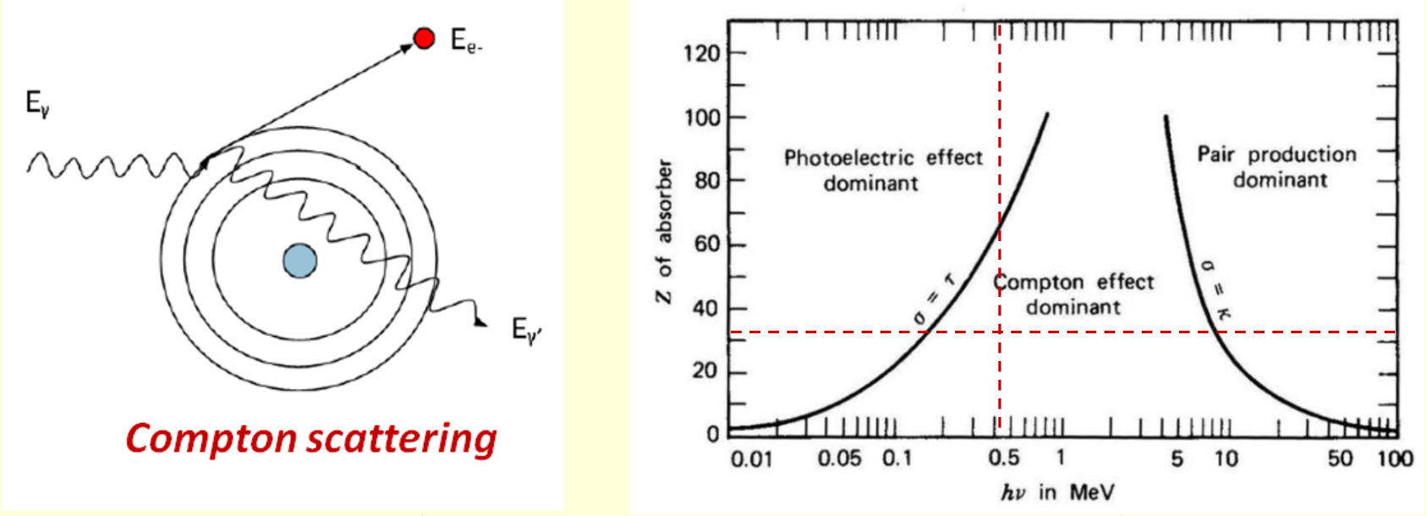


Figure 2: Illustration of Compton scattering and domination of the mechanisms in terms of Z. Germanium (Z=32) good detector material as Compton scattering dominates at 478 keV.

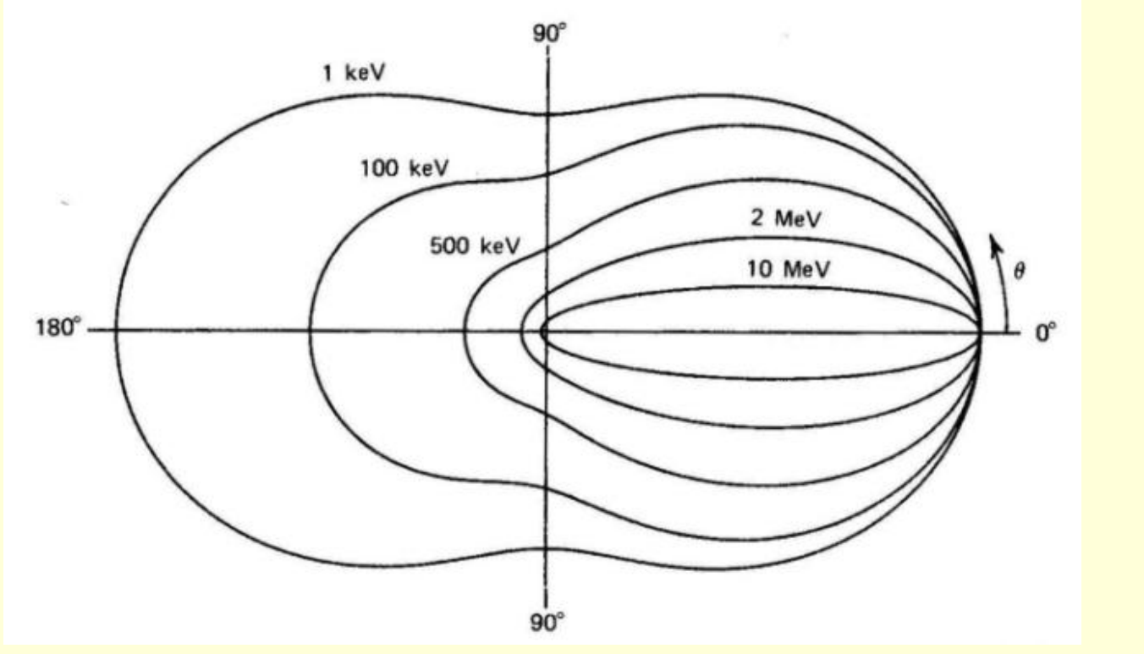
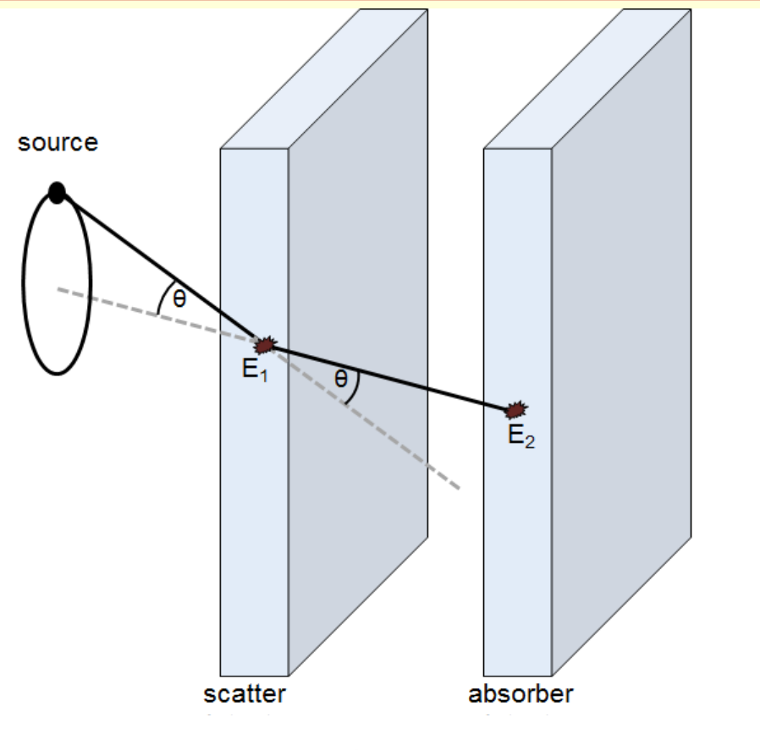


Figure 3: The angular distribution of scattered γ-rays is given by the Klein-Nishina formula for the differential cross section. The plot shows that at higher energies, forward scattering dominates. This suggest that the two Compton camera detectors should be placed behind each other.

Compton Camera

Compton cameras are used for source imaging based on Compton scattering kinematics. The system consists of at least two detectors; ***scatter*** and ***absorber***. The incident γ-ray, with an initial energy E_0, loses energy in the first detector via Compton scattering before being fully absorbed in the second detector. The Compton scattering formula is used to calculate the angle between the incident and the scattered photon. This angle is the vertex angle of the cone shown in Figure 4. The possible origins of the incident γ-ray lie somewhere on the perimeter of this cone. Images are created by overlapping cones from many interactions. The two factors that influence the quality of the image are the energy resolution and the position sensitivity.



$$E_1 = \frac{1}{1 + \frac{E_0}{m_e c^2}(1 - cos\theta)}$$

Figure 4: Setup of a Compton camera syststem with two detectors and the Compton scattering formula.

GAMOS Simulations

To investigate the feasibilty of using a Compton camera system during BNCT, simulations were performed with GAMOS. GAMOS is a GEANT4-based framework primarily developed for the use in medical physics that makes use of Monte-Carlo techniques in C++ language.

A Compton camera system with two germanium detectors and an isotropic point source emitting 478keV γ-rays were simulated in GAMOS. 25 simulations were performed for different source positions. Figure 6(a) shows the investigated 10cm x 10cm grid with each dot representing a position of the point source. The colour intensity plot (Figure 6(b)) shows a typical reconstructed image of the source and Figure 6(c) shows the projection in the x-direction. The peak is Gaussian fitted on a quadratic background. Figure 6(b, c) were created with 20,990 cones, with 70,000,000 γ-rays being emitted by the source.

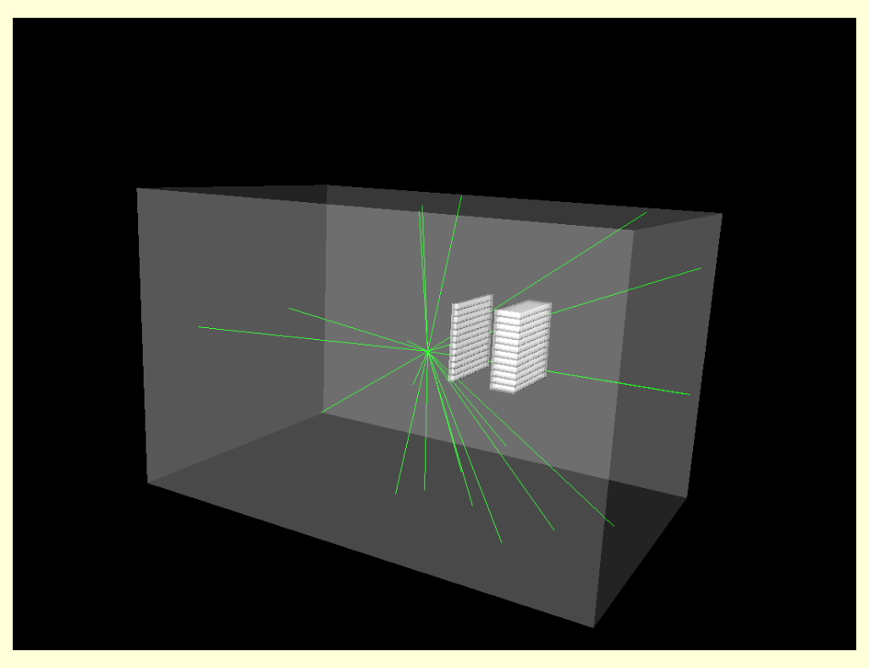


Figure 5: This is a snapshot of the Compton camera setup. The detecotrs are placed behind each other. The γ-rays are displayed in green.

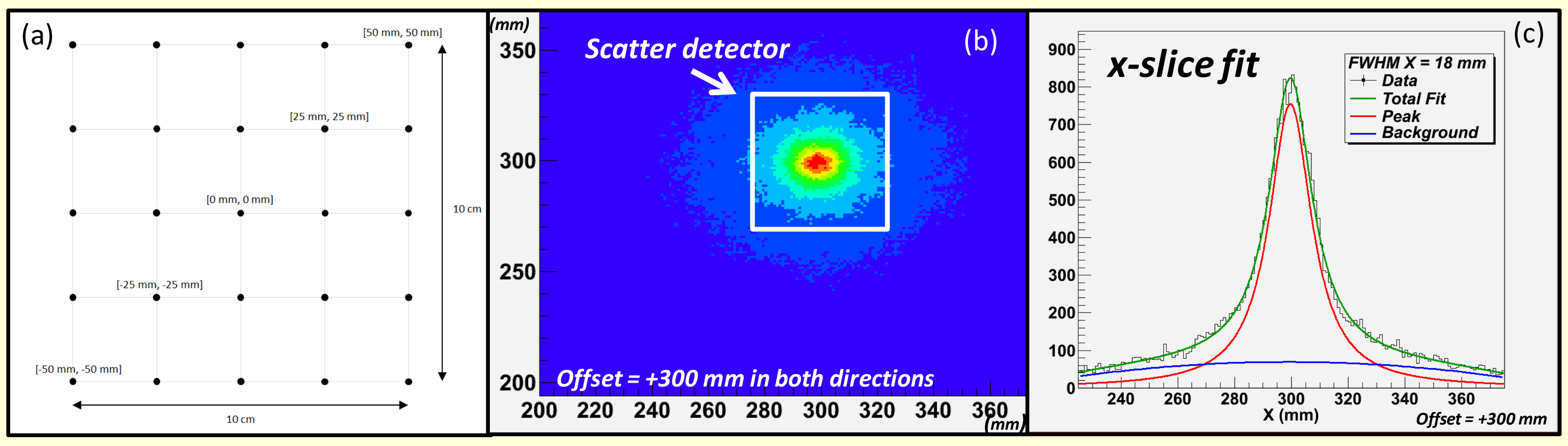


Figure 6: (a) shows the 10cm x 10cm grid being investigated, (b) shows the typical reconstruction of a source by overlapping cones at the [0mm,0mm] and (c) shows the fit of this image. A Gaussian peak is fitted on a quadratic background.

As the source moves further away from the origin, the number of cones decreases (Figure 7(a)). Figure 7(b) shows that the further the point source is moved from the origin, the greater the difference between the reconstructed and actual position of the source. On average, 173keV is deposited in the scatter detector, and the remaining 305keV is absorbed in the second detector. The matrix in Figure 8 shows the energy deposited in the scatter detector against energy deposited in the absorber detector. When the source is moved from the [0mm,0mm] position to the [50mm,50mm] position, the energy deposited in the scatter detector increases

→ ***solid angle effect***

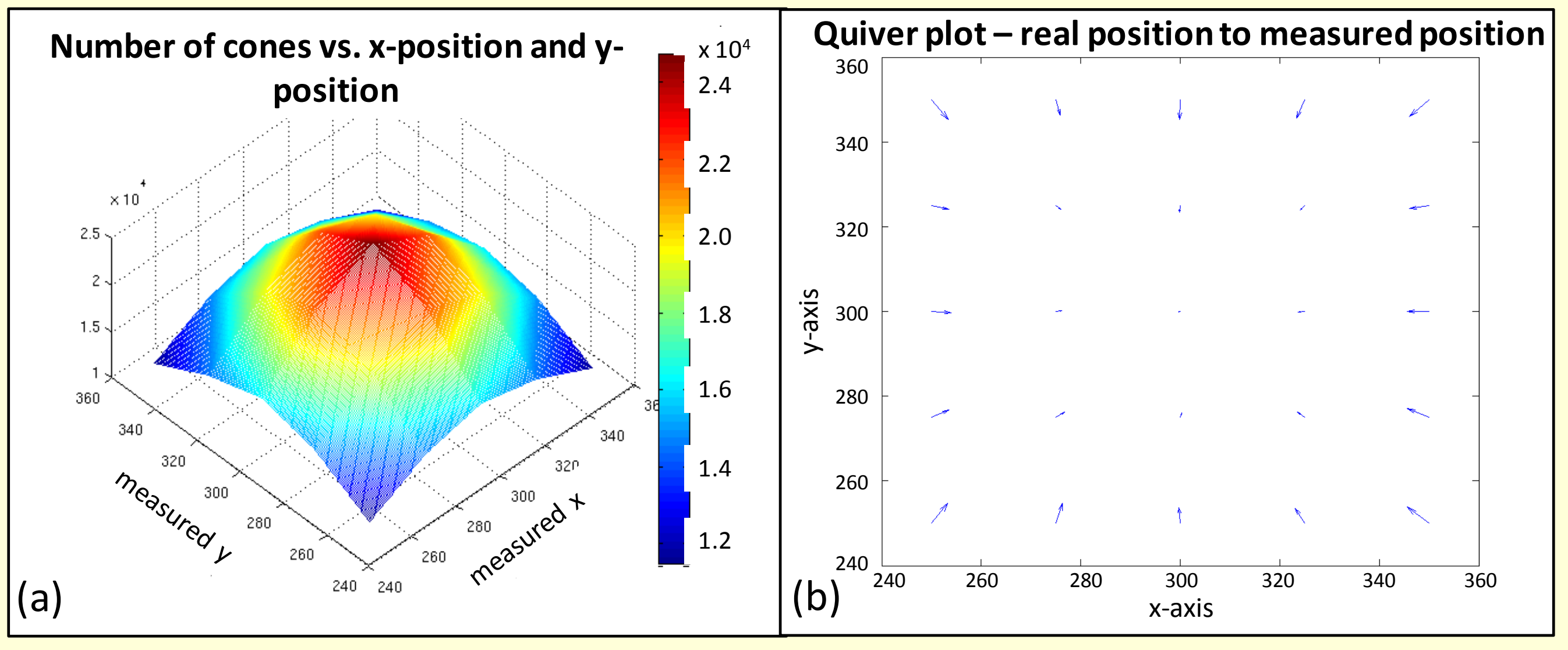


Figure 7: (a) shows the number of cones used tor the image reconstruction against the x-position and y-position of the source as an colour intensity chart (b) shows a quiverplot with the arrows pointing from the real to the measured position of the source.

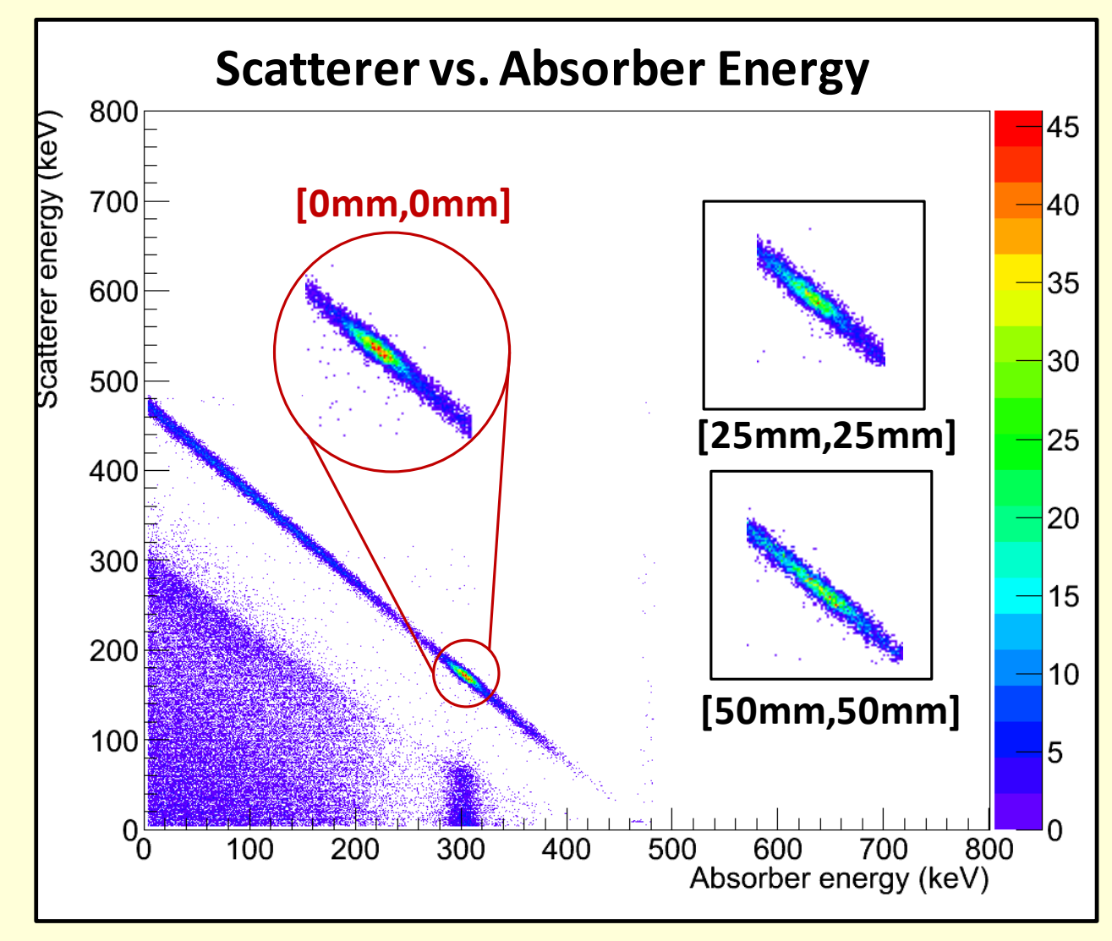


Figure 8: This matrix shows the energy deposited in the scatter detector against the energy deposited in the absorber detector.

Various simulations were performed with GAMOS to optimise the Compton camera setup. The ideal thickness of the scatter detector was found to be around 10mm, and another simulation suggested that a combined thickness of 90mm for both detectors was required for the full absorption of the 478keV γ-rays. With an ideal set up and multiple interactions taken into account, the number of incident γ-rays can be lowered to 100,000 giving approximately 100 cones, which is sufficient to reconstruct an image.

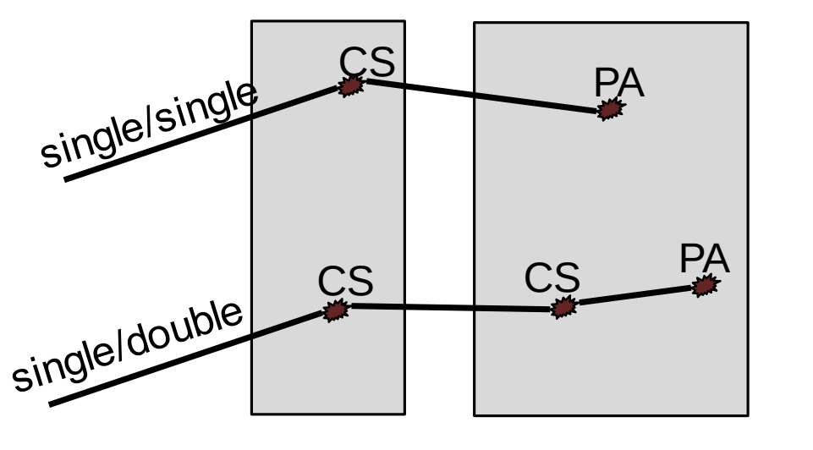
Why are so few cones used for reconstruction?

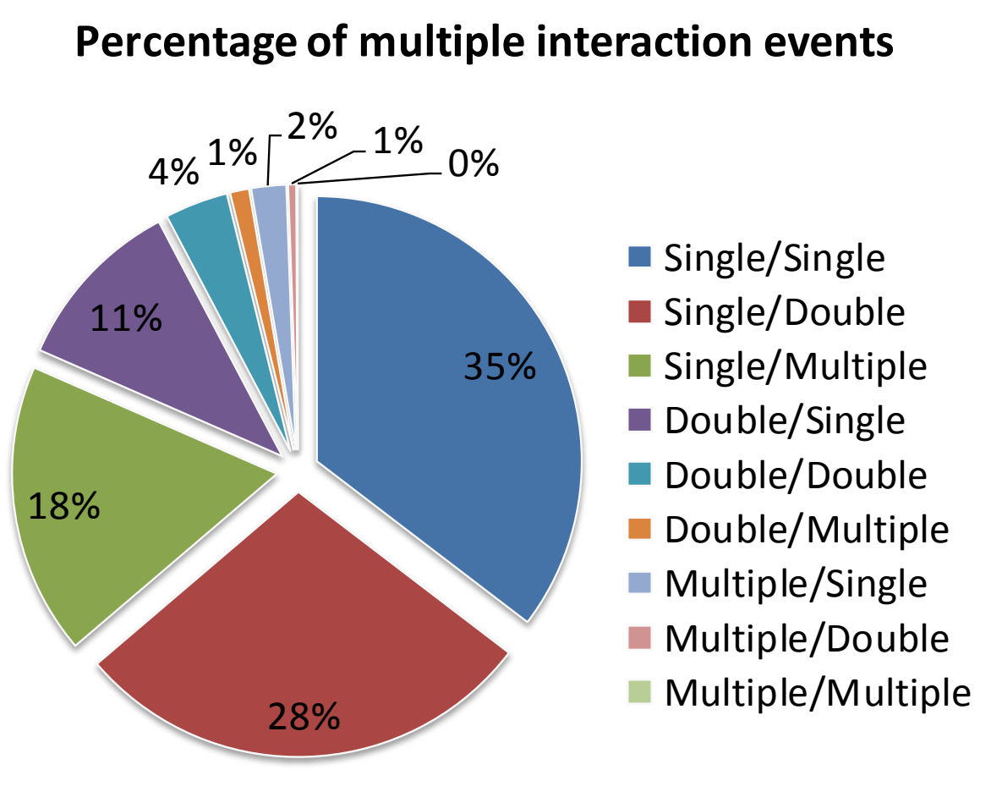
70.000.000 γ-rays → 20.990 cones used for reconstruction ([0mm,0mm] position, only single/single events counted)

- Solid angle source-scatter detector~ ***7,000,000***
- Attenuation in detector~ ***4,500,000***
- Scattering out of the system~ **1,000,000**
- Multiple interactions in both detectors~ ***350,000***
- Solid angle scatter–absorber detector~ ***100,000***
- Scattering out of absorber~ ***20,000***

Event classification in GAMOS

GAMOS classifies different events according to the interactions in the detectors.





Boron Spectroscopy And Neutron Detection

An experiment was set up to investigate the number of counts in the boron peak and to estimate the number of thermal neutrons, when a boron containing material is exposed to a neutron source. Figure 9 shows the experimental set-up in the neutron lab. An ***Am/Be neutron source*** (10^6 n/s) is placed in a ***H_20-filled tank*** and can be either in the thermal or high energy position. Various sized ***CH_2 sheets with 5% ^{10}B*** are exposed in front of the source. A ***germanium detector*** (Ge) is placed next to the tank to collect the γ-ray spectra and the ***helium-3 detector*** (He-3) collects the neutron spectra.

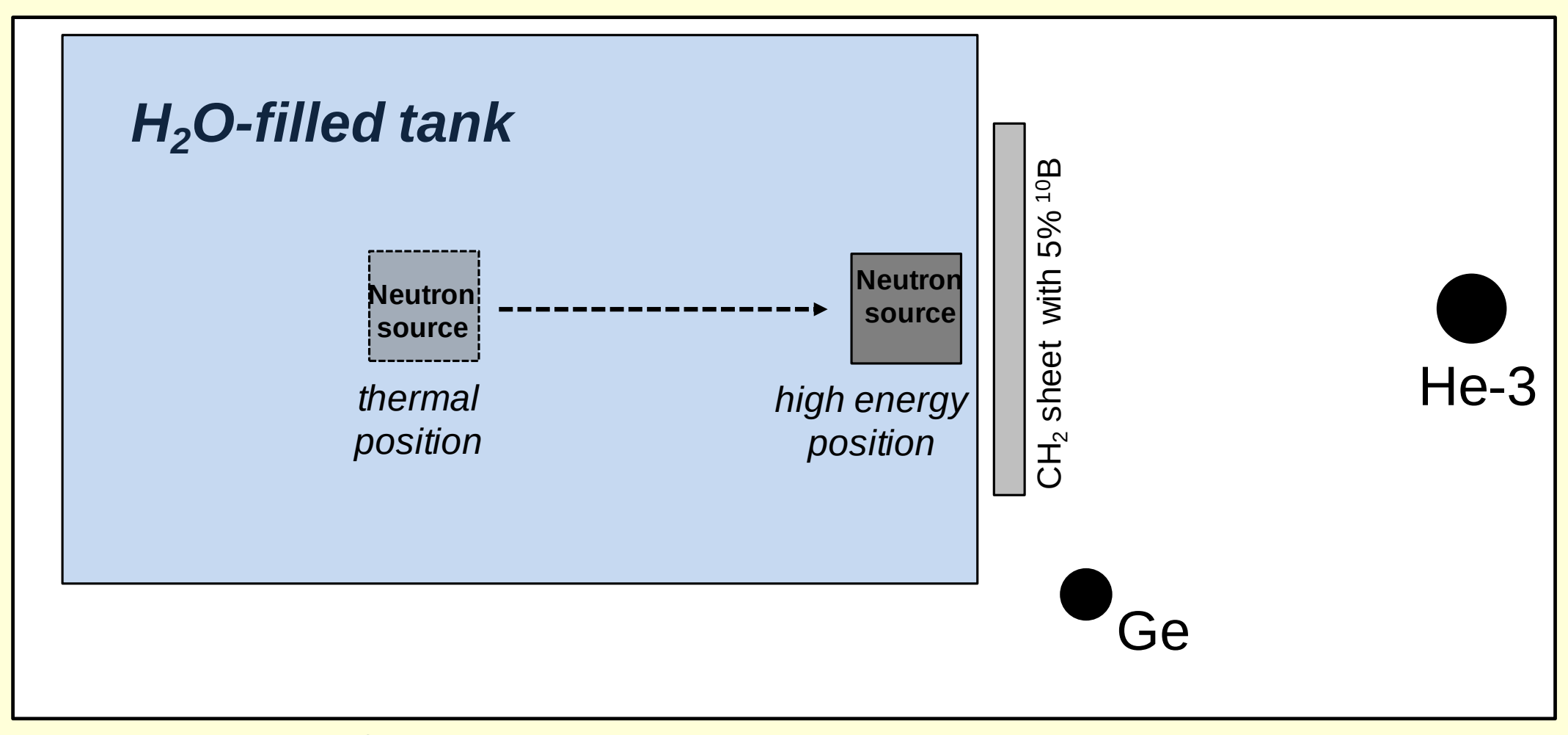


Figure 9: Illustration of the experimental setup in the T4 laboratory in the Chadwick building.

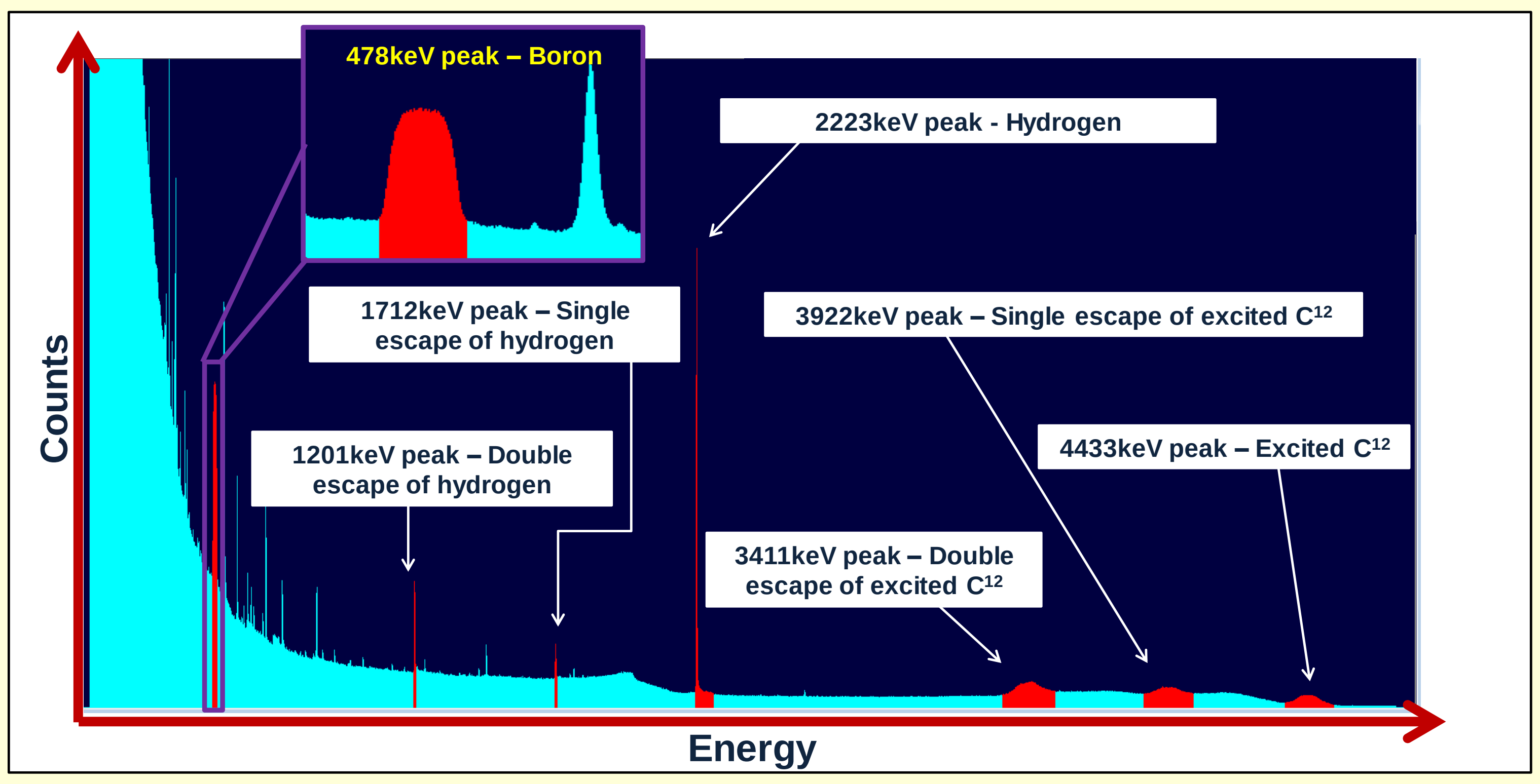


Figure 10: This is a typical germanium spectrum. The boron peak at 478keV and the hydrogen peak at 2223keV (and its single and double escape peaks) are clearly visible. At the higher end of the spectrum, the broad peak of excited C^{12} at 4433keV and its single and double escape peaks can be identfied. The boron peak is Doppler broadend, which is caused by the decay of neutron captured ^{10}B.

Boron peak

The number of counts increases in the boron peak, as the CH_2-sheet with 5% ^{10}B size is increased → more ^{10}B leads to more neutron capture and therefore the release of more 478keV γ-rays. More counts in the boron peak are recorded in the high energy position, as the solid angle between source and sheet is significantly smaller in the low energy position.

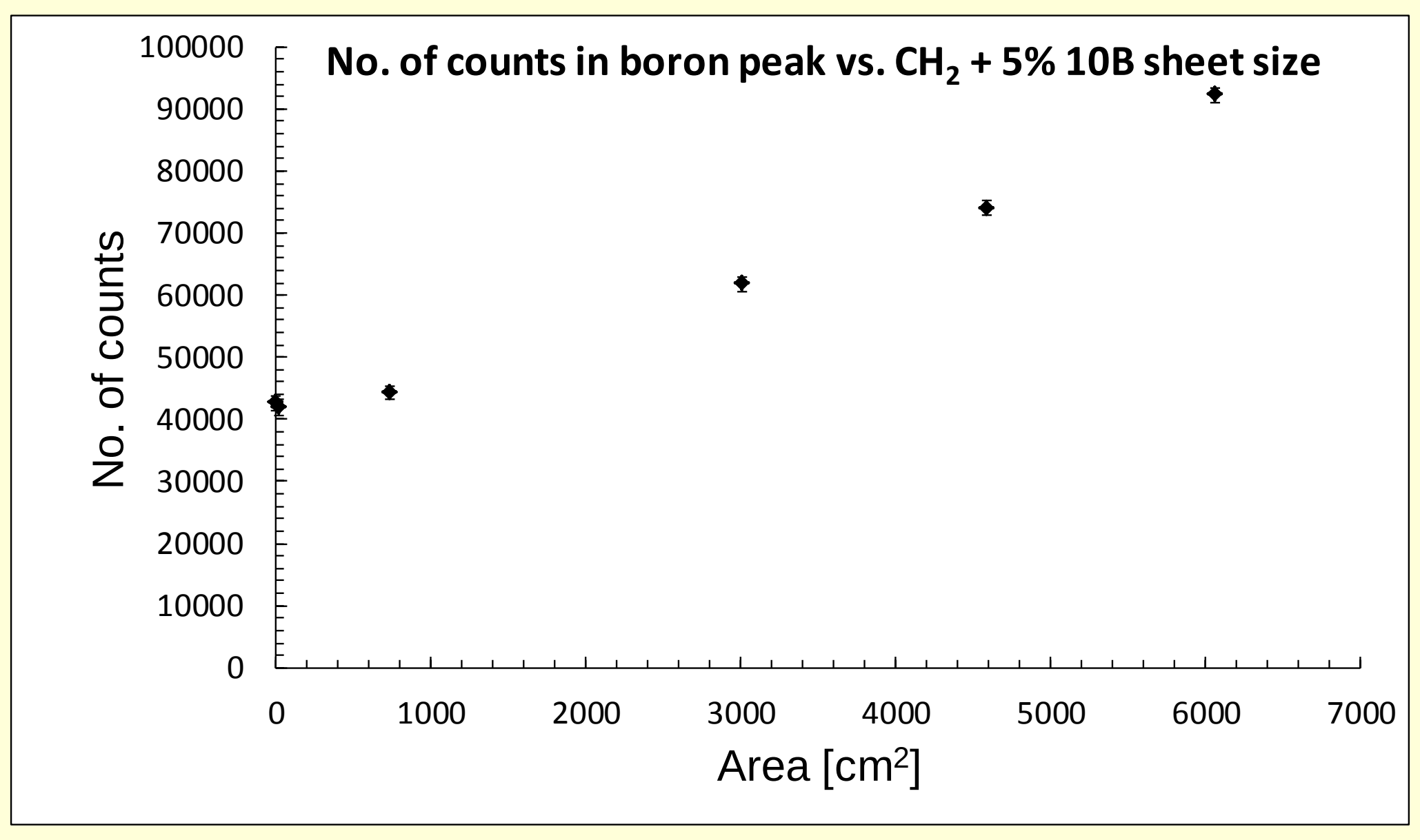


Figure 11: This plot shows the number of counts in the boron peak against the size of the CH_2 sheet with 5% ^{10}B concentration.

Number of neutrons

The helium-3 detector is used for the neutron detection. A typical spectrum is shown in figure 12, which has to be integrated (whole spectrum) to give the total number of neutrons per time interval. High energy position: ~3000 n/s; Low energy position: ~400 n/s (solid angle and water reduce the number of detected neutrons).

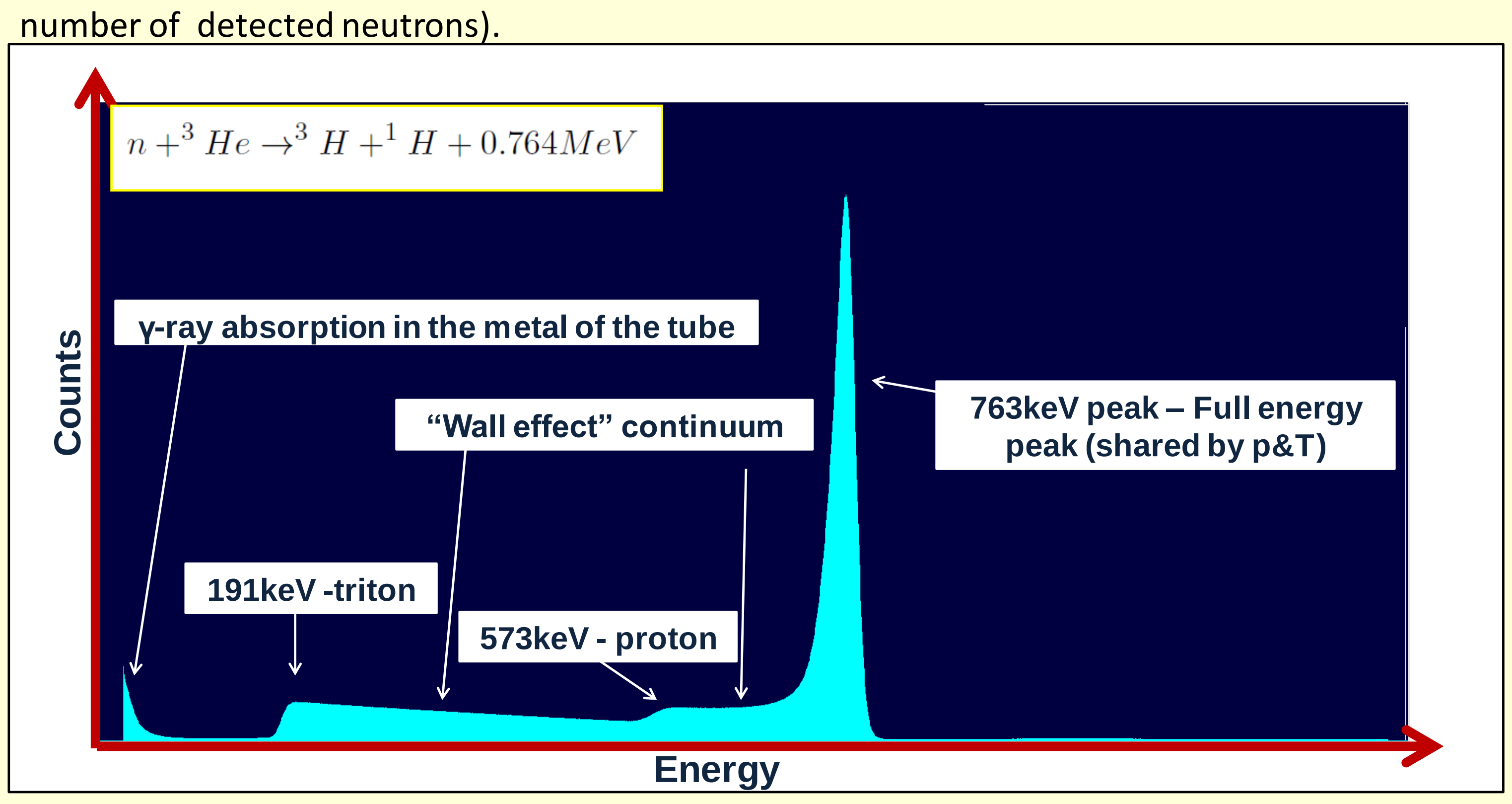


Figure 12: This is a typical helium spectrum. The triton peak at 191keV , proton peak at 573keV and the full energy peak at 763 keV (shared by triton and protium) can be clearly identified.

Conclusion and Outlook

This project has shown that spectroscopy in the boron peak is possible. The results of the GAMOS simulation and boron spectroscopy and neutron detection are combined to scale the number of counts in the boron peak for a realistic BNCT treatment case. Two main assumptions have to be made: Firstly, a 10^{12} n/s neutron beam generator will be used in Birmingham, which increases the number of neutrons per second by 10^9. This leads to greater ^{10}B capture in the target and hence an increase in released γ-rays. Secondly, during treatment, the germanium detector will be placed next to the patient, which significantly increases the solid angle. By taking these assumption into account, the number of counts can be increased from 17,288 in a 5cmx5cmx2.5cm (=62cm³) volume in the boron peak to 160,000,000 in 18h or from 0.2 counts/s to 1860 counts/s respectively. It has been shown that roughly 100,000 γ-rays are needed to create 100 cones, which is sufficient for a good image reconstruction. Hence, it would take 53s to collect enough γ-rays. However, the concentration of boron in the patient's body is significantly lower; 0.0052% in the tumour, compared to 5% in the CH_2-sheet. Therefore, it would take roughly 5,000s (about 1.5h) to collect enough counts in the 62cm³ volume. Furthermore, for a 1cm³ volume, which would be desirable during treatment, a total of around 100h would be required. Thus, in order for the Compton camera system to be viable in producing an image of the region being treated, a higher yield of cones for a given number of γ-rays will be required. This should be investigated in the future and the GAMOS simulations validated with an experiment.

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