Real Time Spectrometer for thermal neutrons from Radiotherapic Accelerators

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Outlines

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  • Currently used neutron detectors
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  • Detector and electronics description

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The Boron Neutron Capture Therapy

Boron Neutron Capture Therapy (BNCT) is an oncology radiotherapy treatment that exploits the capture of thermal neutrons by $^{10}\text{B}$ and the following emission of an $\alpha$ particle and a nucleus of $^7\text{Li}$.

$$\text{n} + ^{10}\text{B} \rightarrow \alpha + ^7\text{Li} + 2.972 \text{ Mev}$$

- Boron is delivered mainly to tumoral cells; specific drugs are being developed for this purpose.
- $^{10}\text{B}$ thermal neutron cross section is $10^3 - 10^4$ times greater than body tissue one.
- Short range (<10$\mu$m) and high Linear Energy Transfer (LET)

A real hope for some kinds of tumors like extended tumors (lung, liver, pancreas, skin) or tumors located in particular positions (brain).
The BNCT with wide-spread Radiotherapy accelerators: the PHONES project
A big issue for the BNCT is the need of a nuclear reactor providing a suitable thermal neutron flux. The aim of the PHONES project is to provide a competitive thermal neutron source using clinical radiotherapy linacs.

- High energy photons (>10 MeV) hit an high Z target
- Fast Neutrons are produced by Giant Dipole Resonance
- Neutrons are slowed down by moderating materials
- Neutron capture inside the device should be kept low
- With as low as possible residual gamma field

To obtain PHOton NEutron Source useful for medical purposes the following requirements have to be fulfilled:

- A thermal neutron flux greater than $10^8 \frac{n}{(cm^2 \times s)}$
- A fast neutron and gamma dose per thermal neutron lower than $2*10^{-12} \frac{(Sv \times cm^2)}{n}$
Different prototypes and simulations have been developed (2005-2006) for optimizing the following parameters:

- Photoconverter Lead thickness
- Moderator shape and thickness
- Moderator material ($D_2O$ vs. $H_2O$)

The first prototype of the PHONES photon to neutron converter faced to the Varian Clinac 1800 head at Sant'Anna Hospital - Como

Best PHONES converter results, so far:
Thermal neutron flux
$1.8 \times 10^7 \pm 1 \times 10^7 \frac{n}{(cm^2 \times s)}$

Fast neutron dose
$12 \times 10^{-12} \left(\frac{Sv \times cm^2}{n}\right)$

In this framework a development of neutron detection methods for direct and diffused dose evaluation is of primary importance.
Commercial Neutron detectors:

Bubble dosimeters
- Integral measure over time and energy
- Slow and not automatic readout
- Single shot (need hours to recovery)
- Poor spatial resolution

TLDs
- Integral measure over time and energy
- Slow readout
- Calibration needed
- Also sensitive to photons
- High dynamic range

$BF_3$ counters
- Real time readout
- Gas detector with almost fixed geometry (anode wire) and size
- High electronics dead time (shaper)

Material Activation
- Integral measure over time and energy
- A Ge or NaI detector nearby is needed. Usually one sample per time. Almost real time.
Can Boron loaded plastic scintillators with photomultiplier readout be successfully used?
Very difficult due to the high photon/neutron ratio

But the bunched particle emission suggests a different approach...

**Beam time structure (Varian Clinac 1800):**

Electrons (as well as secondary photons) are emitted in a 3-5 μs wide bunch at 50-150 Hz repetition rate (dose rate dependent).

It means up to tens of ms “empty” time between two following bunches.

In this time interval there are no more electrons nor photons in the environment, only neutrons survive. --> Low background for neutron detection. Of course our detector should be sensitive also to neutrons.

Bunch emission waveform obtained under the beam with a low gain scintillation detector
Plastic scintillators are sensitive to neutrons in a wide energy range:

Fast neutrons:
- neutron recoil on protons (mainly H atoms)
  - proton energy being limited by neutron one, this process can work with neutrons with energy > 0.5-1 MeV

For Slower neutrons we can take advantage of:

\[ ^1H(n,\gamma)^2H \]

\[ \sigma = 0.33 \text{ barn} \quad E = 2.2 \text{ MeV} \]

\[ \gamma \]

-> photon easy to detect (provided it stops in the sensitive volume)

Plastic scintillators are rich in Hydrogen:
- e.g. Hydrogen in polystyrene is 7% in mass and 50% in atom number

From Endef/Exfor database
A preliminary evaluation of our energy acceptance

Much geometry dependent; Suppose:
A bunch time width (jitters and detector dead time included) of 20 μs
A distance between the detector and neutron photo production region of 20 cm
The fastest neutrons the detector is able to see have an energy:

\[ 20\text{cm}/2*10^{-6}\text{s} = 10000 \text{ m/s} \approx 1.4 \text{ eV} \Rightarrow \text{ still in epithermal neutron range, but increase with the square of the distance} \]

the slowest neutron, supposing a 20ms interval between bunches:

\[ 20\text{cm}/20*10^{-3}\text{s} = 10 \text{ m/s} < 1\mu \text{ eV} \]

Estimate of the number of neutrons per bunch detected:

\[ \Phi \Delta T \sigma N \gamma \approx 250 \]

Where \( \Phi \) is the expected flux, \( \sigma \) the cross section evaluated at 2200 m/s, \( N \) the number of H atoms in the detector, \( \gamma \) the detector efficiency for 2.2MeV (3%, from Geant 3.2 simulations)
The detector:

- A polystyrene plastic scintillator 2x2x1cm³
- Primary scintillation fluorine p-Terphenyl (PTP) - 1% weight
- Secondary fluorine bis-MSB 0.01%

- Two 1” P30CW5 photomultipliers by Electron Tubes with integrated high voltage power supply facing the two opposite sides of the scintillator – to avoid dark counts and improve reliability. PMTs Voltage = 1230 V
signals on the oscilloscope (1 PMT, 50 Ohm)

- end of the Linac bunch
- detector recovery (from a $10^{11-12}$ particle bunch!) $\approx 15\mu$s
- spikes are signals from captured neutrons

Our detection system should be able to return the number of captured neutrons and their arrival time.
P.H. Information not used at the moment.

The read out electronics:
Signals from scintillator are digitized by a NIM discriminator, threshold 30mV
The coincidence between the two scintillators (width 200ns) is shifted to LVDS and then to sampler.
The read out electronics/2:

- Digital sampling done by one Altera Cyclone II FPGA
- Board developed by INFN-TS for VATAP2.1 asic digital read out.
- Analog section not used – sampling up to 4 LVDS inputs
- Sampling rate up to 640MHz
- 1 Mbit on-chip memory
- Parallel data transfer (8bit) to a VME I/O board
- SBS Bit3 bridge from VME bus to PC
- Trigger (on the bunch emission) given by the Linac itself

- For this measurements a 65536 bit shift-register has been implemented
- At 12.5MHz sampling frequency -> ≈ 5 ms wide acquisition gate
- Comparable dead time during data transfer to PC
• Output example: each '111' corresponds to an impinging neutron.
• For each experimental condition several bunches have been collected.
• Obtaining an arrival time profile:

- Detector at 16 cm from Linac head, no moderator
- Profile over 1000 Linac bunches ->
- ≈600 hit per bunch
- The total number of hit is, bunch per bunch, proportional to the neutron flux.
Comparison with Al activation method:
Al cylindric sample, 1cm radius, 0.5cm thickness
NaI 2”x2” detector from Saint-Gobain, Ortec spectroscopy chain, CAEN V785 ADC.
Correction for dead time.
Efficiency obtained from Geant Simulation

Capture cross section comparison:

- Both $\sigma$ show $1/v$ behavior
- $\sigma$ for Al 0.45 times smaller than the H one up to $2*10^3$ eV.
- Over $2*10^3$ eV $\sigma$ for Al is greater: integrated cross section from $2*10^3$ eV to $10^6$ eV: $47\text{eV}^*\text{barn (H)}$ vs. $880 \text{eV}^*\text{barn (Al)}$

From Endef/Exfor database
Comparison with Al activation method /2:

- different measurements have been taken varying the distance from the linac head
- flux on scintillator has been evaluated counting the number of detected neutrons in the sampling gate
- this number has been compared with neutron flux from Al activation
- a normalization is needed

good agreement up to 250 cm; for greater distances a bigger fraction of fast neutrons enters our gate

point at 90cm shows scintillator saturation

This distance corresponds to 1keV n entering the gate
Comparison with Al activation method /3:

The Neutron flux has been measured in different positions on the back side of the Phones Moderator (1\textsuperscript{st} prototype) and on-axis up to 160cm (point 8) normalized to position 5.

- overestimates the flux being sensitive to higher energy neutrons
- still follows flux variations

- Scintillator saturation
- sensitive to positioning errors
Comparison with BF$_3$ counter
A 62cmx5cm cylindrical BF$_3$ counter (Politecnico of Milan)
Discriminated signal from the counter sent to the same daq after shaping
BF$_3$ and scintillator in the same position.

- Profile over 1000 bunches
- Data has been normalized (different cross sections and sizes)
- Good agreement after 1.5 ms.
- Saturation effect for BF$_3$ (due to a 10$\mu$s shaping time) from .8 to 1.5 ms.
- Extreme BF$_3$ saturation soon after the bunch
The same validation has been repeated at different positions.
Towards the ToF

In principle the arrival time of a neutron depends on the speed (energy) and the path, but:
- absolutely no point-like source
- moderator thickness and travel comparable
- possible walls backscatter

A true energy spectrum measurements possible only with MC simulation comparison.
A trial...
Measurements with the detector as far as possible from the Phones moderator (161cm), on axis.
Neutron energy has been calculated from arrival time data

Preliminary results.
No correction for the cross section energy dependence included.
No cross-check with other detector available.

Residual gamma field blinds the detector for a longer time (on axis), lowering $E_{\text{max}}$. 
Future developments /1

To extract the maximum information from our detector Monte Carlo simulations are needed.

MCNP4b-GN simulations will allow to:
• calculate the ratio between total and detected neutrons to reach a better flux evaluation
• obtain neutron spectra at the exit face of the moderator, to allow a calculation of the arrival times on a far away detector.

Time domain (e.g. Geant 4) simulations to:
• obtain directly the arrival time spectrum on our detector
• adjust parameters to match measured data
• overall detector efficiency for an absolute flux measurement.
Future developments /2

Multi channel system for the mapping of the neutron field:
From the electronics point of view:
Straightforward upgrade to a 64 channel system exploiting the VA64TAP2.1 on board ASIC and one Hamamatsu multianode photomultiplier
For the detector:
A multi channel module with bulk sensitive scintillators and optical fiber readout will be designed, taking into account mainly the range of the 2.2 MeV gammas (shielding..)

The front-end board connected with a 64 channel Hamamatsu MA-PMT

The VATA642.1 ASICS from IDEAS, providing amplification, fast shaping, discrimination and parallel trigger output.
Can a Boron loaded scintillator improve our system?

**Standard**
- $H \sigma (0.025\text{eV}) = 0.33 \text{barn} - \frac{1}{\nu}$ dependence
- atom density $H = 5.2 \times 10^{22} \frac{1}{\text{cm}^3}$
- Efficiency = 3% (geo. dep.)

**Boron loaded**
- $B^{10} \sigma (0.025\text{eV}) = 3840 \text{barn} - \frac{1}{\nu}$ dependence
- atom density $B^{10} = 5.6 \times 10^{20} \frac{1}{\text{cm}^3}$
- efficiency = 100%

Boron loaded scintillator detects up to $3 \times 10^3$ more neutrons

- for our fluxes saturation will occur
  - much more expensive
- but useful if very small volumes are needed
Conclusions

- A neutron detector useful in a medical Linac environment has been developed.
- The comparison with activation methods states that it can give relative measurements of neutron fluxes.
  - Has been cross-checked with a BF3 counter.
  - A powerful method providing also spectral information.
  - Monte Carlo simulations foreseen for this purpose.
- Multi channel device for neutron field mapping is being developed.
Thanks ...  

To the whole Radiotherapy Division of S. Anna Hospital, Como