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HIGH EFFICIENCY COLLIMATOR-CONVERTERS
FOR NEUTRAL PARTICLE IMAGING WITH MWPC

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I. Introduction

The use of multiwire proportional chambers (MWPC) for detection and spatial localization of neutral particles is limited by the low conversion efficiency of the chamber gas. For low energy gamma radiation, the combination of a noble gas of high atomic number with pressurization produces a satisfactory detection efficiency. But as the energy of the gamma radiation increases, the detection efficiency decreases rapidly, and the spatial resolution degrades because the more energetic conversion electrons travel farther in the gas. Similar problems arise in neutron radiography, in particular for neutrons of greater than thermal energy. In practical applications in medical radioisotope imaging and neutron radiography, one is confronted with problems of both detection efficiency and spatial resolution.

A combination of collimator-converter coupled directly to the active region of a MWPC can improve both detection efficiency and spatial resolution. The efficiency of such a converter depends on the following:

1. The interaction probability of the non-ionizing radiation in the converter material producing charged reaction products. This is a function of the total gm/cm² of converter.
2. The escape probability of charged reaction products into the detector gas. This is a function of the mean distance to an escape surface and the range of the charged secondaries.
3. The amount of ionization produced in the gas and the extraction efficiency of ionization electrons from the converters into the multiplication region of the chamber. This is a function of collision mean free paths and the magnitude and contour of an extraction electric field.

A MWPC with external collimator converter system has been developed specifically for the detection of 0.511 MeV gammas in a positron camera. The design basis is applicable also to the imaging of other gammas and neutrons. The converter consists of honeycomb cells which provide an enhanced area of escape surface as well as restricting the range of conversion electrons to the cell dimensions.

II. Theoretical Analysis

1. Conversion yield

For a converter with periodic cells, the practical wall thickness, T, is limited to the maximum range of the most energetic conversion electrons. Consider an array of square cross section cells with dimension as shown in Fig. (1). Conversion electrons, resulting from either photoelectric or Compton interaction of the incident gammas with the material, have to traverse the solid and escape into the gas region where ionization can occur.

\[
e = \sum_{j=1}^{n} \sum_{i=1}^{2} \int_{x_{i}}^{x_{i+1}} Q_{ij} \left( \frac{1}{i+2} + \frac{1}{i+1} \right) \text{Pesc}(x, E_i) \text{d}x \text{... (1)}
\]

where \( i \) indicates the type of interaction (photoelectric and Compton), \( Q_{ij} \) is the probability of emitting an electron into the \( j \)th cell space, \( \text{Pesc} \) is the escape probability of a conversion electron with energy \( E_i \) at \( x \), and \( Q_{ij} \) is the probability that an \( i \)th type electron is produced in cell \( j \).

Fig. 1. Schematic of a square cross section cell array with unit-cell dimensions specified.

Fig. 2. Detector geometry for a point source with wide angular spread.
1a. Parallel beam geometry

In the idealized case of a collimated beam with a small angular spread, a photon can either pass through a cell without any interaction or traverse the full height of the cell wall. The average electron production probability per cell, \( Q \), is given by the product of the cell-wall volume fraction and its interaction probability.

\[
Q = \sum_{i=1}^{n} \frac{4(L+T+T)^2}{(L+2T)^2} \int_{0}^{T} \gamma_{i} \rho \exp(-\gamma_{i} \rho L) dz \ldots \ldots \ldots (2a)
\]

For small \( L \), and \( L \gg T \), the probability that an electron is emitted into the cell cavity per gamma, \( \epsilon \), is simplified as follows:

\[
\epsilon = \sum_{i=1}^{n} \int_{0}^{T} Q_{i} \frac{(L+2x)}{(L+T)} dx \rho \exp(-\gamma_{i} \rho L) \ldots \ldots \ldots (2b)
\]

where \( \epsilon_{\text{int}} \) is called the intrinsic conversion yield. The coefficient of \( \epsilon_{\text{int}} \) in equation (2b) is just the ratio of total surface area to the projected detector area. Thus a high detection efficiency is achieved by the increase of surface area. The intrinsic conversion yields of various types of cathode materials have been measured. (5) They can also be calculated for different materials from an analytical form for the escape probability (6). Both measured and calculated results of \( \epsilon_{\text{int}} \) for various materials versus energy are shown in Fig. (3).

![Fig. 3. Measured and calculated results of intrinsic conversion yield for various materials as functions of incident gamma energy.](image)

1b. Point source

In case of a point source with a wide angular spread, a photon can traverse several cells of the converter, and the average number of electrons produced per gamma over the solid angle subtended by the source and converter is calculated, Appendix (1). The conversion yield, \( \epsilon \), for a point source can be expressed as

\[
\epsilon = 2G \sum_{i=1}^{n} \frac{4(L+2x)}{(L+T)} \int_{0}^{T} \gamma_{i} \rho \exp(-\gamma_{i} \rho L) dx \ldots \ldots \ldots (3)
\]

where \( G \) is the geometric factor. From Appendix (1), \( G \) is shown to be a function of a particular source and converter geometry.

1c. Escape probability

In order to calculate the conversion yield, an analytic form for the escape probability is required. Spencer (4) used a numerical method of spatial moments to evaluate \( \rho_{\text{esc}} \).

\[
\rho_{\text{esc}}(x, E_i) = \exp \left[ \frac{1-x}{R(E_i)} \right] \exp \left\{ -\frac{A}{1-x/R(E_i)} \right\} \ldots \ldots (4)
\]

\( A \) is a function of source energy and scattering material, \( p \) is a constant, \( R(E_i) \) is the residual range. Using the experimental results of Seliger's work (7), the values of \( A, p \), can be obtained (8). Equation (4) is relatively insensitive to the value of \( p \). The best fit value \( p=-3 \) was used in the calculation of the conversion yield.

1d. Photoelectric and Compton electrons

The residual range \( R(E_i) \) is determined from the kinetic energy of the two types of conversion electrons. In photoelectric interactions, the energy of the conversion electrons is given by the difference of incident gamma energy and the binding energies of the electrons.

\[ E_p = E_f - E_i \]

Contribution from \( L, M \) shells should be included for high Z materials. Since the Compton interaction yields a continuous spectrum, an average Compton electron energy is used to calculate the escape probability.

\[ \bar{\epsilon_c} = \int_{E_c(\theta)}^{E_c(\theta)} \frac{dx}{d\sigma(\theta)} \]

\( E_c(\theta) \) is the kinetic energy of scattered electrons and \( dx/d\sigma(\theta) \) is the differential scattering cross section. (9)

In order to simplify the calculations further, we assume that the three processes—interaction, escape, and ionization electron extraction are functionally independent.

2. Extraction efficiency

In order to extract ionization electrons from the gas regions within the cells, multiple lead strips are used and electrically biased to produce a drift field. A profile of the electric field is shown in Fig. (4).

![Fig. 4. Schematic configuration of the lead converters, showing the electric drift field lines.](image)
To estimate the influence of field profiles on the extraction efficiency, we assume a cylindrical cell geometry Fig. (5).

\[
\begin{align*}
\text{Fig. 5. A cylindrical cell geometry showing an inner tube (radius } r) \text{ where field lines are continuous along the length of the cell. The line segment } T(r), \text{ the ionization track length in this tube.}
\\
R \text{ is the radius of the cylinder and } H \text{ is the height of a section of the lead material; } \bar{r} \text{ is taken as the average radius of an inner tube through which field lines are continuous along the length of the cell. The calculated ratio, } \bar{T}^2/R^2, \text{ is shown in Fig. (6) as a function of } R/H.
\end{align*}
\]

\[
\text{Fig. 6. Intersection probability } P(T/R) \text{ and extraction volume fraction } T^2/R^2 \text{ are shown as functions of } R/H.
\]

The probability of detecting a gamma ray which has produced a conversion electron in a cylindrical cell space depends on the probability that the ionization track intersects the inner tube and produces within it a sufficient number of secondary electrons. Total converter efficiency is then expressed as a product of conversion yield, intersection probability and detection probability

\[
\eta = \epsilon \times e_{\text{extraction}} \times D(E_t)
\]

where \( \epsilon \) is the conversion yield, \( P(T/R) \) is the intersection probability and \( D(E_t) \) is the detection probability. Assuming a cosine distribution of particle emissions from converter walls, the interaction probability can be expressed as

\[
P \left( \frac{T}{R} \right) = 1 - \frac{4}{\pi} \int_0^\mu \cos^{-1} \left[ \frac{\mu \bar{r}}{R(1 - \mu^2)} \right] d\mu \ldots (5)
\]

where

\[
\mu = \left[ 1 + \left( \frac{T}{R} \right)^2 \right]^{-\frac{1}{2}}
\]

The detection probability, \( D(E_t) \), is calculated from the effective track-length-distribution \( T(r) \), through the inner cylinder. \( T(r) \) is estimated by multiplying the track-length-distribution in the outer cylinder. (10), by volume ratio \( T^2/R^2 \).

\[
D(E_t) = \int_{E_t}^{E_{\text{max}}} \frac{1}{E} e^{-\frac{E}{E_{\text{max}}}} dE = \int_{r_t}^{r_{\text{max}}} T(r) dr
\]

\( E_t \) is the energy threshold for detection and \( r_t \) is the corresponding minimum track length (in the numerical calculations, a uniform energy loss in the gas of 3.2 KeV per cm. was assumed).

For our converters \( P(T/R) \) has a value of 0.75 and \( D(E_t) \) is greater than 0.95 since the avalanche gain in the MWPC is sufficiently high.

III. Converter design

As expected, the higher \( Z \) materials have higher conversion yields over the energy range 250 KeV-1 MeV. Fig. (3) shows calculated and measured conversion yields for several materials. The measured values for aluminum(5) are in good agreement with calculations using Spencer's formula. (A small angular beam geometry is assumed in the conversion yield calculations). The Bi measurements are, however, almost 20\% higher than the calculated values. Because Pb is inexpensive and readily available, it was used for our converters. The optimum thickness of cell walls made of lead was calculated to be 75 microns. Photoetching and electroplating methods were employed to construct these thin walled converters. Bands of copper were photoetched on sheets made of 50 microns of mylar clad on both sides with 50 microns of copper. Subsequently, a layer of lead 75 microns thick was electroplated onto the copper. Strips of selected width were cut from these sheets and corrugated with two meshing gears. The strips were then soldered together to form a honeycomb structure. Metal bands at the same height were connected by a common buswire. A drift field is provided to each cell by applying graded voltages to the bus wires. Fig. (7).

IV. Test chamber and results

A MWPC test chamber with 25 x 25 cm² sensitive area was used to measure the detection efficiency of 511 KeV gammas for converters of various cell dimensions. The chamber consists of two cathode planes of stainless steel wires 100 micron in diameter and 2 mm spacing between wires. The anode plane consists of stainless steel wires 25 micron in

\[
\text{Fig. 7. A section of the layered, honey-comb shaped collimator-converter. Graded voltages are applied through bus-wires to individual cells.}
\]

\[
\text{IV. Test chamber and results}
\]

A MWPC test chamber with 25 x 25 cm² sensitive area was used to measure the detection efficiency of 511 KeV gammas for converters of various cell dimensions. The chamber consists of two cathode planes of stainless steel wires 100 micron in diameter and 2 mm spacing between wires. The anode plane consists of stainless steel wires 25 micron in
diameter with a 3mm spacing between wires. Test converters 15 x 15 cm² were placed parallel to the cathode plane and separated from it by 4mm Fig. (8).

Fig. 8. Test chamber with test converter at the bottom separated from the cathode plane by a 4 mm spacing.

The signal was read from the anode plane with a low noise charge sensitive amplifier. A Na²² positron source (~100 µCi) was placed mid-way between the test chamber and a NaI detector. The detection efficiency of various converters was measured by comparing the coincidence counting rate with the singles rate of the NaI detector. For a pure positron emitter, the detection efficiency ε₄ is given by the ratio of the net coincidence count rate C (Coincidence-background) to the single count rate S.

\[
\frac{C}{S} = \frac{N_{0} G \varepsilon_1 \varepsilon_2}{N_{0} G \varepsilon_1} = \varepsilon_2 \equiv \varepsilon_4
\]

N₀ is the source strength, G is a geometric factor, ε₁ is the detection efficiency of NaI detector, ε₂ is the detection efficiency of the converter. A correction has to be made to the Na22 coincidence counts since a 1.27 MeV gamma is also emitted with every pair of annihilation gammas.

Table 1 compares the calculated values of ε₄ with the measured detection efficiencies for various cell dimensions. As can be seen from the table, the measured extraction efficiencies which vary between 0.73 - 0.83 are in good agreement with the calculated values.

V. Conclusion

Four large lead converters 48 x 48 cm² with cell dimensions 3mm x 3mm x 12mm coupled to MWPCs have been developed for a positron camera, and detection efficiency of 3.2% per converter with a spatial resolution of 6mm FWHM has been reported previously. Further improvement in detection efficiency and spatial resolution is obtainable by decreasing the cell size and other techniques. As can be seen from Fig. (6), the greater the ratio of R/H the greater will be the extraction efficiency. Therefore, another design scheme, that of using high surface resistivity lead glass tubing as the conversion medium is under investigation. Though the intrinsic conversion yield of lead glass is lower than that of pure lead, a more uniform drift field and higher electron collection efficiency may be obtainable with a converter made of lead glass tubing having a suitable surface conductivity (10⁸-10¹² ohms/square). A comparison of conversion yield of lead glass of various compositions with that of lead is shown in Fig. (9).

The analysis and calculation methods for gamma converters given here are also applicable for neutron converters. Thermal and epithermal neutron sensitive materials with charged particle reaction products such as Boron, Gadolinium, Lithium can be substituted for lead to form the wall of the converter cells. For example, alpha particles are emitted into the cell space following an interaction of neutrons with a Boron converter. The ionization electrons are then extracted from the cell space into the multiplication region of the chamber as before. For fast neutron detection, hydrogenous materials can be used as the conversion medium. Some preliminary calculations and measurements have been made for a polyethylene converter with close packed holes as shown in Table II. Silver conductive paint electrodes were applied on both converter faces to provide the extraction field. Because of the predominance of forward scattering in n-p collisions, Fig. (10), the collimator converter produced only a small net increase in efficiency. However, spatial resolution is improved from that of a plane converter.

Fig. 9. Comparison of conversion yield of pure lead with lead glass of various compositions as functions of cell wall thickness. A point source wide-angular-spread geometry is assumed.

![Comparison of conversion yield of pure lead with lead glass of various compositions as functions of cell wall thickness.](image)

Fig. 10. Recoil proton energy and range in polyethylene as functions of proton recoil angle in (n,p) scattering.
TABLE I

<table>
<thead>
<tr>
<th>Converter cell</th>
<th>Surface area</th>
<th>$\epsilon_t$ (cal.) (%)</th>
<th>$\epsilon_t$ (exp.) (%)</th>
<th>$\epsilon_t$ (exp.) plane (%)</th>
<th>Measured Extraction Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb(511 keV gamma)</td>
<td>4LH/L^2</td>
<td>0.26</td>
<td>0.26</td>
<td>1.0</td>
<td>1.00</td>
</tr>
<tr>
<td>Plane converter</td>
<td>1</td>
<td>3.12</td>
<td>3.20</td>
<td>12.3</td>
<td>0.76</td>
</tr>
<tr>
<td>3mm x 3mm x 12mm</td>
<td>16</td>
<td>4.29</td>
<td>4.20</td>
<td>16.2</td>
<td>0.73</td>
</tr>
<tr>
<td>2.2mm x 2.2mm x 12mm</td>
<td>22</td>
<td>1.56</td>
<td>1.55</td>
<td>5.4</td>
<td>0.74</td>
</tr>
<tr>
<td>2mm x 2mm x 4mm</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TABLE II

<table>
<thead>
<tr>
<th>Neutron converter Polyethylene (Pu $^{239}$ Be neutron fission spectrum)</th>
<th>Surface area</th>
<th>$\epsilon_t$ (cal.) (%)</th>
<th>$\epsilon_t$ (exp.) (%)</th>
<th>$\epsilon_t$ (exp.) plane (%)</th>
<th>Measured Extraction Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plane converter</td>
<td>1</td>
<td>0.11</td>
<td>0.11</td>
<td>1.0</td>
<td>1.00</td>
</tr>
<tr>
<td>3.6mm dia. x 12mm</td>
<td>8</td>
<td>0.18</td>
<td>0.15</td>
<td>1.4</td>
<td>0.83</td>
</tr>
</tbody>
</table>

References

Appendix (1)
To calculate the geometric factor $G$

The converter can be considered as two sets of infinitely long parallel walls running in the $\hat{x}$ and $\hat{y}$ directions. The height of the walls is $h$. A point source is located at a distance $H_1$ above the top of the converter and emits $\gamma$-rays in all directions. For the $\gamma$-ray photon shown in the diagram, let the coordinates of the points of intercept with the $z=0$ and $z=h$ planes be $(x_0, y_0, 0)$ and $(x_0, y_0, h)$ respectively.
The number of walls parallel to \( \hat{x} \)-direction intercepted by the \( \gamma \)-ray path is equal to

\[
\begin{align*}
X_e \ &= \ X_e \ H_1 / H \\
Y_e \ &= \ Y_e \ H_1 / H
\end{align*}
\]

Similarly, the number of walls parallel to \( \hat{y} \)-direction intercepted by the \( \gamma \)-ray path is

\[
\begin{align*}
Y_e \ &= \ Y_e \ H_1 / H \\
X_e \ &= \ X_e \ H_1 / H
\end{align*}
\]

Then the total thickness \( t_e \) traversed by the photon is

\[
t_e \ = \ m_x (e) \ t (\sec \ e_1) + m_y (e) \ t (\sec \ e_2)
\]

(we neglect the double counting in the regions common to both sets of walls)

From the geometry it can be seen

\[
\sec \ e_1 = \frac{X_e + Y_e + H}{Y_e}, \quad \sec \ e_2 = \frac{X_e + Y_e + H}{X_e}
\]

Hence

\[
t_e = t \frac{X_e + Y_e + H}{X_e}, \quad \left\{ \begin{align*}
\int (Y_e - Y) - \int (H_1 Y_e - Y) \\
\int (H - X_e - X)
\end{align*} \right\}
\]

The number of \( i^{th} \) type electrons produced in the converter is

\[
n_e \ = \ \int_0^t \delta \rho \ e^{- \sigma_T \rho \ t} \ ds
\]

\[
= \frac{1 - e^{- \sigma_T \rho \ t_e}}{\delta \rho}
\]

Hence the average number of \( i^{th} \) type electrons, \( Q_i \) produced by a \( \gamma \)-ray photon emitted towards the converter within a solid angle \( \Omega \) is given by

\[
Q_i = \frac{\int n_e \ d\Omega}{\int \Omega}
\]

\[
= \int_0^t \frac{1 - e^{- \sigma_T \rho \ t_e}}{\sigma_T \rho} \ d\Omega
\]

Comparing the expression for \( Q_i \) to the definition

\[
Q_i = G \sigma_T \rho \ t
\]

we can identify the quantity

\[
\int_0^t \frac{1 - e^{- \sigma_T \rho \ t_e}}{\sigma_T \rho} \ d\Omega
\]

as the geometry factor \( G \), which is independent of the type of electrons.
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