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GAMMA-RAY DETECTION WITH PbO GLASS CONVERTERS IN MWPC: ELECTRON CONVERSION EFFICIENCY AND TIME RESOLUTION

G.K. Lum, V. Perez-Mendez, and B. Sleaford

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GAMMA-RAY DETECTION WITH PbO GLASS CONVERTERS IN MWPC: ELECTRON CONVERSION EFFICIENCY AND TIME RESOLUTION

G.K. Lum†, V. Perez-Mendez and B. Sleaford,
Lawrence Berkeley Laboratory, Berkeley, CA
and
Dept. of Radiology, University of California,
San Francisco, CA

ABSTRACT

The development of glass tube converters for efficient gamma-ray detection in multi-wire proportional chambers (MWPC) has led to an investigation of the improvement of conductivity on glass surfaces and to an investigation of gas mixtures which will improve on the electron conversion efficiency and electron transit time within the tubes. Efforts to establish uniform electric field lines within small diameter tubes has resulted in an improved H_2 reducing treatment. For a 2cm thick converter made of glass tubing(0.9 mmID:1.10 mmOD) the electron conversion efficiency ε was measured to be 9.0% and 10.4% at 511 keV, using Ar mixtures containing 10% CF_4 and 30% isobutane, respectively. The effects of gas mixtures on ε and on τ, the mean transit time on conversion electrons within the converter, and the projection of these results to the performance of a modified MWPC positron camera are presented.

INTRODUCTION

The detection of gamma rays in the energy range of 100 keV to 10 MeV using multi-wire proportional chambers (MWPC) requires the development of special converters with large surface-to-volume ratios[1]. These converters are generally designed from high atomic number materials, such as lead or tungsten. Some designs that have been implemented were fabricated from isolated stacked tungsten wire meshes, corrugated lead-banded strips and perforated lead sheets. We have pursued this development by constructing converters from glass capillaries of high lead content fused to form honeycomb matrices (80% PbO by weight, glass density of 6.2g per cm^3).

The extraction of gamma-conversion electrons from within the tubes is achieved by making the glass surfaces uniformly conductive with a fairly high resistivity. Then as a voltage is applied between the ends of the tubes, electrons are drifted along electric field lines to the wire planes of a MWPC. Figure 1 shows the layout of such converters coupled to a conventional three plane MWPC.

These MWPC-converter detectors are position sensitive and can be used in such fields as particle physics, solid-state physics and nuclear medicine. Figure 1 shows two of the detectors coupled for the detection of paired 511 keV gammas emitted from a positron source distributed within a patient in a nuclear medical imaging situation. With the aid of a computer the reconstruction of the spatial distribution of the positron source provides tomographic images of the organ under investigation. In solid-state research, positron emiting isotopes are used to measure the energy distribution of electrons in crystals.[2] In this application, the converters can be more than a few centimeters thick, since the gammas are incident on the counters at angles of 90° ± δ (δ < 1°).

† Present Address: Lockheed Missiles and Space Co. Inc. Sunnyvale, CA.

Our continuing efforts to develop efficient gamma-ray PbO glass tube converters have led us to the use of tubes with smaller inner diameters and thinner walls, i.e., 0.9]-mm I.D., 0.096-mm wall[3] than those previously reported[4], which had dimensions 1.4-mm I.D., 0.129-mm wall. The smallness of the tubes has also led us to an investigation of gas mixtures which increase the secondary electron yield and the electron transit time.

CONSTRUCTION AND TREATMENT OF LEAD GLASS CONVERTERS

Converters were constructed by slicing glass capillaries approximately 13-cm in length, stacking them densely into a graphite mold and fusing them at 440°C. Details of the fabrication process are given in references 4 and 5. A conductive surface was developed on the glass by a hydrogen-reducing reaction, namely, PbO + H_2 = Pb + H_2O. We selected the appropriate surface resistivity by adjusting the temperatures and the treatment time. Whenever the resistivity of the treated glass surface was too high, such as 10^{10} ohm per square, we found that the conversion efficiency would be low. This problem was related to non-uniform surface resistivity which contributed to poor electron drifting capabilities. By lowering the temperature of the hydrogen reduction furnace to 350°C which is 70° lower than the previously used temperature[5] the bulk resistance of a 5-cm by 5-cm by 2-cm thick (0.9]-mm I.D., 0.096-mm wall converter was reduced from 270MΩ to 300 KΩ. The applied voltage gradient measured with microprobes within the tubes was then extremely constant. We also found that the period needed for the hydrogen reduction of the glass to achieve good surface conductivity could be reduced to 5 hours. Qualitatively, for 80% PbO glass our results agree with Blodgett's[6] 60% PbO glass which shows the H_2 reduction temperature lies within a range of about 100°C where conductivity can be maximized. For 80% PbO glass the optimum temperature range is between 270° and 375°C as compared to 380° to 480°C for 60% PbO glass.

CONVERTER EFFICIENCY AND DRIFT TIME

In some applications of MWPC with high z converters such as coincident detection of the annihilation gammas from positron conversion it is desirable to have both a high detection efficiency as well as a fast electron drift velocity in order to maximize the yield of true coincidences to accidental events. This is proportional to ε^2/τ where ε is the 511 KeV gamma detection efficiency and τ is the electron drift time through the converter[7].

The increase of ε, as discussed below, depends on the choice of converter material, the dimension of the tubes, as well as the MWPC gas environment. The glass converter material that we use already has the highest Pb content commercially available while still leaving the glass sufficiently ductile. A possible remaining improvement is the addition of a small concentration of bismuth oxide which helps the glass ductility[8]. The choice of wall thicknesses can be estimated from Figure 2 which shows calculated efficiencies as a function of wall thickness for various glass tube matrixes as a function of the hole diameter. If the walls are too

thick, the packing density decreases resulting in a lower detection efficiency; additionally the total absorption for rays increases.

In the formulation and testing of gas mixtures for our applications we required a mixture that would satisfy most of the following requirements. The gas must (1) have a high volume density in order to generate as many secondary electrons in the small distances available; (2) provide for a high electron drift velocity in order to minimize the number of accidental coincidences; (3) provide high avalanche gain for the detection of conversion electrons; (4) not have any electronegative components and (5) provide fast rise time pulses since we are using the delay line method for position determination[7]. A gas mixture consisting of 20% CH_4, 10% CF_4, and 69% Ar was found to yield significantly improved performance over the previous mixture containing 30% CH_4 and 70% Ar. The main areas of improvement were the greater density and higher electron drift velocity of the new mixture. The CF_4 provided increases in density and electron drift velocity[9] but degrades the electron avalanche gain and pulse rise time. Suitable gain was obtained with the addition of ~1% C_2H_2. Faster pulse rise times were attained by adding ~20% CH_4 to the mixture, utilizing the higher positive ion mobility and the Penning effect during the avalanche. The CH_4 also provide quenching for the Argon photons present during the avalanche. Argon was a majority constituent in all mixtures due to its zero electronegativity, density, and its compatibility with the CF_4 in providing high electron drift velocities. Other mixtures investigated included $O[CH_3]_2CH_2$(methylal) and C_4H_{10}(isobutane) with Argon, the primary motivation being to increase the gas density and therefore the efficiency of the converter. Unfortunately both constituents greatly reduce the electron drift velocity though small percentages of methylal help reduce polymerization on the cathode[10].

The electron conversion efficiency and the spread in transit time were measured with 511 keV gammas from a positron ^{68}Ga source using a NaI detector coupled in-coincidence with a MWPC-converter system. The experimental arrangement is shown in Figure 3. The positions of the source and the NaI detector are adjusted to accept an angle θ which can subtend up to ± 45° over the converter. All efficiencies in this paper were measured at θ= ±45°.

The efficiencies ε for a 0.91-mm I.D., 1.10-mm O.D., 2-cm thick converter were determined to be 9.2% and 10.6% when gas mixtures of (1% C_2H_2 (ethylene), 10% CF_4, 20% CH_4, 69% Ar) and (30% isobutane, 70% Ar) respectively, were used. For the above converter we found that in a 30% CH_4, 70% Ar mixture ε was the same as that measured for a 1.4-mm I.D., 2-cm thick converter type, namely, 7.5%. However, when mixtures of 10% dimethoxymethane (methylal), 27% CH_4, 63% Ar and 10% methyal, 27% isobutane, 63% Ar were used, ε was 10.2 and 10.8% respectively. Figure 4 shows the conversion efficiencies versus pulse amplitude threshold for the various gas mixtures. Curves A, C, and D indicate that a gas with a large electron density is necessary to obtain an increase in the electron efficiency as compared to our normal 70% Ar and 30% CH_4 mixture when using the small I.D. tubes. Table 1 summarizes the efficiencies measured for various sizes of converters and gases.

Table 1
Efficiencies of Converters at 511 keV

Inner Diameter I.D. (mm)	Thickness (cm)	Measured Electron Conversion Efficiency (%)	MWPC Gas Mixture
0.91	1	5.2	70% Ar+30% CH_4; 1% C_2H_2+10% CF_4+ 20% CH_4+69% Ar
0.91	2	10.8	10% Methylal + 27% isobutane + 63% Ar
		9.2	1% C_2H_2+10%CF_4+ 20% CH_4+69% Ar
1.33	2	8	70%Ar+30%CH_4; 5% methylal+28%CH_4 + 67% Ar
0.91	4	17	3% methylal+30% Isobutane + 67% Ar

Comparing the calculated values from Fig. 2 with our measured ones in Fig 4, we find that there are still discrepancies between the two, possibly due to thick walls or nonuniform field lines which are essential in drifting electrons efficiently out of the tubes. We also measured the total absorption of 511 keV gammas by 1-cm and 2-cm thick (0.91-mm I.D., 1·10-mm O.D.) converters and found them to be in agreement with calculations. Table 2 lists these measurements.

Table 2
Total % of 511 keV Gamma Absorption by Converter

I.D. (mm)	Thickness (cm)	Measured Absorption (%)
0.91	1	17
0.91	2	30
1.33	2	28

The use of 1% C_2H_2, 10% CF_4, 20% CH_4, 69% Ar showed that τ was 50 ns smaller than that of a 30% CH_4,70% Ar mixture. Figure 5 shows the timing resolution of these gases using the experimental arrangement in Figure 3. We noted also in Figure 4 that although a 30% isobutane mixture provided a high ε as compared to 30% CH_4 mixture, τ was large, namely 220 ns for a 1-cm thick converter as compared to 110 ns for a 10% CF_4 mixture. Table 3 lists values for the various gases mixtures.

As discussed earlier, a gas that has a high electron density and can provide a fast drift speed for electrons is essential in improving the coincidence counting rate of a positron camera. For such a case ε^2/τ was improved by a factor of 1.5 by use of a 10% CF_4 rather than a 30% CH_4 mixture. Figure 6 contains some plots of ε^2/τ versus τ for some of the gases and Table 4 lists their maximum values.

Table 3 Timing Spread of Conversion Electrons in Converters with Various MWPC Gases

I.D. (mm)	Thickness (cm)	τ at FWHM full width at half maximum (nanosec)	MWPC Gas Mixture Used
0.91	1	110	1%C_2H_2+10%CF_4+ 20%CH_4+69% Ar
		150	30% CH_4+70% Ar
		220	30% isobutane + 70% Ar
0.91	2	230	1%C_2H_2+10% CF_4+ 20% CH_4+69% Ar
		290	30% CH_4+ 70% Ar
		>1000	10% methylal+30% isobutane + 60% Ar
1.33	2	300	30% CH_4+ 70%Ar
0.91	4	~4000	10% methylal + 30% Isobutane + 60% Ar
		~2000	3% methylal + 30% isobutane + 67% Ar

Table 4 ε^2/τ of a Single-Layer Converter-MWPC Assembly with Various Gases

I.D. (mm)	Thickness (cm)	ε^2/τ in units of 10^3 per sec	MWPC Gas Mixture
0.91	1	14	30% isobutane + 70% Ar
		15	30% CH_4 + 70% Ar
		17	1% C_2H_2 + 10% CF_4 + 20% + 20% CH_4 + 69% Ar
0.91	2	17	30% CH_4 + 70% Ar
		26	1% C_2H_2 + 10% CF_4 + 20% CH_4 + 69% Ar
1.33	2	17	30% CH_4 + 70% Ar

PERFORMANCE OF A MWPC POSITRON CAMERA

An estimation of the performance of a MWPC lead glass converter positron camera based on our measurements is shown in Table 5. Each MWPC detector is assumed to contain two layers of converters and a MWPC, as shown in Figure 1. Columns 1 and 2 of Table 4 list the size and thickness of the converters. A gas mixture of 1% C_2H_2, 10% CF_4, 20% CH_4 and 69% Ar was selected since it provided a high ε and a small τ. From

$$\varepsilon^2/\tau = \frac{8\ (\text{true coincidences})}{\text{accidentals}}$$

taken from reference 7, and assuming that the rates of coincidences and accidentals are equal, the above equation reduces to the fact that the number of coincidences equals $\varepsilon^2/(8\tau)$ which is listed in Column 3.

Table 5 Performances of MWPC Positron Camera on Converter Thickness. Each Chamber Contains Two Layers of Converters. Rate of Coincidences equals Rate of Accidentals. Gas Mixture is: 1% C_2H_2, 10% CF_4 , 20% CH_4, 69% Ar

I.D. (mm)	Thickness (cm)	Coincidences(in units of 10^3 per sec)
0.91	1	8.2
0.91	2	11.1
1.33	2	6.0

CONCLUSIONS

We have established that our technique is quite simple and economical in developing gamma-ray converters from high density PbO tubes for various applications, specifically, a positron imaging camera. These MWPC converters have been coupled to form arrays of large areas, such as, 50-cm by 50-cm and used to form high absorbing detectors with thickness as large as 4-cm. The applications of the gas mixtures mentioned above are governed by what these detectors will measure. For high efficiencies, a 3% methylal, 30% isobutane, 67% Ar could be used at low counting rates. However when high counting rates are essential, a 1% C_2H_2, 10% CF_4, 20% CH_4, 69% Ar mixture was found to be the best.

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FIGURE CAPTIONS

Fig. 1 - A pair of MWPC-converter detectors coupled in-coincidence for detection of paired 511 keV gammas. The gammas are generated by the annihilation of an electron with a positron. The wire grids and the two counters in each chamber are shown schematically.

Fig. 2 - Calculated values of the conversion efficiency of lead glass converters 2-cm thick as a function of PbO concentration and wall thickness.

Fig. 3 - Experimental arrangement used to measure the conversion yield and spread in transit time of electrons produced by 511 keV gammas incident upon a converter.

Fig. 4 - Electron conversion efficiency (%) versus anode discriminator threshold voltage.

Fig. 5 - Electron transit time spread of various gas mixtures. The spread of a peak is due mainly to the detection time differences between gamma rays that interact at different depths within the converter and the secondary electrons that finally reach the MWPC.

Fig. 6 - ε^2/τ versus τ of three gas mixtures for 1-cm and 2-cm thick converters. The maxima are listed in Table 4.

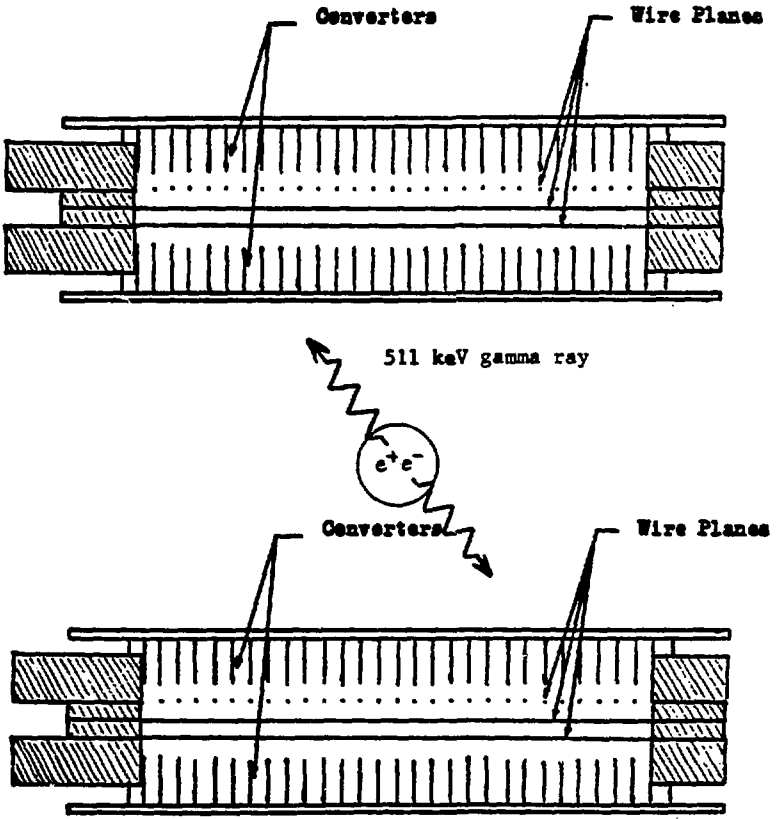
Converters
Wire Planes
511 keV gamma ray
e+e-
Converters
Wire Planes

Fig. 1

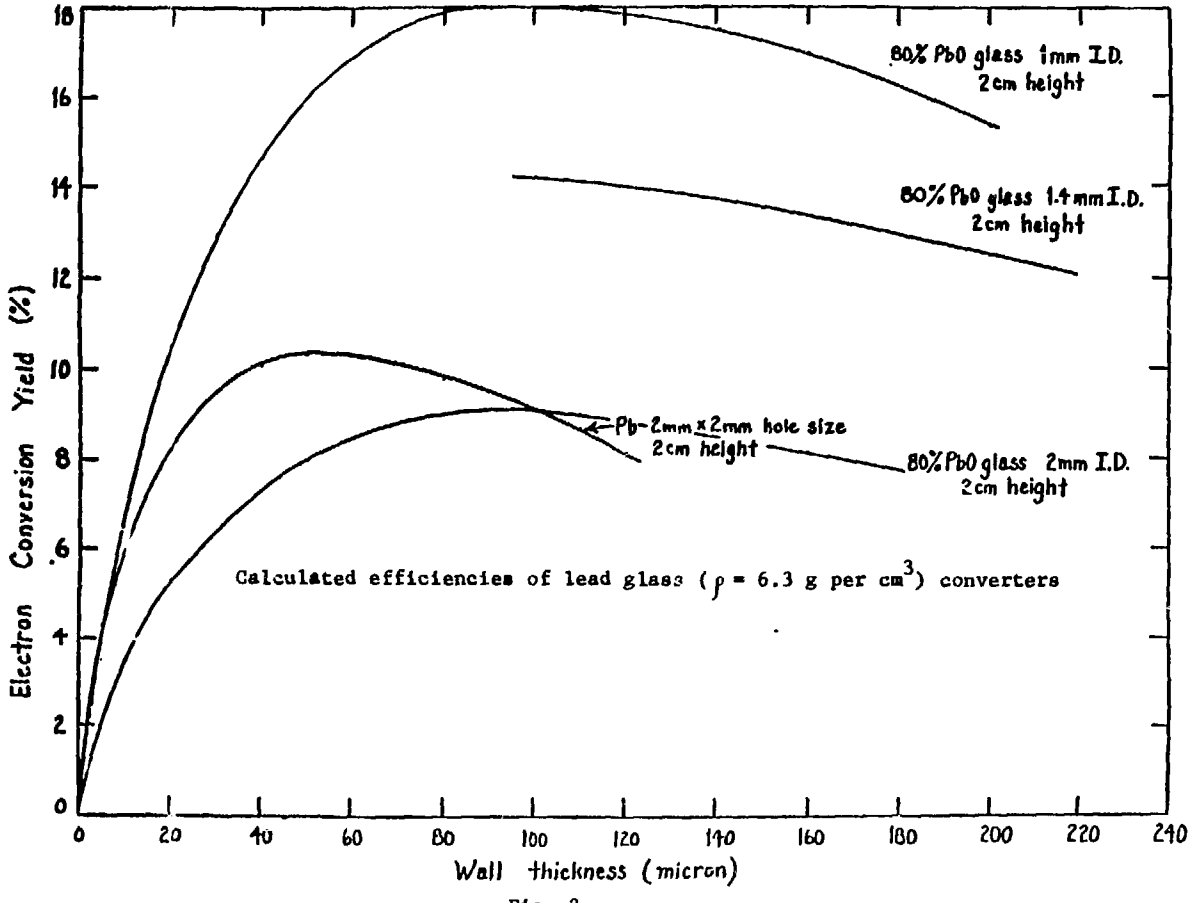
80% PbO glass 1mm I.D.
2cm height
80% PbO glass 1.4mm I.D.
2cm height
Pb-2mm x 2mm hole size
2cm height
80% PbO glass 2mm I.D.
2cm height
Calculated efficiencies of lead glass (ρ = 6.3 g per cm^3) converters
Electron Conversion Yield (%)
Wall thickness (micron)
0
2
4
6
8
10
12
14
16
18
0
20
40
60
80
100
120
140
160
180
200
220
240

Fig. 2

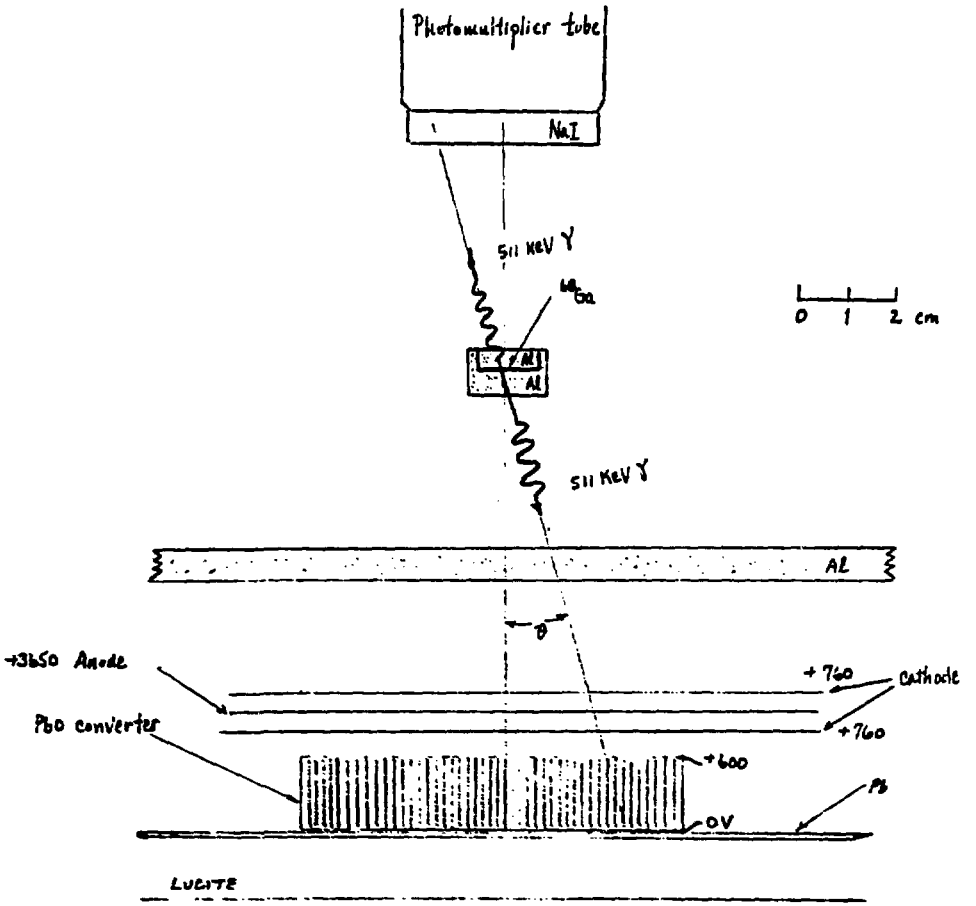
Photomultiplier tube
NaI
511 KeV γ
^{68}Ga
Al
Al
511 KeV γ
0 1 2 cm
AL
θ
+3650 Anode
+760
Cathode
PbO converter
+760
+600
Pb
0V
LUCITE

Fig. 3

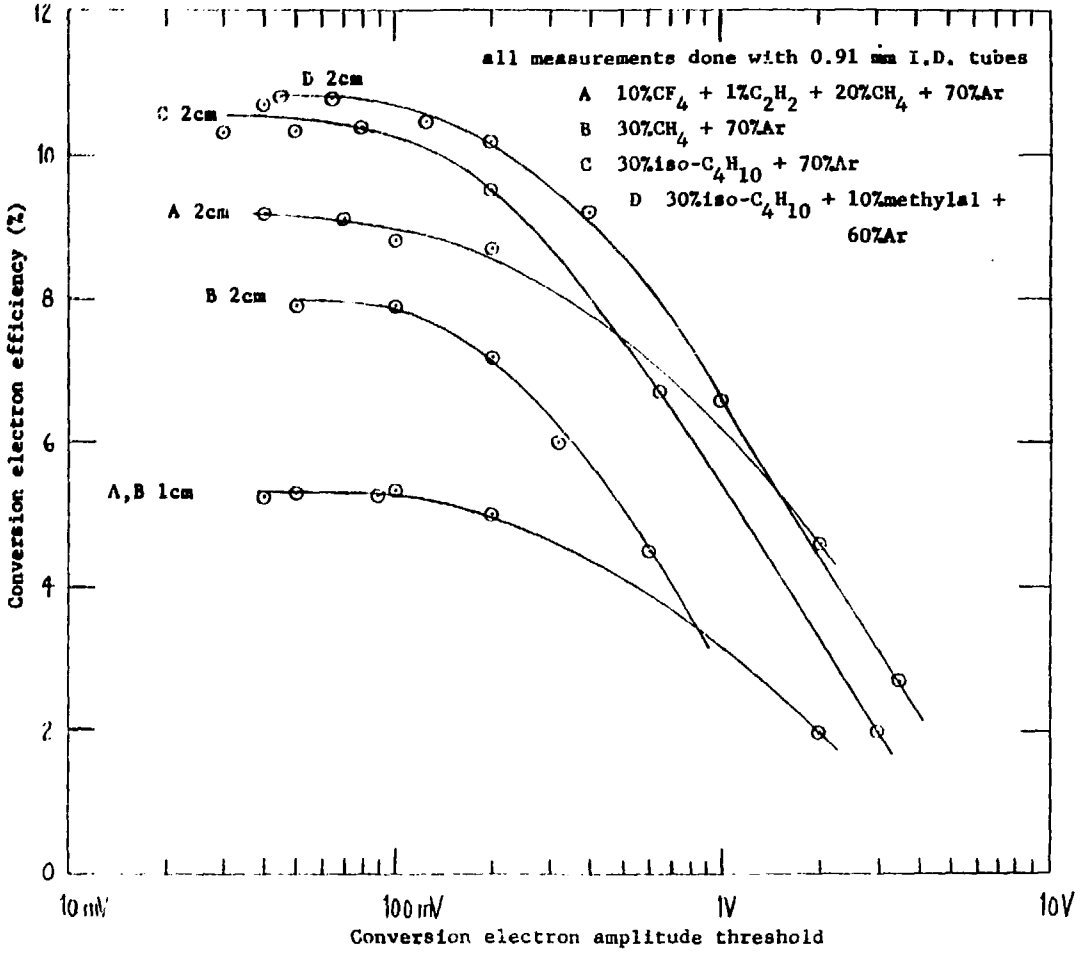
all measurements done with 0.91 mm I.D. tubes
A 10%CF4 + 1%C2H2 + 20%CH4 + 70%Ar
B 30%CH4 + 70%Ar
C 30%iso-C4H10 + 70%Ar
D 30%iso-C4H10 + 10%methylal + 60%Ar
D 2cm
C 2cm
A 2cm
B 2cm
A,B 1cm
Conversion electron efficiency (%)
0
2
4
6
8
10
12
10 mV
100 mV
1V
10V
Conversion electron amplitude threshold

Fig. 4

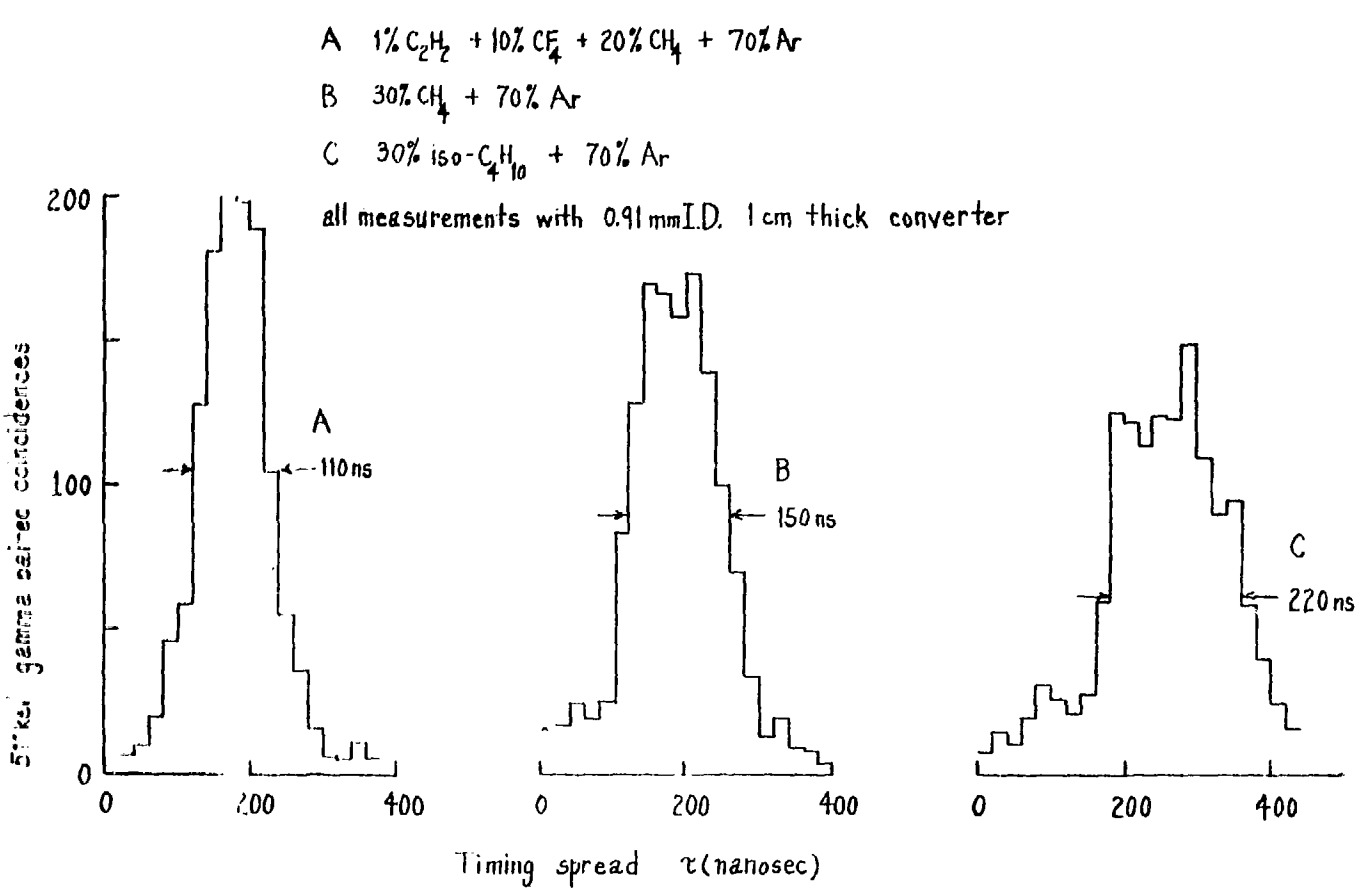
A 1% C_2H_2 + 10% CF_4 + 20% CH_4 + 70% Ar
B 30% CH_4 + 70% Ar
C 30% iso-C_4H_{10} + 70% Ar
all measurements with 0.91 mm I.D. 1 cm thick converter
511 keV gamma pairec coincidences
200
100
0
A
110 ns
B
150 ns
C
220 ns
0
200
400
Timing spread τ (nanosec)

Fig. 5

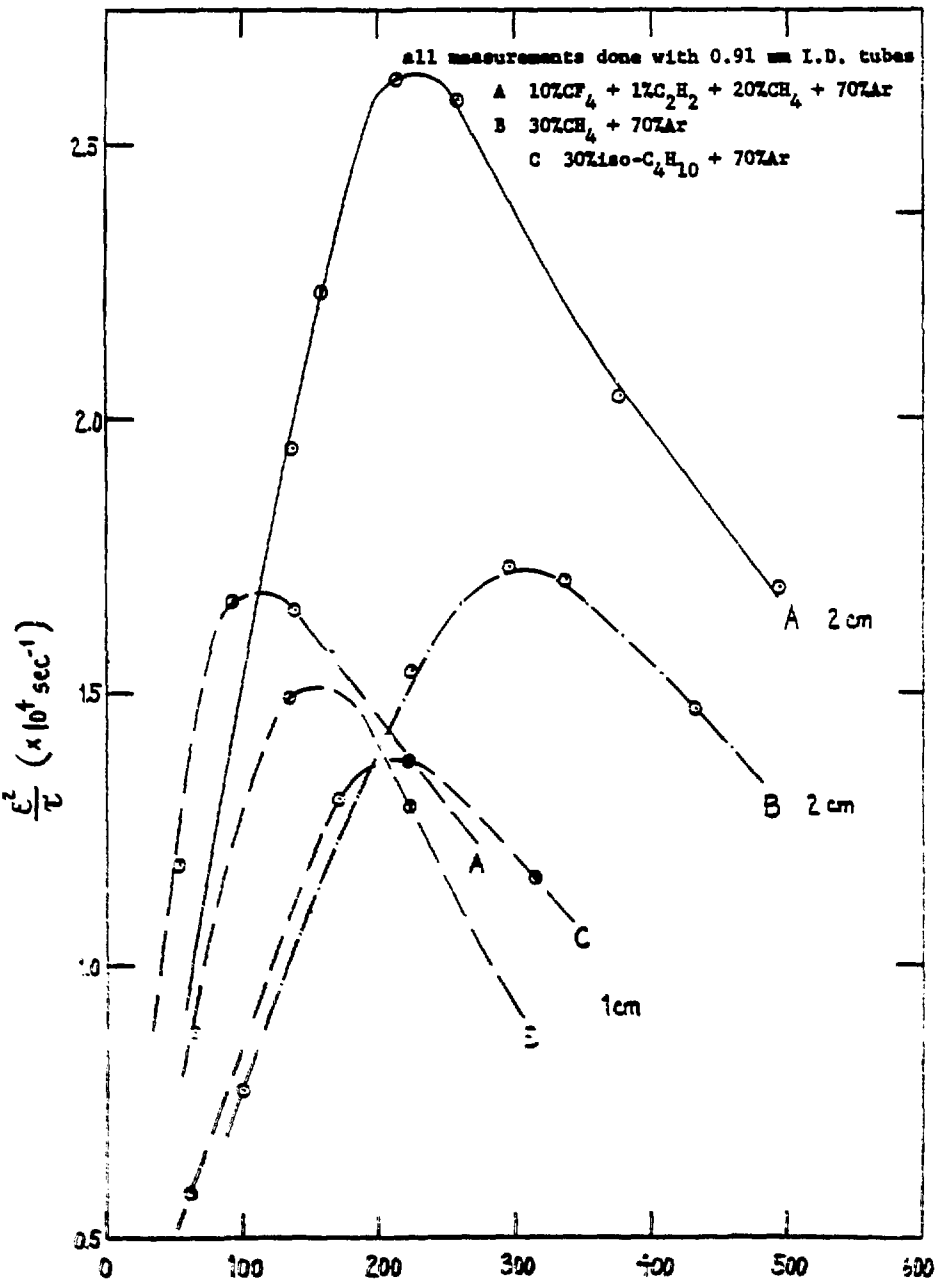

Fig. 6 τ (nanosec), resolving time