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POSITRON ANNIHILATION SPECTROSCOPY WITH MAGNETICALLY ANALYZED BEAMS

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ABSTRACT

Lifetime measurements with magnetically analyzed positron beams have been made in condensed media with uniform and non-uniform properties. As expected, the lifetime values with magnetically analyzed beams in uniform targets are similar to those obtained with conventional positron sources. However, the lifetime values with magnetically analyzed beams in targets which have non-uniform properties vary with positron energy and are different from the conventional positron source-derived lifetime values in these targets.

INTRODUCTION

Positron Annihilation Spectroscopy (PAS) is usually conducted with positrons having a continuous energy spectrum.[1-3] This is quite satisfactory when the medium properties of interest are uniform throughout the medium. Positrons of all energies encounter the same kind of molecular environment and, hence, undergo common decay processes. However, if the medium properties are spatially-dependent, the positron annihilation characteristics will vary depending on where the positrons come to rest. For example, if the defects in a material are confined to the surface layers,[4] only those positrons which stop in the surface regions will get trapped and exhibit damage-dependent decay. The positrons which penetrate deeper will not be affected by the surface defects and will exhibit normal positron decay features. The resultant lifetime spectrum will be a mixture of the two types of annihilation spectra. Similarly, if the moisture in an organic matrix is not uniformly distributed, the positron annihilation characteristics will vary depending on where the positrons are thermalized in it. Those positrons which stop in the drier regions of the target will have different lifetimes from those which stop in the regions where more moisture is present.[5,6] The resultant lifetime spectrum will be quite complex, being a mixture of spectra characterized by different lifetimes. Thus, positrons of appropriate, well-defined, energies are needed for studying spatially-dependent properties of the test media. The only practical means, currently feasible, for producing monoenergetic positron beams of various energies is to magnetically analyze positrons emitted from appropriate radioactive sources. In this paper, we describe an experimental procedure for producing monoenergetic positron beams. These monoenergetic positron beams have been used for investigating spatial dependence of moisture concentration in selected target media. The results of these studies are presented in the following sections.

EXPERIMENTAL PROCEDURE

Production of Monoenergetic Positron Beams

A specially prepared 10 mc Na^{22} source was used as the positron emitter. A 0.39 cm diameter, 7.62 cm long stainless steel tube placed over the source produced a well-collimated positron beam. This narrow, collimated, beam of positrons entered an 8.84 cm radius circular magnetic analyzer and, after bending through 90°, exited through a specially designed collimated port. Figure 1 shows the experimental arrangement for producing magnetically analyzed positron beams. Figures 2(a) and 2(b) show the source holder and the collimator used in the entrance channel. Figure 2(c) shows the geometrical details of the collimator through which the magnetically analzyed positrons had to pass before arriving at the test target. The exit-channel collimator was covered with a 0.25 cm thick carbon annular disc in order to minimize Bremsstrahlung production at it. Figure 3 and 4 show computed trajectories of the positron beams through the magnetic analysis system at two different energies.[7]

One of the important considerations in using magnetically-analyzed positron beams is the survival of the positrons in the magnetic analyzer. This is not expected to be a problem if the analyzer box is pumped down to $\lesssim 10^{-5}$ torr. Another important factor in using magnetically-analyzed positron beams for PAS is the time reference for positron lifetime measurement. If one is to continue to use the 1.28 MeV gamma ray as the signal for the birth of the Na^{22} positrons, it is essential that the transit time for their passages through the analyzer be small and--more importantly--the spread in it be much less than the resolution time of the lifetime measurement system. Computed values for the transit times and the energy resolution of the magnetic analysis system for two energies are given in Tables I and II.[7] It is apparent that the energy resolution, $\Delta E/E$, is quite satisfactory ($\lesssim$ 10%) and the spread in the positron transit time is much less than the system resolution of $\sim$450 picoseconds. Thus, it may be expected that conventional PAS can be conducted successfully with magnetically-analyzed positron beams derived from a Na^{22} source or similar sources where the positron emission is followed by a prompt gamma emission. For positron sources without associated gamma emission, it will be necessary to generate a reference time marker before the positrons entered the test medium. One technique for producing such a reference marker would entail the use of a Cerenkov counter placed in front of the test target.[6]

Preparation of the Test Targets

Three different types of targets were used in the present study. A 2.54 cm diameter, 0.25 cm thick lucite disc which had been stored in a controlled environment (relative humidity = 50%; temperature = 75°F) for several years was used as the target with uniform moisture distribution in it. Two specially designed assemblies served as targets with non-uniform properties: one of them, made up of two dry, 2.54 cm diameter, 381 μm thick nylon-6 discs placed back-to-back served as target assembly # 2. The other one, made up of one dry 2.54 cm diameter, 381 μm thick nylon-6 disc placed next to an identical disc saturated with water served as target assembly # 3. The water-saturated disc in target assembly # 3 was sealed in a 2.54 μm thick aluminized mylar to prevent moisture loss during the positron lifetime measurement.

Target assemblies 2 and 3 were designed for use with 250 keV positron beams.(*) The thicknesses of the two discs comprising these two target assemblies are such that 250 keV positrons pass through the first disc and come to rest in the second. Thus, the 250 keV positrons will come to rest in the dry disc in target assembly # 2 and water-saturated disc in target assembly # 3.

EXPERIMENTAL RESULTS

A conventional, fast-slow, constant fraction positron lifetime spectrometer, shown in figure 5, was used in the present study.[8] The spectrometer had a full width at half maximum resolution of about 450 picoseconds. Each full source spectrum was accumulated until it contained at least 10^6 counts and was repeated several times to obtain average values of the lifetime for the long-life component. The spectra with magnetically-analyzed beams were accumulated until a statistical accuracy of at least 10 percent was achieved in the short lifetime peak. All measurements were made at the room temperature (75°). The lifetime spectra were analyzed using a two-component exponential least-squares fit program.[5]

Figures 6(a) and 6(b) show the lifetime spectra in lucite observed with magnetically-analyzed 250 keV positron beams and the full Na^{22} positron spectrum, respectively. Even though the statistical accuracy of the data shown in figure 6(a) is rather poor, the measured values of the long-component lifetimes indicated in these figures are in agreement with each other within the accuracy of the measurements. Figures 7(a) and 7(b) illustrate the lifetime spectra observed with 250 keV positron beams striking target assembly # 2 and target assembly # 3, respectively. Again, the statistical accuracy of the data shown in these figures is not very high, thus producing rather large uncertainties in the long-component lifetime values.

(*) 250 keV was selected as the test energy for the analyzed positron beams for reasons of workable beam intensity from a Na^{22} source. It is also appropriate for investigating typical composite structural components whose thickness is ~762 μm.

Figures 8(a) and 8(b) show the positron lifetime spectra obtained with the full Na^{22} positron spectrum in dry and water-saturated nylon-6 targets, respectively. It is noted that the positron lifetime in target assembly # 2 (Fig. 7(a)) is in agreement with the value in dry nylon-6 target whereas the lifetime in target assembly # 3 (Fig. 7(b)) is in agreement with the value in wet nylon-6 target within the accuracy of the respective measurements.

CONCLUSIONS

The following general conclusions have been drawn on the basis of the data presented in this report:

1. Positron annihilation spectroscopy can be conducted with magnetically-analyzed positron beams using a conventional, fast-slow, constant fraction positron lifetime spectrometer.

2. Magnetically-analyzed positron beams can be used to monitor non-uniform properties of certain targets--such as non-uniform moisture distribution in molecular substances. This feature is especially useful in measuring moisture profiles in polymeric materials.

However, a much stronger positron source ($\gtrsim$ 25 mc) and longer data recording times would be needed for improved statistical accuracy with magnetically-analyzed positron beams.

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Table I. Summary of Critical Parameters for Positrons Arriving at Target for Magnetic Field Set for 200 keV (Ref. 7)

[Convex source configuration; 1000 positrons emitted at the source]

Parameter	Target Diameter 1 cm	Target Diameter 2.54 cm
Y_c = 9 cm		
E_{β^+} (min), keV	175.83	154.91
E_{β^+} (max), keV	230.75	263.40
τ (min), ps	996.10	982.49
τ (max), ps	1085.64	1118.87
No. of hits	68	174
Y_c = 12 cm		
E_{β^+} (min), keV	187.34	165.20
E_{β^+} (max), keV	218.70	247.30
τ (min), ps	1143.53	1123.25
τ (max), ps	1215.44	1241.45
No. of hits	44	140
Y_c = 16 cm		
E_{β^+} (min), keV	187.94	174.86
E_{β^+} (max), keV	211.70	230.75
τ (min), ps	1350.55	1320.40
τ (max), ps	1411.32	1436.76
No. of hits	38	103
Y_c = 20 cm		
E_{β^+} (min), keV	191.72	179.44
E_{β^+} (max), keV	208.06	224.71
τ (min), ps	1549.43	1518.31
τ (max), ps	1587.12	1610.38
No. of hits	28	77

Table II. Summary of Critical Parameters for Positrons Arriving at Target for Magnetic Field Set for 300 keV (Ref. 7)

[Convex source configuration; 1000 positrons emitted at the source]

Parameter	Target Diameter	
	1 cm	2.54 cm
Y_c = 9 cm		
E_{β^+} (min), keV	272.96	235.58
E_{β^+} (max), keV	347.05	398.60
τ (min), ps	900.02	894.96
τ (max), ps	952.90	972.04
No. of hits	74	161
Y_c = 12 cm		
E_{β^+} (min), keV	277.95	250.92
E_{β^+} (max), keV	328.33	365.64
τ (min), ps	1030.65	1025.05
τ (max), ps	1081.73	1101.24
No. of hits	58	127
Y_c = 16 cm		
E_{β^+} (min), keV	285.76	262.36
E_{β^+} (max), keV	317.88	347.05
τ (min), ps	1210.39	1192.08
τ (max), ps	1253.52	1260.10
No. of hits	44	98
Y_c = 20 cm		
E_{β^+} (min), keV	288.78	272.24
E_{β^+} (max), keV	315.12	332.66
τ (min), ps	1381.06	1367.96
τ (max), ps	1425.30	1433.93
No. of hits	31	84

NOT TO SCALE

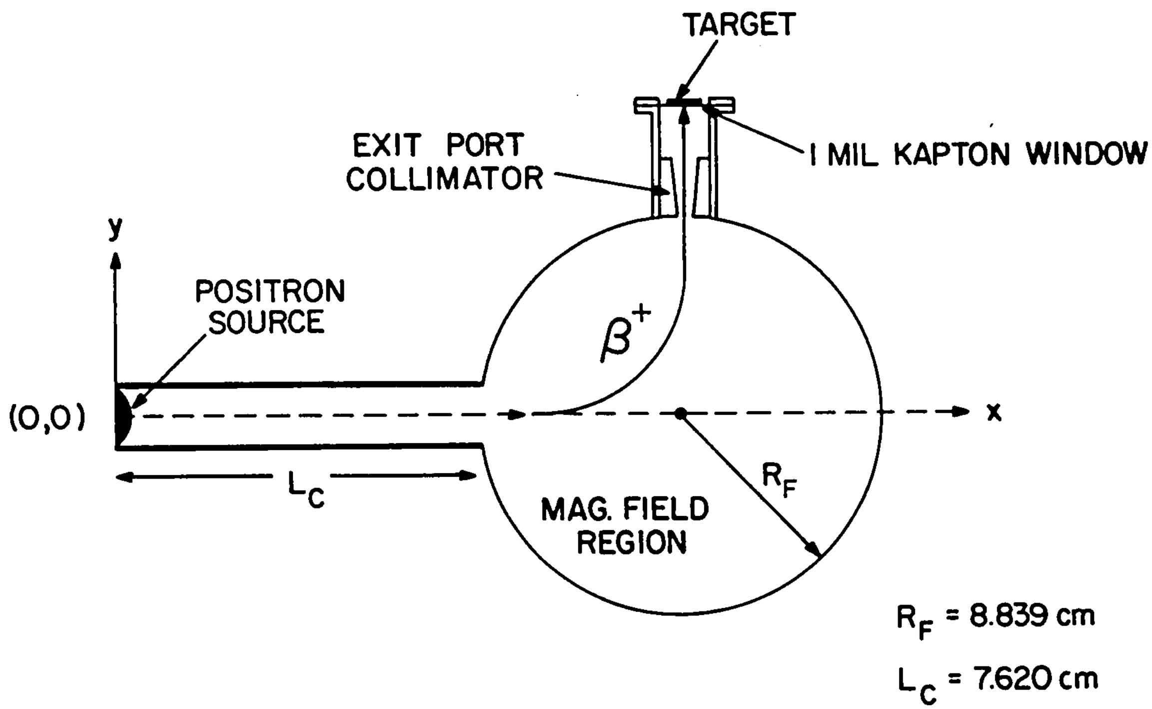
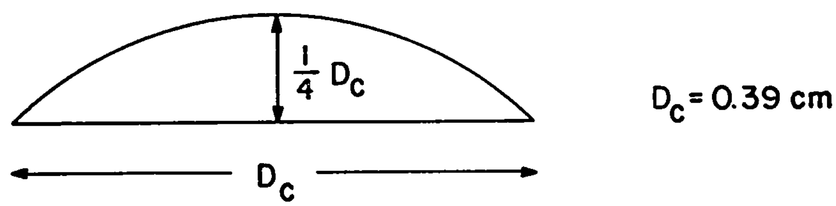
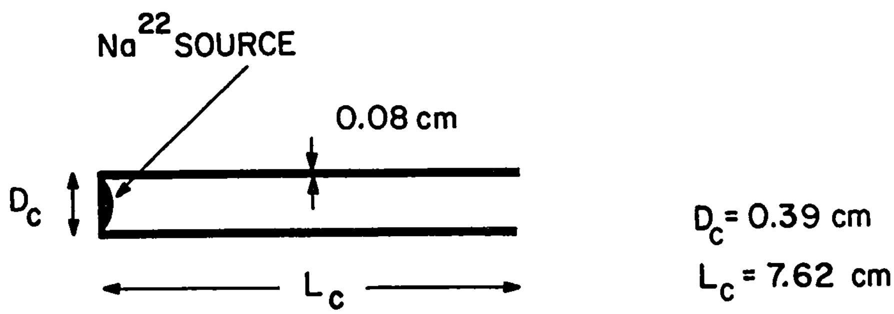


FIGURE 1 - SCHEMATIC DRAWING SHOWING SOURCE COLLIMATOR AND MAGNETIC FIELD REGION.

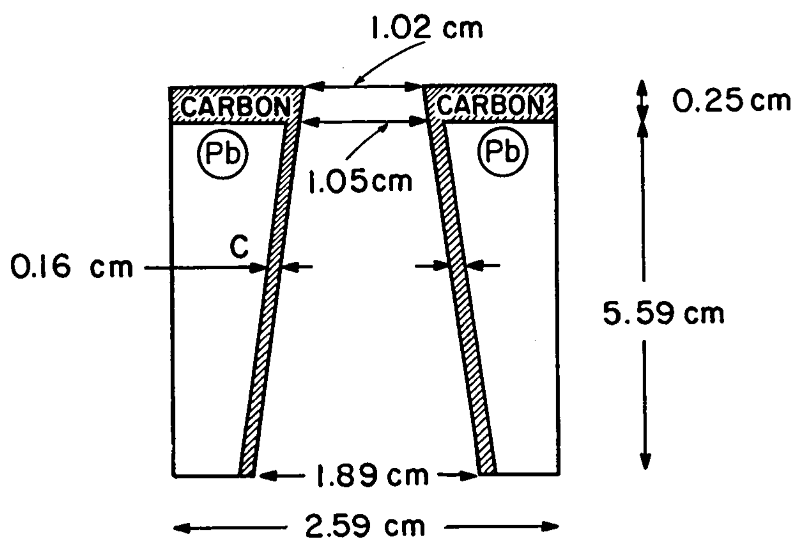
NOT TO SCALE



(a) PROFILE OF Na^{22} SOURCE DEPOSITED AT BOTTOM OF COLLIMATOR SELECTED FOR DETAILED STUDY.

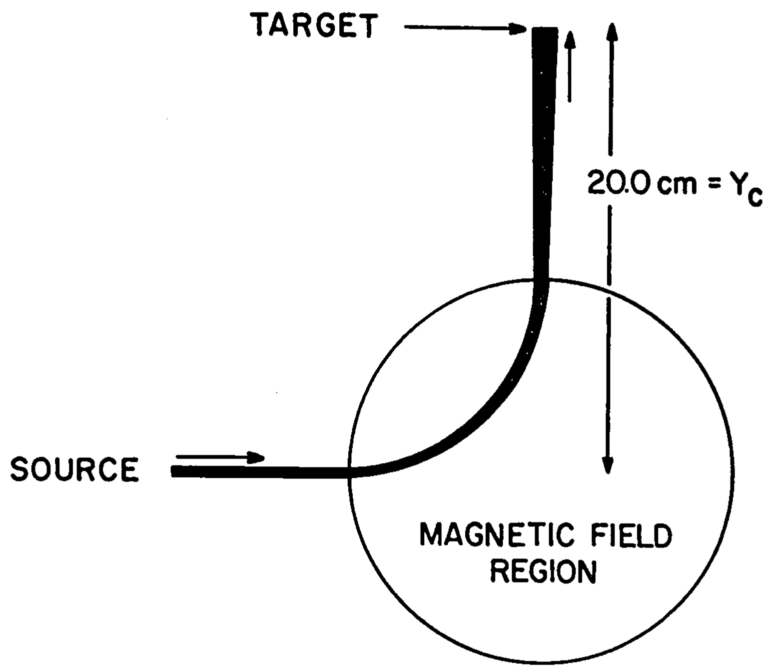


(b) SCHEMATIC DIAGRAM OF SOURCE COLLIMATOR

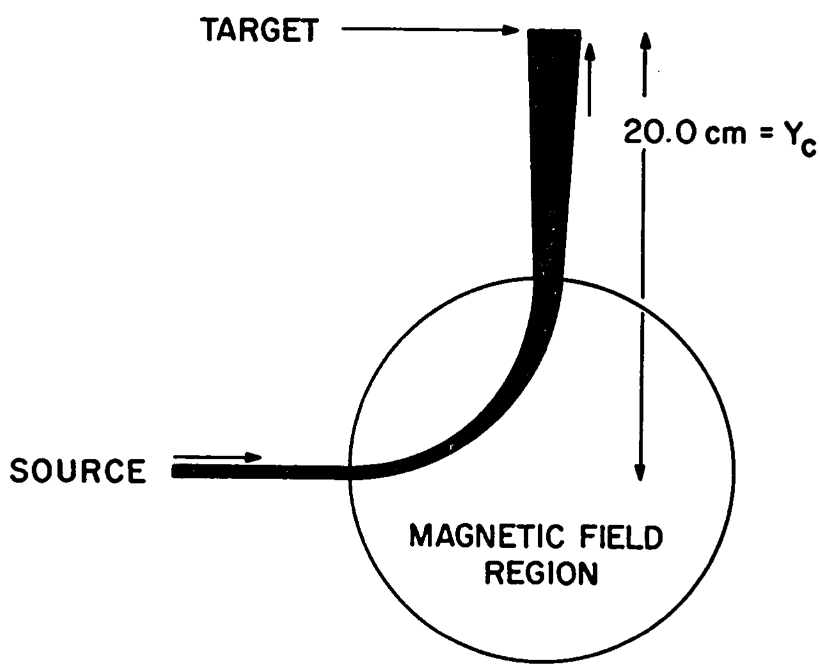


(c) GEOMETRICAL DETAILS OF THE EXIT PORT COLLIMATOR

FIGURE 2.- GEOMETRICAL DETAILS OF THE SOURCE PROFILE, SOURCE COLLIMATOR AND THE EXIT PORT COLLIMATOR.

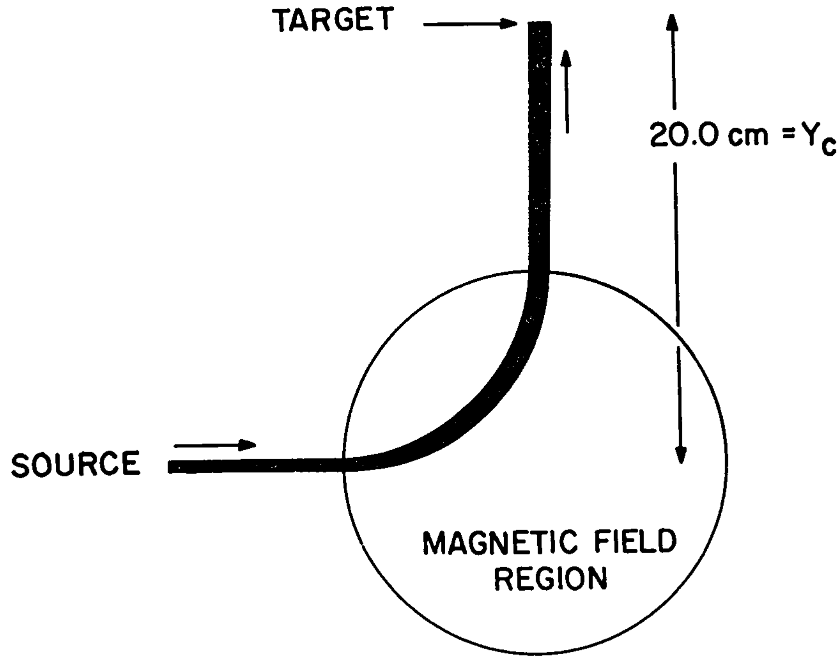


(a) 1-cm-DIAMETER TARGET.

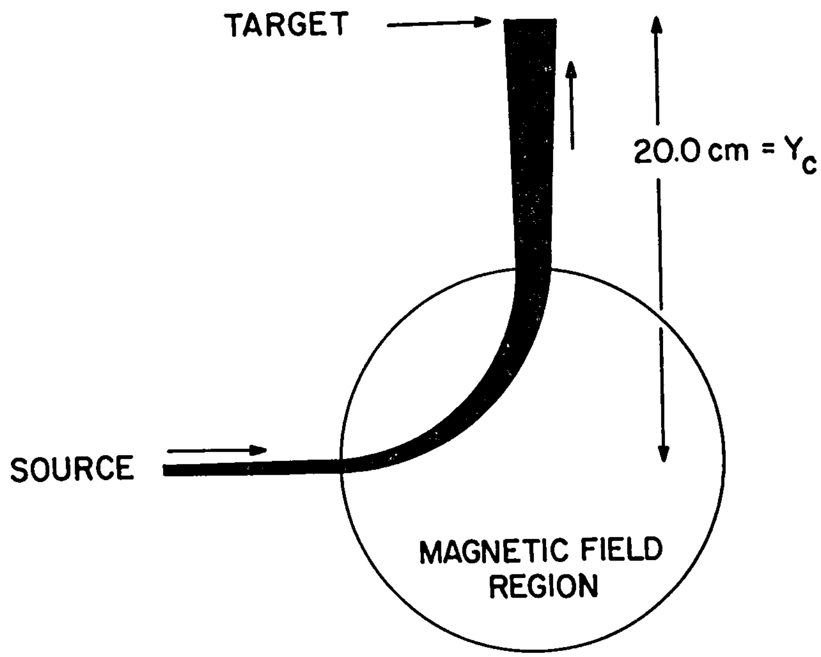


(b) 2.54-cm-DIAMETER TARGET.

FIGURE 3.- TRAJECTORIES OF POSITRONS STRIKING TARGET FROM CONVEX SOURCE CONFIGURATION. MAGNETIC FIELD SET FOR E_{β^+} = 200 keV

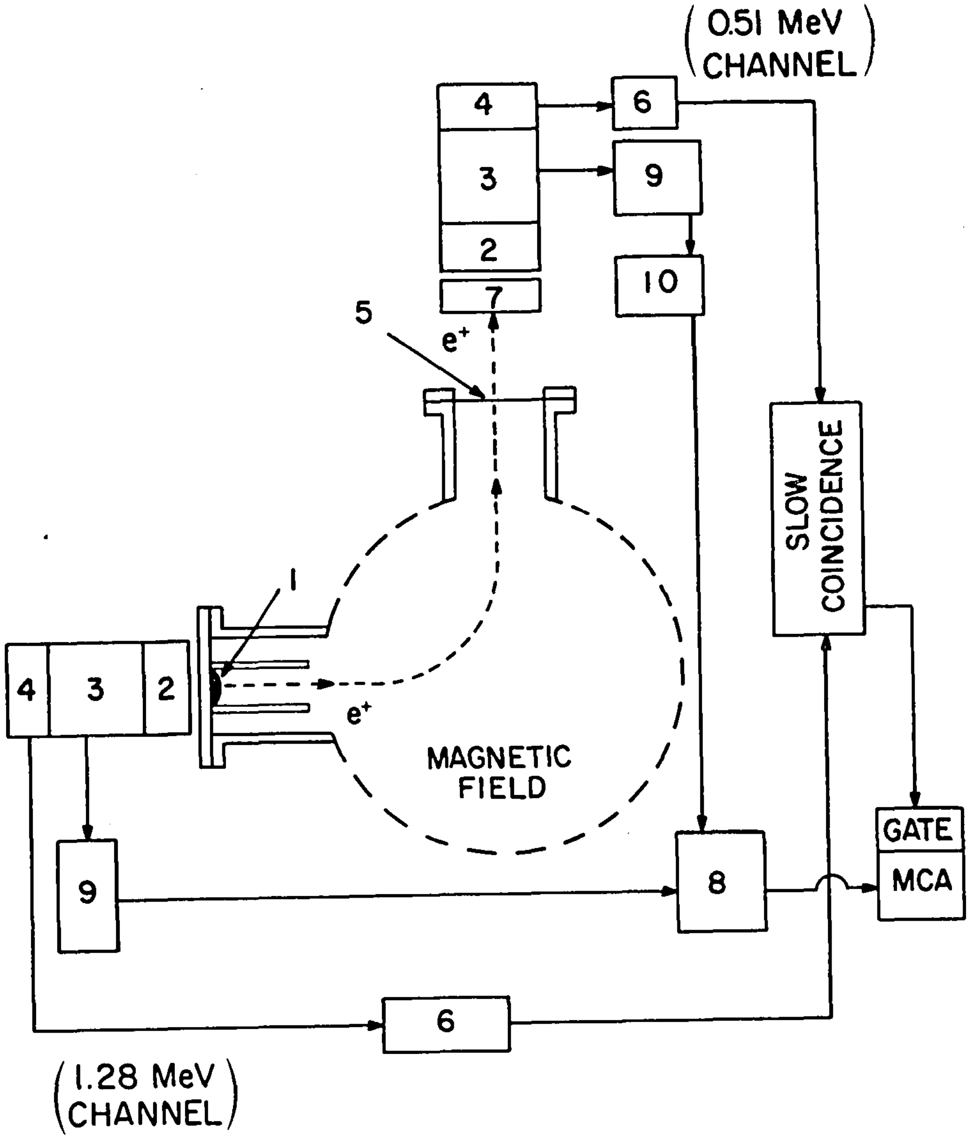


(a) 1-cm- DIAMETER TARGET.



(b) 2.54-cm-DIAMETER TARGET.

FIGURE 4.- TRAJECTORIES OF POSITRONS STRIKING TARGET LOCATED 20 cm FROM CENTER OF MAGNETIC FIELD SET FOR E_{β^+} = 300 keV. CONVEX SOURCE CONFIGURATION.



LEGEND

1 10 mCi COLLIMATED Na^{22} SOURCE
2 PLASTIC SCINTILLATOR
3 PHOTOMULTIPLIER DETECTOR
4 PREAMPLIFIER
5 0.025 mm KAPTON WINDOW
6 AMPLIFIER/DISCRIMINATOR
7 25.4 mm x 25.4 mm x 3.2 mm COMPOSITE TEST TARGET
8 TIME TO PULSE HEIGHT CONVERTOR
9 TIMING DISCRIMINATOR
10 VARIABLE DELAY

FIGURE 5.- SCHEMATIC DIAGRAM OF THE POSITRON LIFETIME MEASUREMENT SYSTEM USING MAGNETICALLY ANALYZED POSITRON BEAMS.

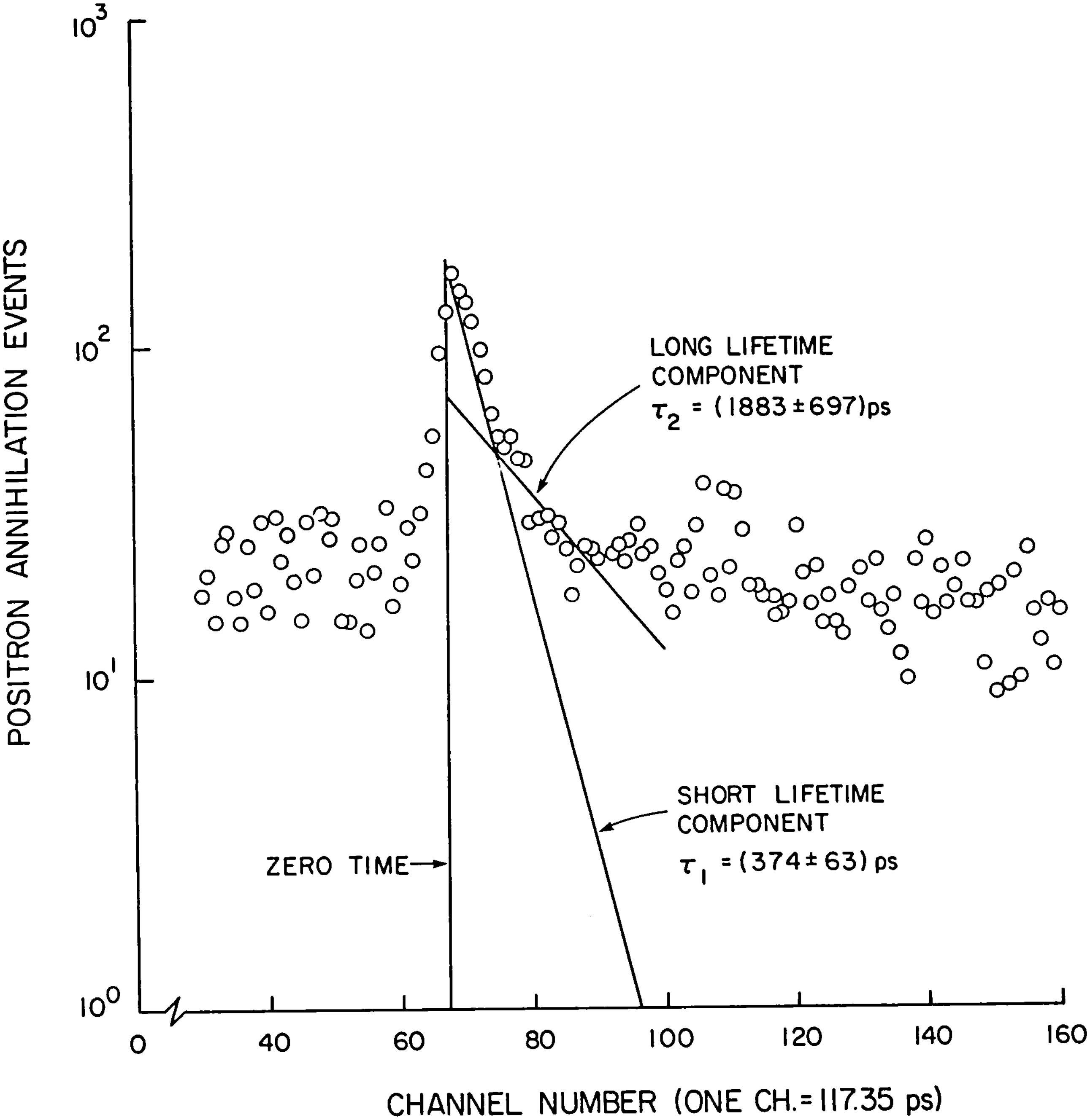


FIGURE 6(a) - POSITRON LIFETIME SPECTRUM OBTAINED WITH 250 KEV POSITRONS INCIDENT ON A LUCITE SPECIMEN.

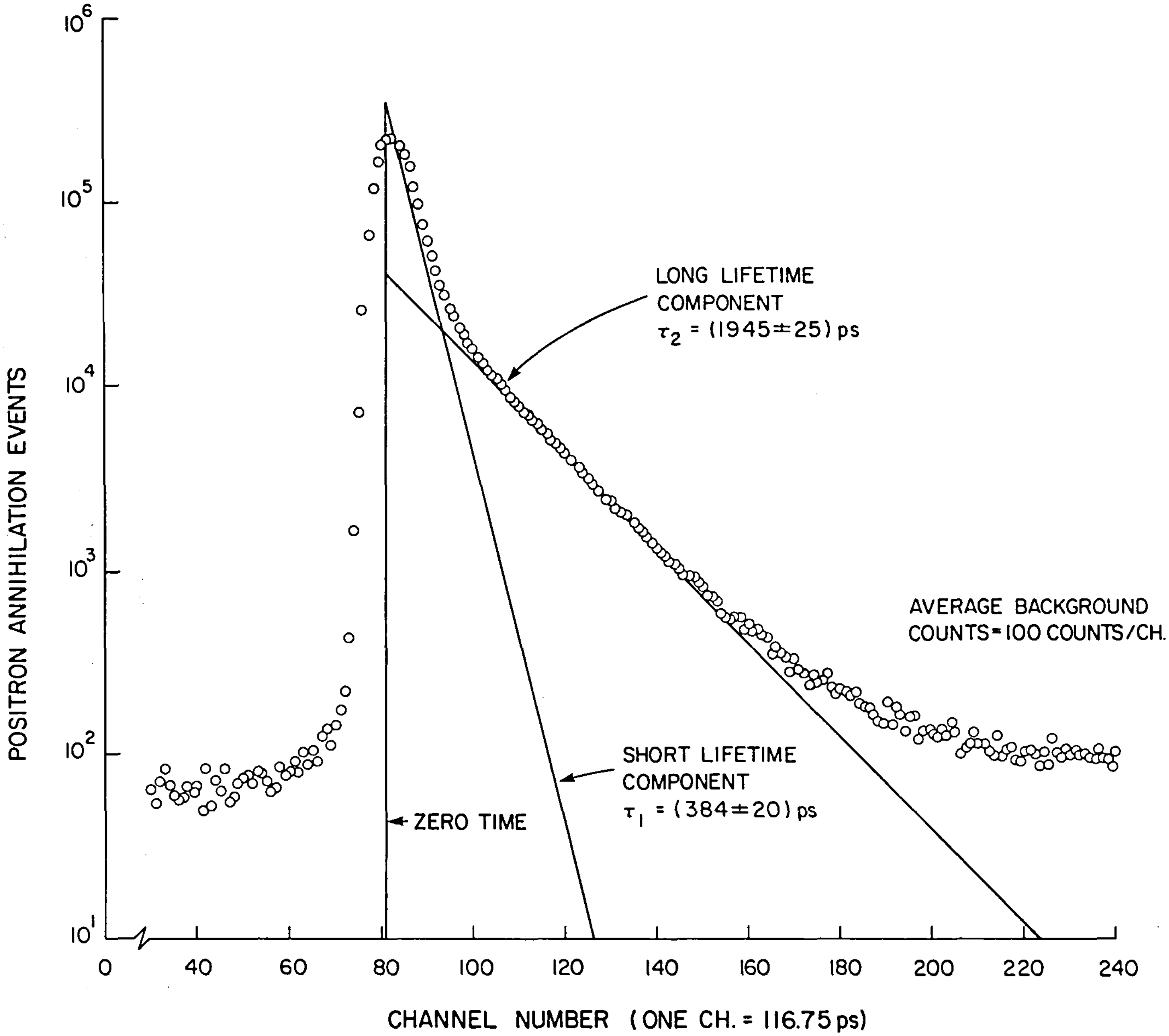


FIGURE 6(b) - TYPICAL POSITRON LIFETIME SPECTRUM IN A LUCITE SPECIMEN USING FULL Na^{22} SPECTRUM.

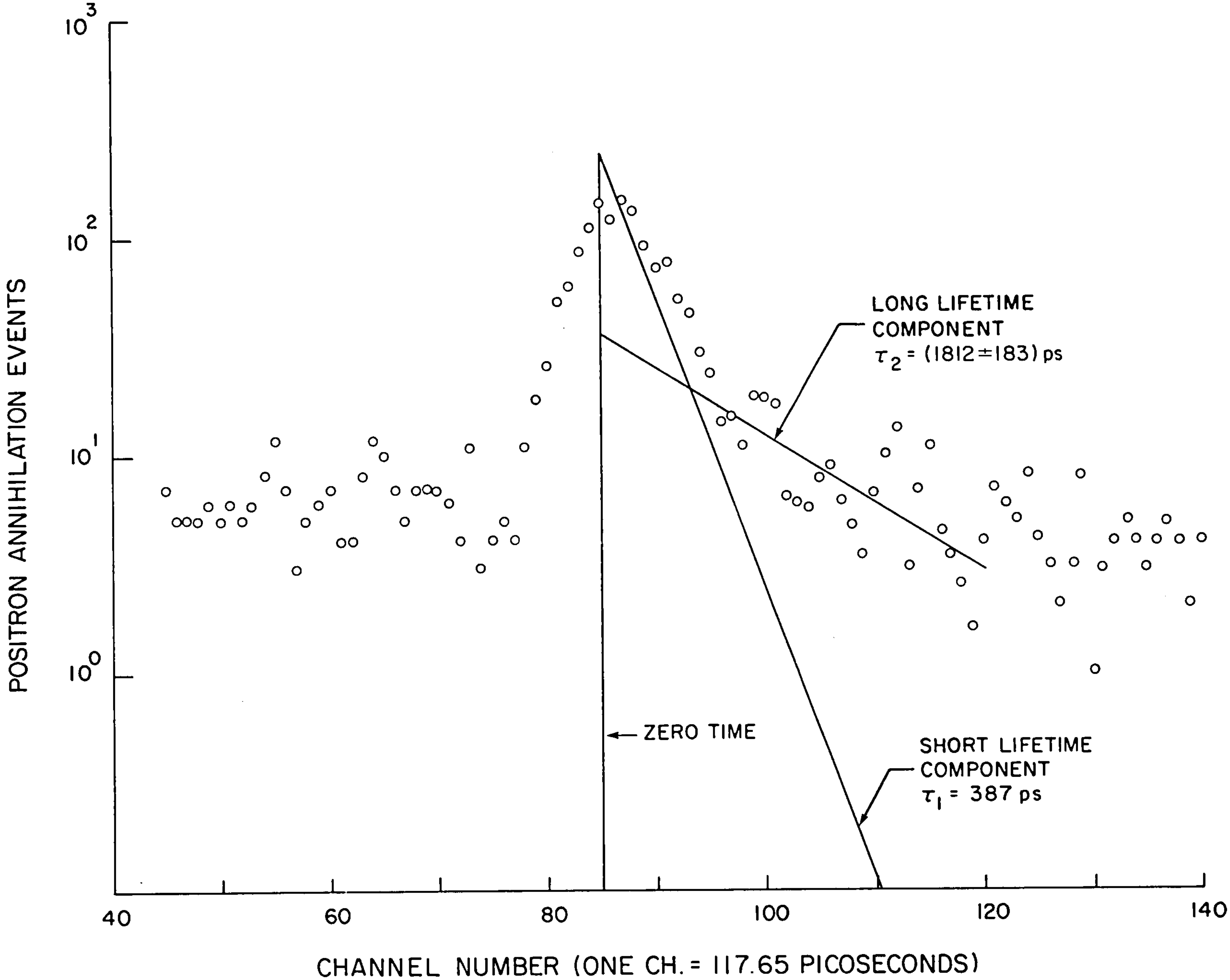


FIGURE 7(a) - POSITRON LIFETIME SPECTRUM OBTAINED WITH 250 KEV POSITRONS INCIDENT ON A NYLON-6 TARGET ASSEMBLY-2 (DRY/DRY).

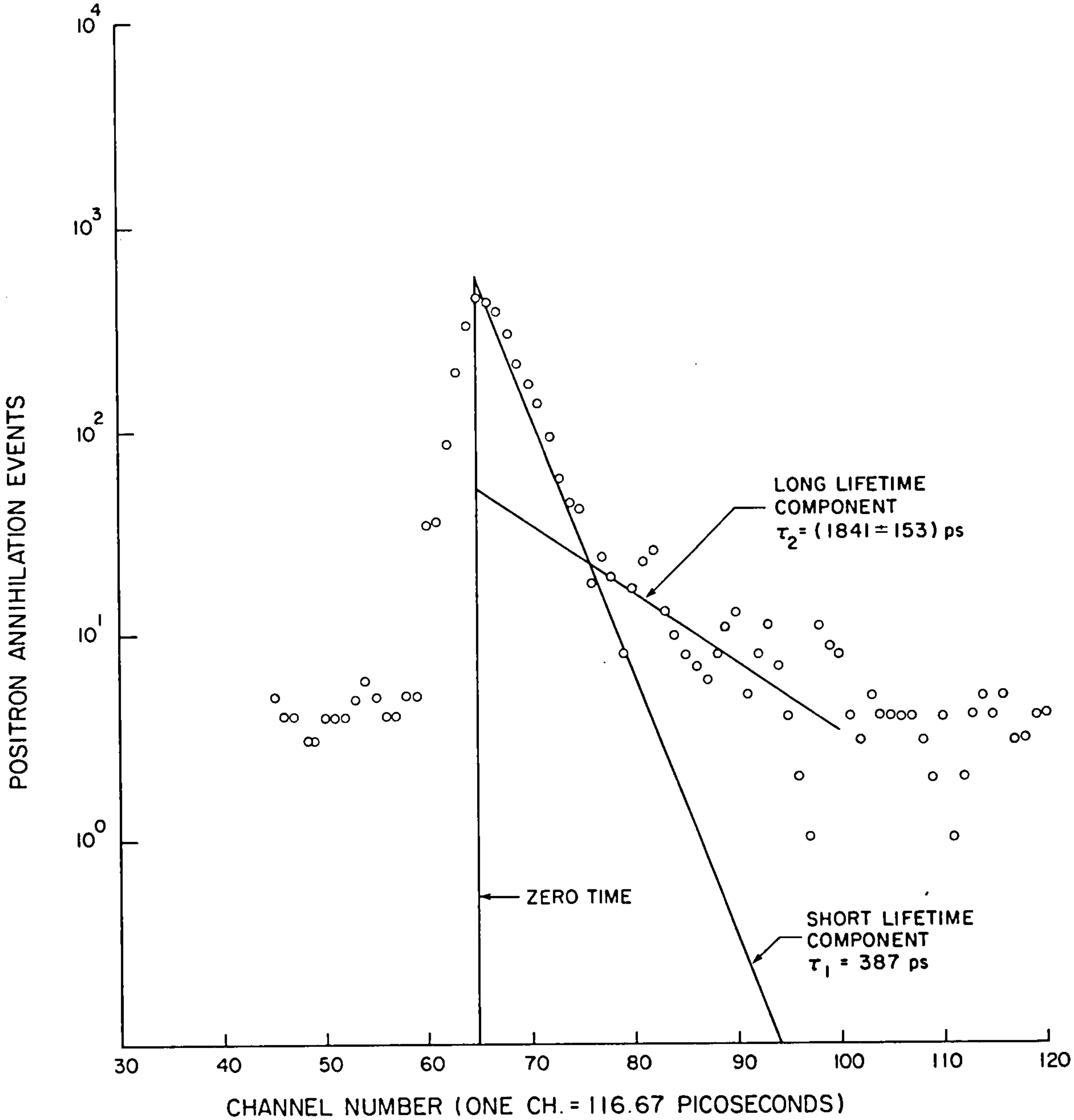


FIGURE 7(b) - POSITRON LIFETIME SPECTRUM OBTAINED WITH 250 KEV POSITRONS INCIDENT ON A NYLON-6 TARGET ASSEMBLY-3 (DRY / WET).

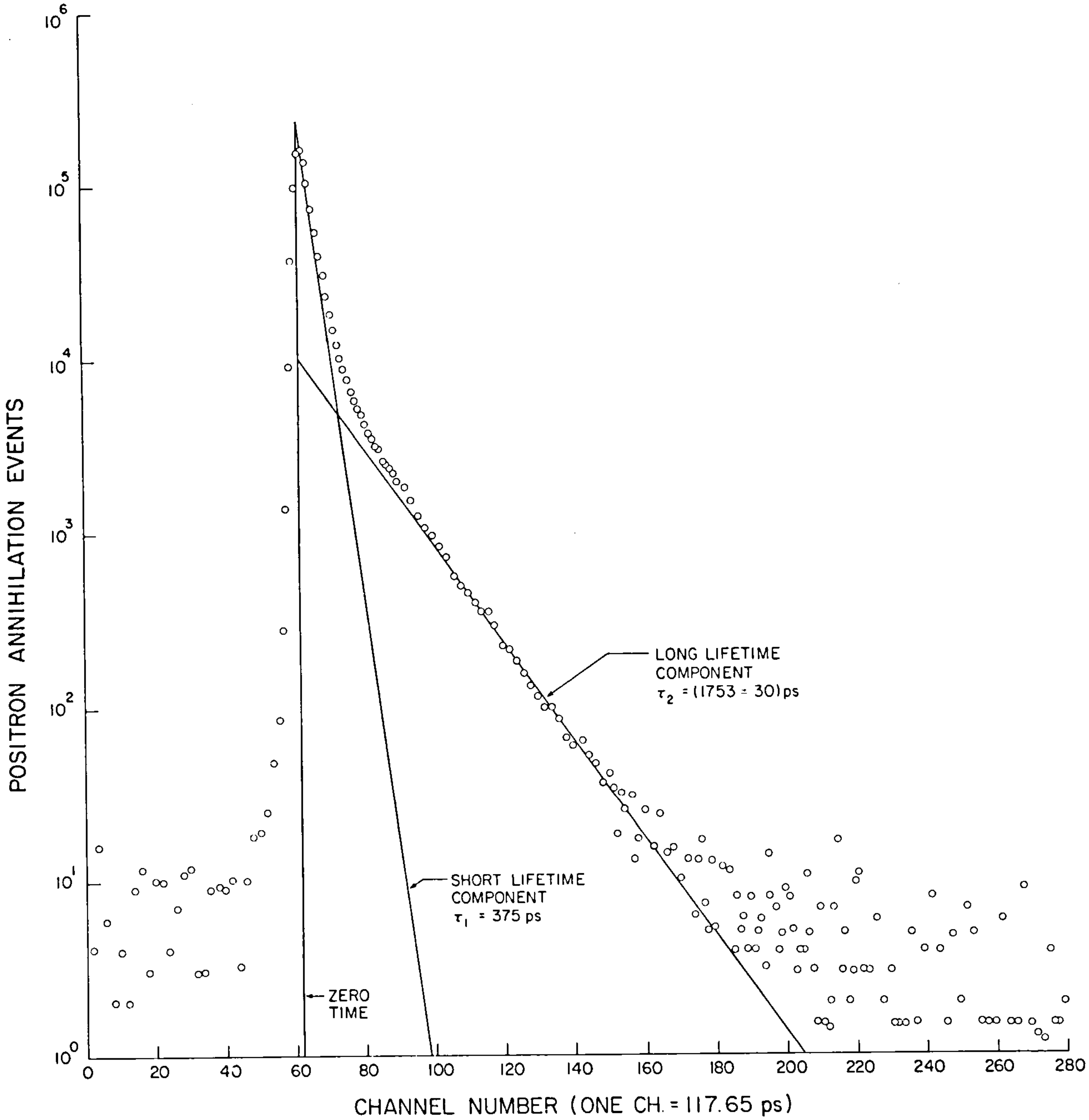


FIGURE 8(a) - TYPICAL POSITRON LIFETIME SPECTRUM IN A DRY NYLON-6 SPECIMEN USING FULL Na^{22} SPECTRUM.

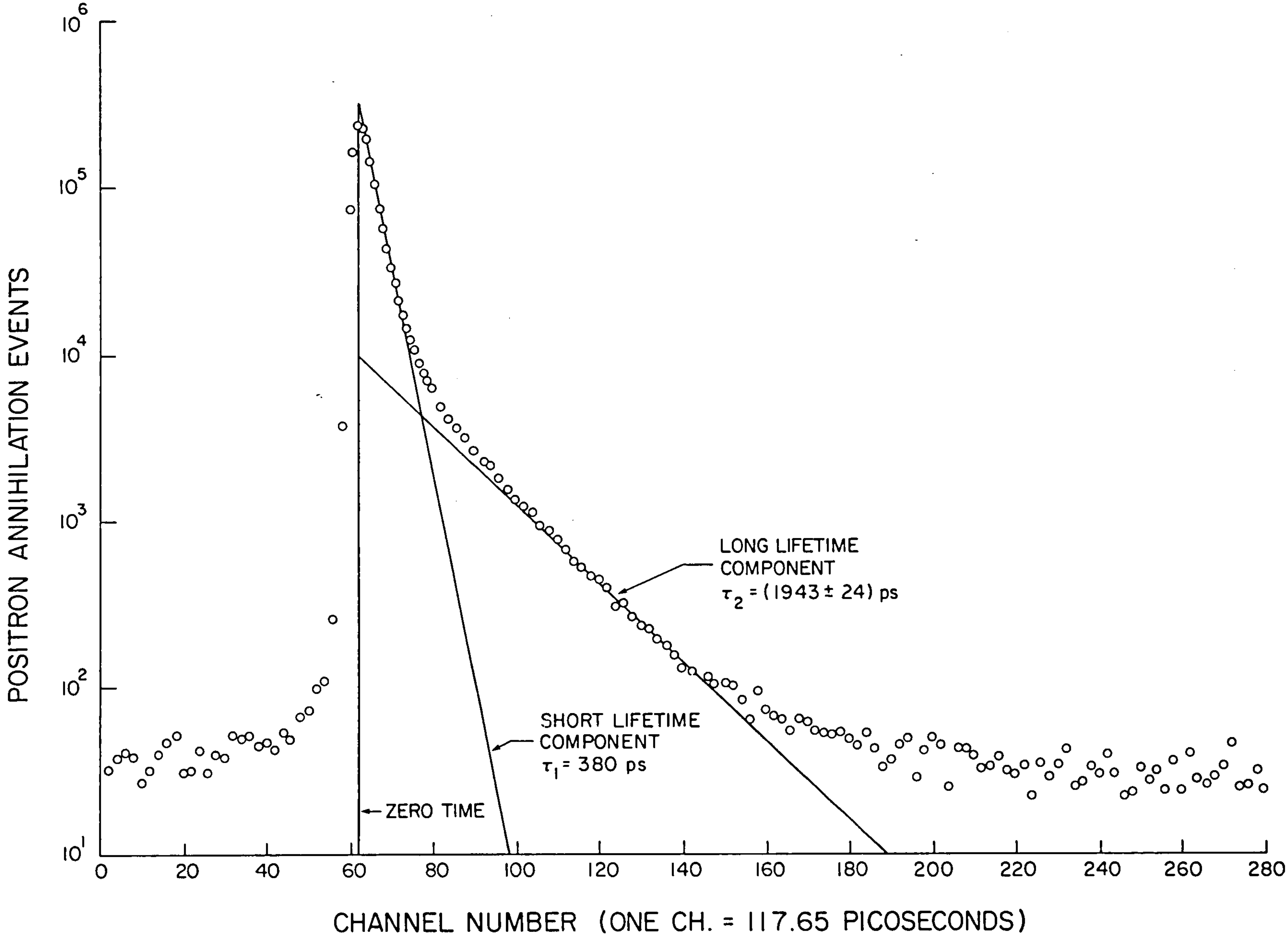


FIGURE 8(b) - TYPICAL POSITRON LIFETIME SPECTRUM IN A WATER - SATURATED NYLON - 6 SPECIMEN USING FULL Na^{22} SPECTRUM.

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15. Supplementary Notes

16. Abstract

Lifetime measurements with magnetically analyzed positron beams have been made in condensed media with uniform and non-uniform properties. As expected, the lifetime values with magnetically analyzed positron beams in uniform targets are similar to those obtained with conventional positron sources. However, the lifetime values with magnetically analyzed beams in targets which have non-uniform properties vary with positron energy and are different from the conventional positron source-derived lifetime values in these targets.

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