POSITRON LIFETIMES IN THE ALKALI HALIDES

by

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CONTENTS

ABSTRACT

The positron lifetimes in the alkali chlorides and sodium halides have been measured. Two lifetimes have been found in each of these materials, with a small fraction (of the order of a few per cent) of the positrons annihilating with the longer lifetime. The lifetimes vary from material to material much more slowly than do the negative ion radii and the average electronic densities. In order to make these measurements a new time-to-amplitude converter that has yielded a time resolution of 3.5×10^{-10} seconds was constructed.

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INTRODUCTION

The time distributions for the annihilation of positrons in a systematically chosen cross-section of the alkali halides were measured. The purpose was to investigate the dependence of lifetime on negative ion radius and on average electronic density. This program required an apparatus with better time resolution than was available, so a new type of time-to-amplitude converter was constructed.

The annihilation of positrons in gases, as well as the properties of the positronium atom can be successfully explained on the basis of quantum electrodynamics, (1,2,3,4, 5,6) so that one may consider the annihilation process itself to be well understood. Experiments to study the annihilation of positrons in liquids and solids were started in 1952 and 1953 (7,8). From these and subsequent experiments, which are summarized by Wallace (9), the following picture emerges:

a) in metals, ionic crystals and valence crystals there exists a single lifetime for positrons, surprisingly constant from material to material, of the order of a few times 10^{-10} seconds (τ_1);

b) in most organic and amorphous substances there is in addition to this main component a second lifetime, ranging in magnitude from 10 to 300 $\times 10^{-10}$ seconds (τ_2), with the fraction of the positrons annihilating with this lifetime (I_2) varying from about 10% to 50%, but being about 30% in most cases.

Recently, Bell and Jørgensen (10) have shown that there is also a longer lifetime component of very weak intensity in aluminum and some of the alkali metals. Perhaps there is some amount of long component in all materials. Although the experimental results for annihilation are in many cases understood at least qualitatively, it is true that there is no satisfactory explanation of the magnitudes of the lifetimes or of I_2 in most cases.

Ferrel (11) argues that in the alkali halides there should be no positronium formation, so that a long component will probably not be observed in these materials. Further, he argues that the lifetime should vary directly as the cube of the negative ion radius. Measurements by Green (12) on LiF, NaI and NaCl do not bear out this prediction; also, he observes no long component. Recently Bell and Jørgensen (unpublished) have measured the annihilation time distribution in NaCl; their results indicate the existence of a long component. Also recently, Millet (private communication to Prof. R.E. Bell) has measured the lifetime distributions for all the alkali halides. His results show a short lifetime of the order of 2 to 4 $\times 10^{-10}$ seconds, and a longer component about twice this length with an I_2 ranging from about 10% to 30%. However his results show no regularities in the variations of the lifetimes and of I_2 from material to material; this is unexpected since almost every chemical property of these materials varies systematically.

Stewart and Pope (13) have measured and analyzed the angular correlations between the annihilation quanta from annihilation in the sodium halides and alkali chlorides. The angular correlations for some of these materials have been measured by others (14, 15, 16) and Ferrel (11) has given an analysis of some of these results.

In view of the somewhat surprising nature of the lifetime measurements for these materials, and the fact that the angular correlations for a systematic cross-section of them have been measured and analyzed, it was decided to measure the lifetime distributions in the sodium halides and alkali chlorides.

This program puts rather strict conditions on the apparatus used: it must be capable of accurate measurement of lifetimes of the order of $3X10^{-10}$ seconds, since the purpose is to decide whether there is a systematic variation in lifetimes that are of this order and are not too different.

APPARATUS AND METHOD OF MEASUREMENT

A. General

In order to satisfy these conditions a fast-slow coincidence circuit (17) incorporating a time-to-amplitude converter (TAC) was constructed. In general terms, such a system works as follows. A source of positrons which emits a gamma-ray and a positron simultaneously is embedded in the material to be studied. (Fig. 1) Two output signals are taken from each of two scintillator-photomultiplier detectors. The dynode outputs are fed into the slow coincidence circuit; the function of this circuit is to gate the kicksorter on only when a desired type of event has occured. (That is, it gives out a pulse only when the gamma-ray simultaneous with the creation of the positron is detected by counter A with a certain pulse height, and one of the annihilation quanta is detected by B with a certain pulse height). The anode outputs of the photomultipliers are used to measure the lifetime of a positron; this is accomplished by a time-to-amplitude converter. Essentially, this circuit gives out a voltage pulse whose height is proportional to the time between the two anode pulses; this pulse is fed into the gated kicksorter, whose voltage scale thus becomes, in effect, a time scale.

B. Some Aspects of Fast Lifetime Measurements from Slopes. Choice of Circuit Elements.

If a gamma-ray source which emits two quanta simultaneously (a "prompt" source) is placed between the two scintillators, an ideal time-measuring circuit would produce output pulses all of identical height; of course, this is not the case in practice. Figure 2 shows a typical prompt curve, P(x); that is, a pulse height distribution obtained when using a prompt source at equal distances from both scintillators. This curve (if normalized to unit area) can be interpreted as the probability that two gamma-rays emitted simultaneously from the source yield a time-analogue pulse whose height is x units. The linearity of the time scale can be checked by placing a prompt source at different distances from each of the scintillators and observing the positions of the centroids of the resulting pulse height distributions. The same effect can also be accomplished by inserting various lengths of cable between one of the detectors and the TAC.

Now suppose the prompt source is replaced by a "delayed" source, that is, one in which one of the gamma rays follows the other by a detectable time. Also suppose this source exhibits two lifetimes; that is, the probability density that the delayed gamma-ray is emitted a time t after the one in coincidence with it is given by

$$p(t) = I_1 \lambda_1 e^{-\lambda_1 t} + I_2 \lambda_2 e^{-\lambda_2 t} \quad , \text{[redacted]}\ t \geqslant 0$$

$$= 0 \quad , \ t < 0 ,$$

$$I_1 + I_2 = 1 .$$

Then the observed pulse height distribution (normalized) will be

$$D(x) = \int_{-\infty}^{\infty} p(t)\, P(x-t)\, dt .$$

Then,

$$D(x) = I_1\lambda_1 e^{-\lambda_1 x}\left(\int_{-\infty}^{x} e^{\lambda_1 y} P(y)\,dy\right) + I_2\lambda_2\left(\int_{-\infty}^{x} e^{\lambda_2 y}\,dy\,P(y)\right)e^{-\lambda_2 x}$$

Using this expression it is not hard to show that

$$\frac{d}{dx}\left(\ln D(x)\right) = \left(I_1\lambda_1 + I_2\lambda_2\right)\frac{P(x)}{D(x)} - \lambda_1\frac{1}{1+\frac{D_2(x)}{D_1(x)}} - \lambda_2\frac{1}{1+\frac{D_1(x)}{D_2(x)}}$$

where

$$D_1(x) = I_1\lambda_1\, e^{-\lambda_1 x}\int_{-\infty}^{x} e^{\lambda_1 y}\, P(y)\,dy$$

$$D_2(x) = I_2\lambda_2\, e^{-\lambda_2 x}\int_{-\infty}^{x} e^{\lambda_2 y}\, P(y)\,dy$$

which are just the expressions for the distributions that would be obtained from two delayed sources each with a single lifetime $1/\lambda_1$ or $1/\lambda_2$ in them, multiplied by the constants I_1 and I_2 respectively. Now, in the region where the delayed curve is much larger than the prompt curve, the delayed curve will first show a slope $-\lambda_1$, and then curve over to a slope $-\lambda_2$, so the lifetimes can be found by slope measurements on a logarithmic plot.

Also, at large x,

$$D(x) \simeq I_2\lambda_2\, e^{-\lambda_2 x}\left[2\tau_2/W \sinh W/2\tau_2\right]$$

where W is the full width at half maximum of the prompt curve, and the origin for x is taken at the centroid of the prompt curve.

Hence, I_2 can be found by extrapolating the straight longer lifetime component of the delayed curve back to the centroid position of the prompt curve and using the height of the intercept to calculate I_2. The factor $2\tau_2/W \sinh W/2\tau_2$ is usually very near unity. Finally, $I_2 =$ (intercept $\div$ total counts in delayed curve) X τ_2 (in channels) $\div$ $2\tau_2/W \sinh W/2\tau_2$

The condition that all the above formulas be true is that the prompt curve is everywhere much smaller than the delayed curve in a region to the right of the peak of the delayed curve which is broad enough so that both slopes in the delayed spectrum are well defined. Hence, a prompt curve which is narrow and whose right hand side falls quickly (with respect to the delayed curve to be obtained) is the criterion to be used in deciding whether the resolution is satisfactory.

It is to be noted that if a prompt curve and a delayed curve with a single lifetime in it are obtained under the same conditions of all the apparatus, the difference in their centroid positions is equal to the mean lifetime of the delayed source (18). Now, because a centroid is so well defined statistically, this method can be used to measure lifetimes so short that a slope measurement is impossible. However, it is extremely difficult to obtain both curves under the same conditions; for example, a slow drift in centroid position will spoil this method entirely, whereas it would not change the results of a slope measurement appreciably.

The choice of scintillator and photomultiplier is governed by the time resolution required (17, 19). The resolution is a function of the ratio of the light pulse decay time to the number of photoelectrons produced by the pulse. Hence, a scintillator for which the ratio of the light pulse decay time to the efficiency of conversion of gamma-ray energy to light is as small as possible is desirable for short lifetime measurements. Also, then, the photocathode used should have as high an efficiency as possible. It is also evident that transit time jitter in the photomultiplier will broaden the prompt curve. Hence a photomultiplier with high cathode efficiency and small transit time jitter is required. It was found that $1\frac{1}{2}$" X $1\frac{1}{2}$" NE 102 plastic scintillators in conjunction with 56AVP photomultipliers were satisfactory. Using Pilot B plastic scintillators of a smaller size gave better resolution, but for the sake of a higher counting rate the larger scintillators were used.

The pulse shaping was done via a limiter pentode (404A, $g_m = 13$ mA/V) following the anode of each photomultiplier. By cutting off the standing current in these tubes, one can obtain two pulses at the TAC of convenient and controllable height.

It was found that the resolution obtained is a function of the size of the photomultiplier pulses used to cut off the limiters. Now, the TAC measures, in some sense, the difference between the mean times of occurrence of the two limiter pulses. This mean time is equal to the time of arrival of the gamma-ray in the scintillator plus some average over the times of arrival of all the electrons that hit the photomultiplier anode before the limiter is cut off. So it seems that there is an optimum part of the photomultiplier pulse over which averaging should be done. No good theoretical estimate of the time resolution to expect from a TAC exists, so various circuits were tried.

Originally, a biased diode followed by an integrating capacitor was used (10, 20). The effect of the circuitry alone was tested by running the output pulse from a mercury relay pulse generator down two branched cables to the grids of the limiter pentodes. Thus all the circuitry was being driven by pulses that were always the same shape and size, and had no relative time jitter. It was found that the width of the prompt curve so obtained was about ten times smaller than that obtained under experimental conditions. So it was concluded that the circuitry contributed only about 0.5% to the width of the prompt curve, and there would be no point in changing the TAC circuit. However, when the circuit now being used was installed (see below), it was found that the width of the prompt curve improved by about 30%, and the slope of the right hand side (logarithmic plot) got steeper by about 40%. This is a considerable improvement, as can be seen by recalling that the real criterion is how fast the right hand side of the prompt curve becomes less than, say, one-twentieth of a delayed curve. It is also to be noted that the photomultiplier pulse heights that gave the best result in each case were about 50% different from those for the previous circuit. Thus it seems that the time resolution is some complicated function of the averaging done by all the circuitry which handles the fast timing pulses.

C. Description of Apparatus

1. Photomultiplier Voltage Divider

The photomultiplier voltage divider chain (Figure 3) is "tapered"; that is, a larger accelerating voltage appears across the first few dynode-dynode spaces than that across the later ones. This is done in order to minimize the effects of random fluctuations in dynode gains and of transit time variation in the cathode to first dynode space. The average dynode gain is an increasing function of inter-stage voltage, so this scheme makes the number of electrons in the pulse large as soon as possible; the average transit time is a decreasing function of inter-stage voltage, so this scheme also minimizes the magnitude of the variations in it. The outputs from the dynodes go through cathode followers to the slow circuit, which is described later.

2. Limiter Pentodes

The limiter pentodes are operated with 25mA standing current. The plate load resistor is about 185 ohms in order to match the impedance of the RG/114U cable following the tube, so that no reflections in the cable will reach the TAC. The output pulse height for any input pulse cutting off the limiter is over two volts. The feed-back from the top of the plate load resistor to the grid stablizes the D-C value of the sum of the plate and screen currents. This has the disadvantage that the standing current is a function of the total counting rate and a weak function of the shape of the energy spectrum of the source, but it gives good current stability for any fixed set of conditions..

3. Delay Cables

Long delay cables (185 ohms impedance) are used to carry the limiter pulses to the TAC. At the junction of these cables is a shorted clipping cable (93 ohms impedance) 15 milli-microseconds (ns) in length. Hence, at this junction, the pulse from each limiter is 30 ns in length (Figure 4). A cable switching unit was constructed which allowed one to vary the length of cable between the limiter on side B and the TAC, in 1 ns steps. By choosing the lengths of all cables properly it was arranged that the back end of the B pulse could be varied with respect to the leading end of the A pulse from -2 ns to 21 ns. In actual use, this was set so that the pulses overlapped by about 7 ns for prompt events (Figure 4).

4. Time-to-Amplitude Converter (TAC)

The TAC (Figure 4) used is rather novel. The principle is as follows. The TAC, whose last component is an integrating capacitor, forms a pulse whose height is proportional to that area of the overlapping limiter pulses which lies above the height of a single pulse. Thus, if two pulses leave the limiters at exactly the same time, the TAC integrates the area of 7 ns overlap which is determined by the cable lengths; if the pulse from B is delayed by a time t ns, then the area measured is that of a (7+t) ns overlap. This is accomplished as follows. The first pentode (D3A,g_m =35mA/V) is biased off so that a single pulse just barely puts it into conduction, but the overlap part of the pulses puts the tube well into conduction. Since the g_m is so high a pulse appears at the plate which is large enough to cut off the next pentode. Since the tube characteristic is quite non-linear near cut-off, the first part of the overlap has little effect on this pulse. The next pentode's grid is tied up to B voltage through a large resistor, so that the grid is slightly positive with respect to the cathode. This means that the first part of the pulse has little effect in cutting off the tube. Also, the top part of the pulse has little effect for the pulse is more than large enough to cut off the tube completely. This arrangement yields the advantage that the time for which this tube is cut off is mainly independent of the rise times (and heights) of the limiter output pulses, for it depends almost solely on the separation between the steep parts of the overlap pulses. The output pulse is formed by an integrating capacitor from the plate of this second pentode to ground.

There are no milli-microsecond pulses after this point in the circuit. The time analogue pulses are inverted because the kicksorter will accept only negative pulses, and are delayed in order that they will arrive at the kicksorter a little after the gate pulse which is generated by the "slow" circuit.

5. "Slow Circuit"

The source of positrons used was Na^{22}. This gives out a 1.28 MeV gamma-ray simultaneous with the creation of a positron. The energy spectrum observed using the plastic scintillators is a Compton distribution due to the gamma-rays ending at about 1 MeV, with the Compton distribution due to the annihilation radiation (0.511 MeV) superimposed on it and ending at about one-third MeV.

The "slow" coincidence circuit (Fig. 1), which contains only conventional circuit elements works as follows. The dynode output pulses are fed through cathode followers into amplifiers and then into single channel analyzers. The window of the A, or prompt side, analyzer is set on the upper edge of the 1.28 MeV gamma-ray Compton distribution. The window of the B, or delayed side, analyzer is set on the upper edge of the 0.511 MeV gamma-ray Compton distribution. The outputs from these analyzers are fed into a diode coincidence circuit whose output triggers a flip-flop circuit which forms the gate pulse. Thus, a true coincidence can occur only when a 1.28 MeV gamma-ray causes a pulse to lie in the window of the A analyzer and a 0.511 MeV gamma-ray due to the annihilation of the corresponding positron causes a pulse to lie in the window of the B analyzer.

The resolving time (21) of the slow coincidence circuit was about 0.5 microseconds. The fast circuit gives out a pulse only if it receives two pulses within 60 ns of each other, so that, considered merely as a coincidence circuit, it has a resolving time of 60 ns (Hence the term "fast coincidence circuit"). The number of chance coincidences per channel, then, is given by

$$2wN_1N_2\ T$$

where w is the time width of one channel

N_1, N_2 are the counting rates in the windows of the analyzers

T is the total counting time.

The factor 2 arises because, due to the nature of the overlap system there are two ways to get a single output pulse height. A slight addition to the circuitry could remove this factor but this was not necessary for the measurements discussed here.

D. Time Calibration Procedure

Time calibrations were always done by using the actual source on which the measurement was to be performed. The time-analogue spectrum was counted for the same preset time for a number of lengths of cable between the B detector and the TAC. These lengths were varied in 1 ns steps using the cable switching unit. The delay time inserted was plotted against the positions of the peaks of the distributions. The slope of this line is the desired time calibration factor.

E. Resolution

Using 1" X 1" Pilot B plastic scintillators, the resolution obtained was: full width at half maximum ($W_{\frac{1}{2}}$) of 3.4×10^{-10} sec., slope of right hand side corresponding to a mean lifetime (τ_{RHS}) of 0.78×10^{-10} sec. This is appreciably better than had been previously attained. One of the scintillators was slightly tapered, the broader end being at the photomultiplier. The scintillator and the tops of the photomultipliers were covered with aluminized mylar foil.

Using $1\frac{1}{2}$" X $1\frac{1}{2}$" NE102 plastic scintillators, which had a powder reflector impacted onto their surfaces, the resolution obtained was $W_{\frac{1}{2}} = 4.0 \times 10^{-10}$ sec., $\tau_{RHS} = 1.2 \times 10^{-10}$ sec. The prompt curves obtained while using these scintillators have tails on their bottom right hand sides with slopes corresponding to a mean lifetime of about 2×10^{-10} sec.

All the prompt curves were obtained using a Co^{60} source, with the pulse height selectors of the slow circuit set up as if for 1.28 MeV - 0.511 MeV gamma-ray coincidences.

Although this TAC yields better resolution than any other, in its present form the linear region is quite restricted (though large enough to perform the measurements reported here).

EXPERIMENTAL MEASUREMENTS

A. Source Preparation

The Na^{22} source was made as follows. About ten microliters of $Na^{22}Cl$ solution was deposited in a drop on 2.7 mgm./cm^2 Al foil which had been degreased. This gave an activity of the order of ten microcuries. The foil was then folded over so the drop was roughly in the middle of the resulting source, and had one foil thickness of Al on each side of it.

The alkali halide material to be studied was ground to a coarse powder and dried by heating it almost to its melting point for about ten minutes. It was immediately placed in an oven and allowed to cool to about 80 degrees C. Then a plastic box about 2 cm x 2 cm x 2 cm, which had been in the oven for some time was half filled with the powder. The Na^{22}-on-Al source was placed on this powder and centered. Then the rest of the box was overfilled with the material. The cover was pressed on and the edges sealed with Scotch black electrical tape. Using this procedure it was found that even the extremely hygroscopic NaI poured as freely and was as free from lumps twenty-four hours later as when it was sealed. About 10% of the positrons will annihilate in the aluminum foil in this arrangement. As it turns out, the annihilation properties of the alkali halides are similar to those of aluminum, so no correction is needed.

B. Experimental Procedure

The photomultiplier gain which gave the best time resolution had been determined. The widest analyzer windows that did not appreciably degrade the time resolution were used throughout the experiment. A source was prepared and placed between the detectors with the plane of the Na^{22}-on-Aluminum source parallel to the end-windows of the photomultipliers. A time calibration was done, then the time-analogue distribution was counted for from eight to twenty hours. The data was read out and a Co^{60} source used to obtain a prompt curve while the next source was being prepared. Then a time calibration was done with the new source, etc. In this way one obtained a time calibration and a prompt curve before and after every measurement, so that any drifting could be detected.

The chance counts per channel were calculated and subtracted from the data before plotting the graphs.

C. Alkali Halide Distributions and Results

1. Long Component not Due To Instrumental Effects

The results of this experiment are listed in Table 1. Figure 5 shows two typical delayed curves and a prompt curve. The curve for NaI and the prompt curve are drawn on the same scales and to the same area. It is obvious that the right hand part of the prompt curve is everywhere much less than the delayed curve, so the tail on the delayed curve is not due to instrumental effects.

2. Determenation of τ_1 and τ_2

The NaI distribution is an example of a curve with a relatively well defined τ_2. The KCl curve is an example of the opposite extreme. In analyzing these curves the τ_2 line was chosen so that, as well as being a reasonable fit to the points in the tail, the τ_1 line, which is the difference between it and the original curve, was straight over three decades. This was of considerable help in fitting such cases as KCl.

3. τ_0?

Some of the curves (NaF, KCl and CsCl) exhibit a prompt bump near the top. (See the KCl curve). This looks as though it could be due to fast annihilations in the Al source, but this suggestion is untenable since the same source was used in all cases and the curves having this effect are not for materials which would give rise to more back-scatter than the others. Perhaps there is a small component of lifetime shorter than the one called τ_1.

4. Determination of I_2

To get I_2, one wishes to know the height of the τ_2 line at the position of the centroid of the prompt curve. Since the centroid position seemed to be more sensitive to counting rate than was felt tolerable, the following procedure was used: after subtracting the τ_2 line, the centroid of the remaining curve was determined. The centroid position of a prompt curve was then taken to be to the left of this position by an amount equal to τ_1.

D. Effect of Moisture

Some curves for NaCl that had not been dried were obtained. These show an I_2 of about 65%. Obviously, then, the drying is important. It is even conceivable that the small intensity long components observed are due to residual amounts of water, though this seems extremely unlikely.

E. Assignment of Errors

The error assigned to each τ_2 is the result of a judgement of what range of τ_2 lines both fit the points in the tails of the distributions and yield a reasonably straight τ_1 line. (The uncertainty in the time calibration factor is also included.) The errors assingned to I_2 are also based on the same judgement.

The error assigned to each τ_1 is the sum of the uncertainty in the correct τ_1 slope and the uncertainty in the time calibration factor.

SUMMARY AND DISCUSSION

The lifetime distributions of positrons in the sodium halides and alkali chlorides have been measured. The prompt curve falls rapidly enough so that the shapes of the distributions (to the right of the peaks) are undistorted by apparatus effects. All the distributions can be fitted very well by two exponentials: the positrons are divided into two classes, those in one class annihilating with mean lifetime τ_1, and those in the other class with mean lifetime τ_2.

The values of τ_1 are all the same, within the assigned errors, for all the sodium halides (Figure 6). There is little variation in τ_1 for the alkali chlorides but there seems to be a slight trend for τ_1 to increase as the positive ion's size increases. τ_2 seems to be about the same in all these materials; perhaps there are slight trends, τ_2 tending to decrease as the sizes of both the negative and positive ions increase. I_2 is very poorly defined, but there seem to be slight trends, I_2 tending to increase as the sizes of both the negative and positive ions increase.

In summary, the short lifetimes are about 3.5×10^{-10} sec, the long lifetimes about 10×10^{-10} sec, and I_2 is of the order of 1% to 10% for the materials investigated. In addition, a few of them perhaps exhibit a lifetime shorter than τ_1.

These results have two interesting features: the existence of two lifetimes and the independence of lifetime with respect to negative ion radius. It is also to be recalled that the angular correlations can be explained on the basis of a plane wave, zero momentum positron with a probability of annihilating with an electron which is independent of electron momentum (13).

If the positrons are bound to the negative ions, the lifetime should vary inversely as the cube of the negative ion radius (approximately) and be relatively independent of positive ion's radius (11). Since the cube of the negative ion radius varies by a factor of four from F^- to I^-, it is clear that neither τ_1 nor τ_2 can be explained on this basis. Calculation of the lifetime by assuming a uniform electronic density and a free positron, using the Dirac cross-section, leads to values that vary by a factor of 2.5 from NaF to NaI, and by a factor of 2 from LiCl and CaCl. Obviously this model is also unsatisfactory. Calculations based on a similar model, but excluding the positron from the volume of the positive ions and the cores of the negative ions lead to quite similar discrepancies. Finally, any calculation using the Dirac cross-section and electronic densities corresponding to 8 electrons in the volume occupied by the outermost s and p shells of the negative ion again leads to a lifetime varying inversely as the cube of the negative ion radius (approximately). None of these calculations lead to a lifetime value which is more than a factor of 4 larger than $_1$.

Since there are two modes of annihilation, at least one of them must be from a bound state. Also, since neither lifetime varies as much as the average electronic density does, either the other mode is from a bound state, or the Coulomb enhancement effect is so strong that overall electronic density is almost irrelevant.

There is also the possibility that the long lifetime component arises from positrons which spend all their time in a non-crystalline region.

The situation seems to be like that in metals, where the angular correlations data can be explained assuming that zero momentum positrons annihilate with electrons independently of the electron momentum, while the lifetime data can be explained only through a strong Coulomb enhancement. Kahana (22) has carried out (incomplete) calculations for metals which show that the exclusion principle leads to annihilation probabilities mainly independent of electron momentum, whereas the Coulomb effect alone would enhance the annihilation probability with slow electrons. His calculations, which include Coulomb effect, produce a curve which has a shape the same as the Bell and Jørgensen (10) experimental curve but different by about a factor of two. Perhaps the results reported here can be explained on a similar basis. It is to be noted that Bell and Jørgensen have observed longer lifetime components in aluminum and some of the alkali metals, which are as yet unexplained.

In conclusion, it seems that ionic crystals and metals exhibit similar positron annihilation properties. The materials investigated in this work exhibit (at least) two lifetimes, neither of which varies nearly as strongly with ionic radius as does average electronic density. It seems likely that one of them is from a bound state and the other is due to "free" annihilations that are subject to strong Coulomb enhancement. It is possible that τ_2 is due to positrons which spend their lifetimes in non-crystalline regions.

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TABLE AND DIAGRAMS

BLOCK DIAGRAM

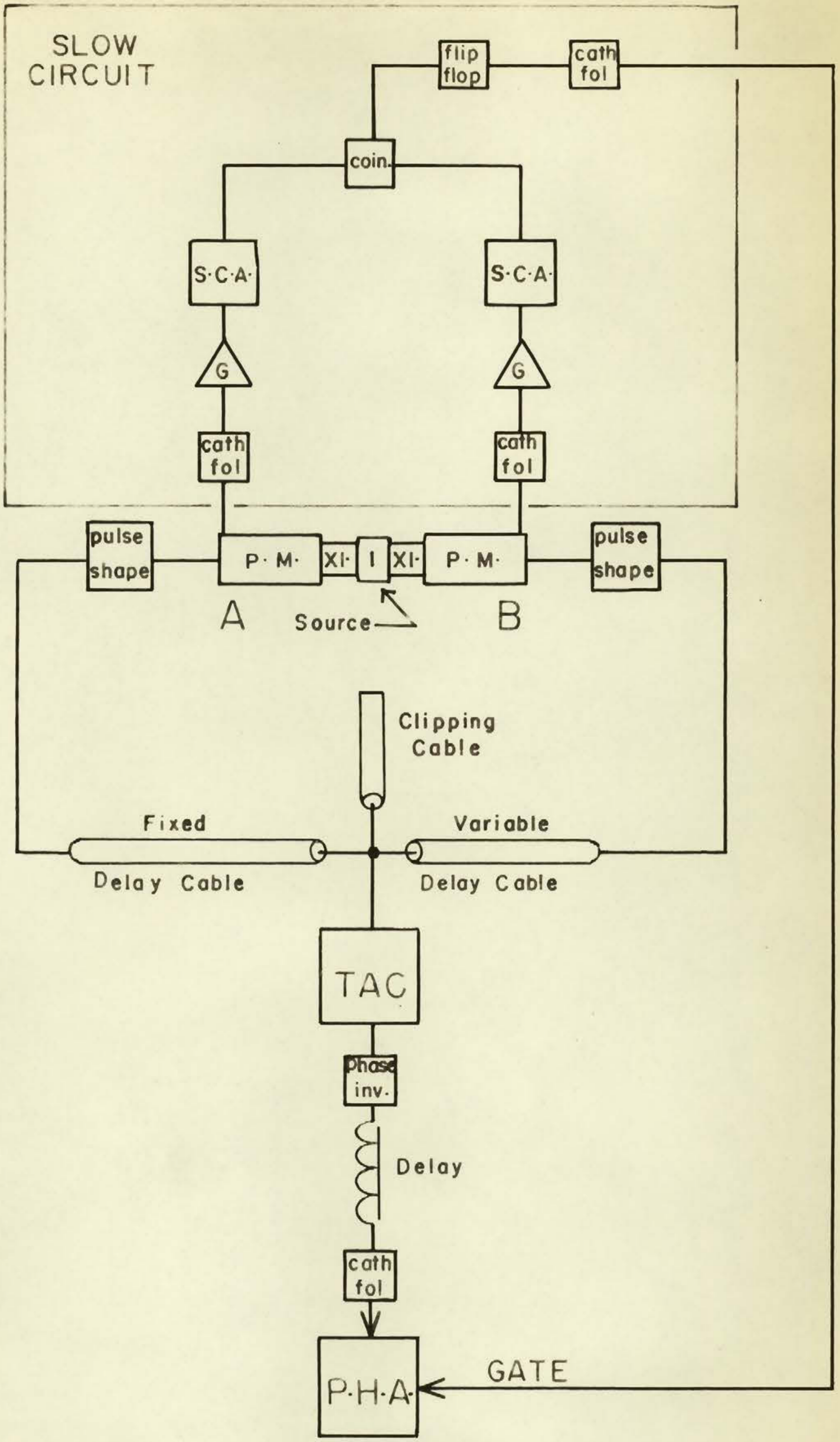


FIGURE I

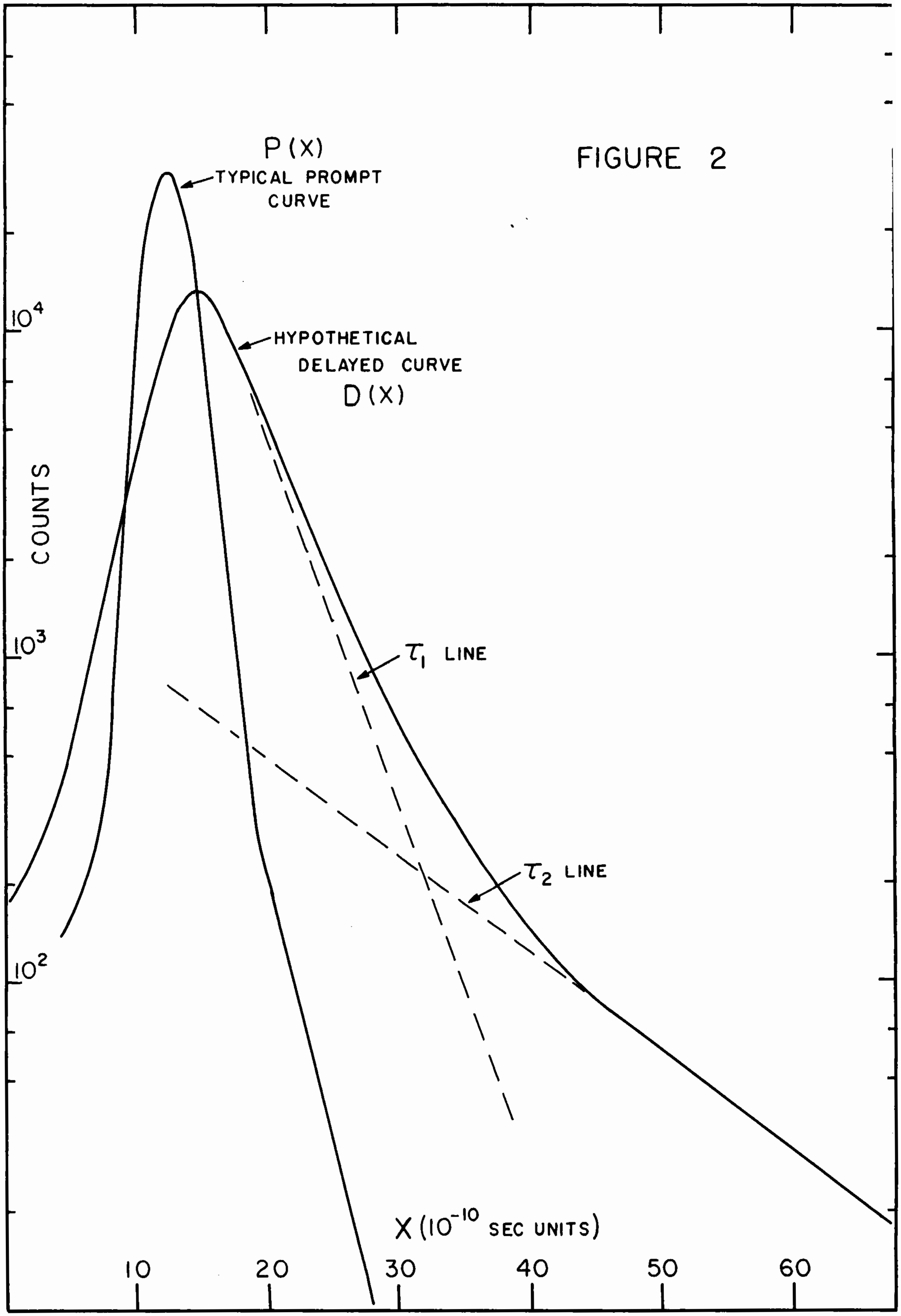
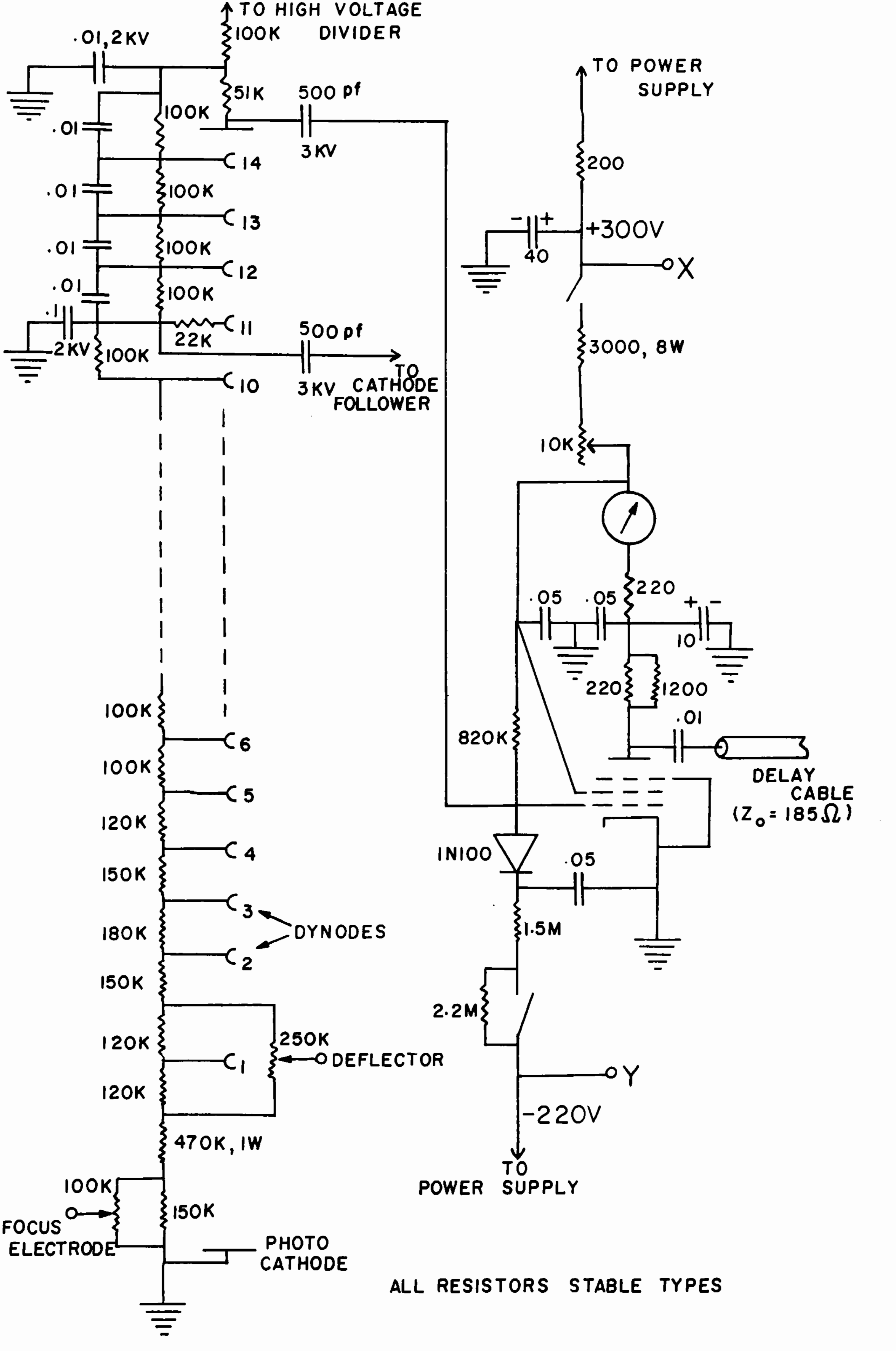


FIGURE 2

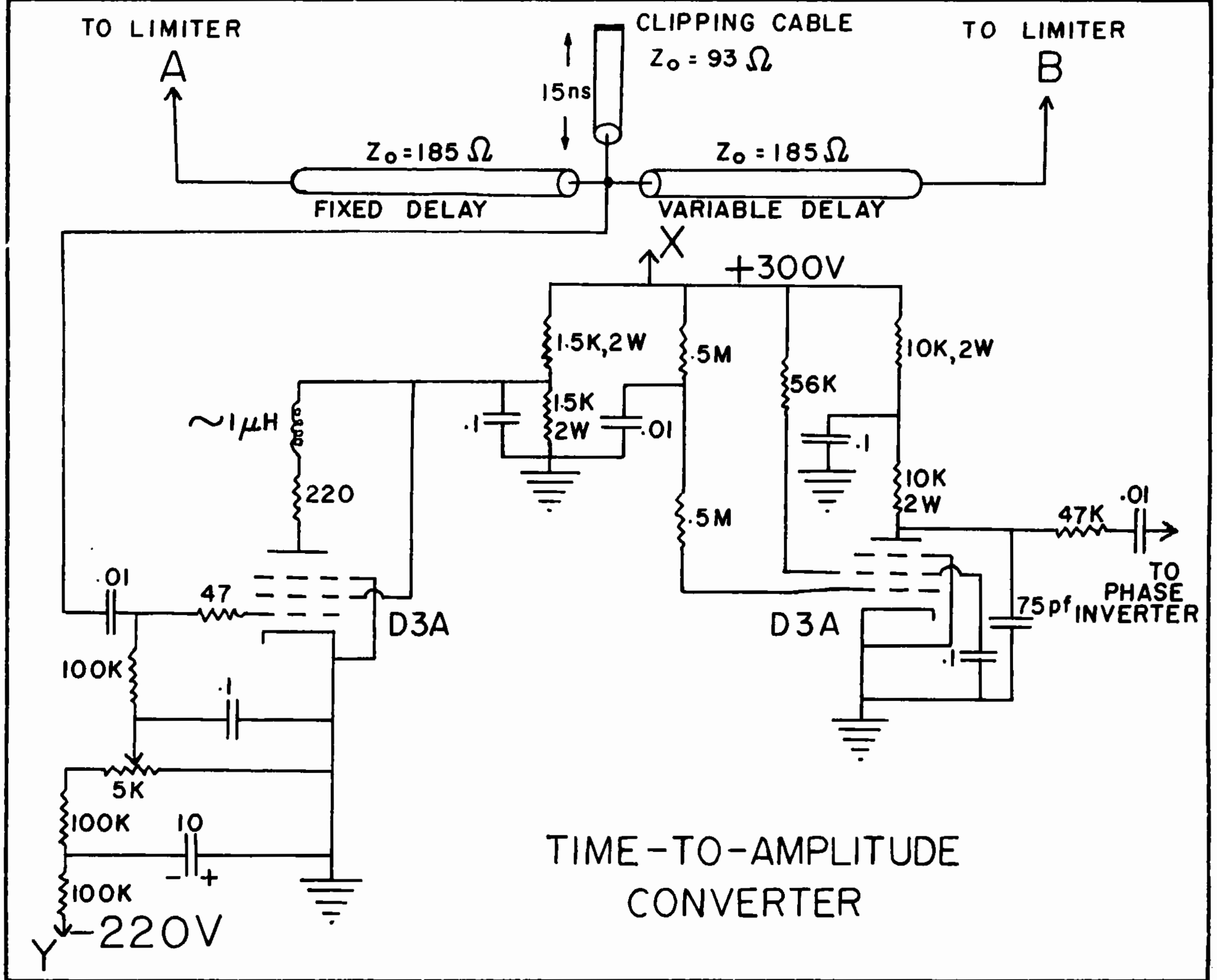
P (X)
TYPICAL PROMPT CURVE
HYPOTHETICAL DELAYED CURVE
D (X)
COUNTS
10^4
10^3
10^2
τ_1 LINE
τ_2 LINE
X (10^{-10} SEC UNITS)
10
20
30
40
50
60



ALL RESISTORS STABLE TYPES

PHOTOMULTIPLIER AND LIMITER-PENTODE CIRCUITS

FIGURE 3



TIME-TO-AMPLITUDE CONVERTER

PULSES AT JUNCTION OF 3 CABLES

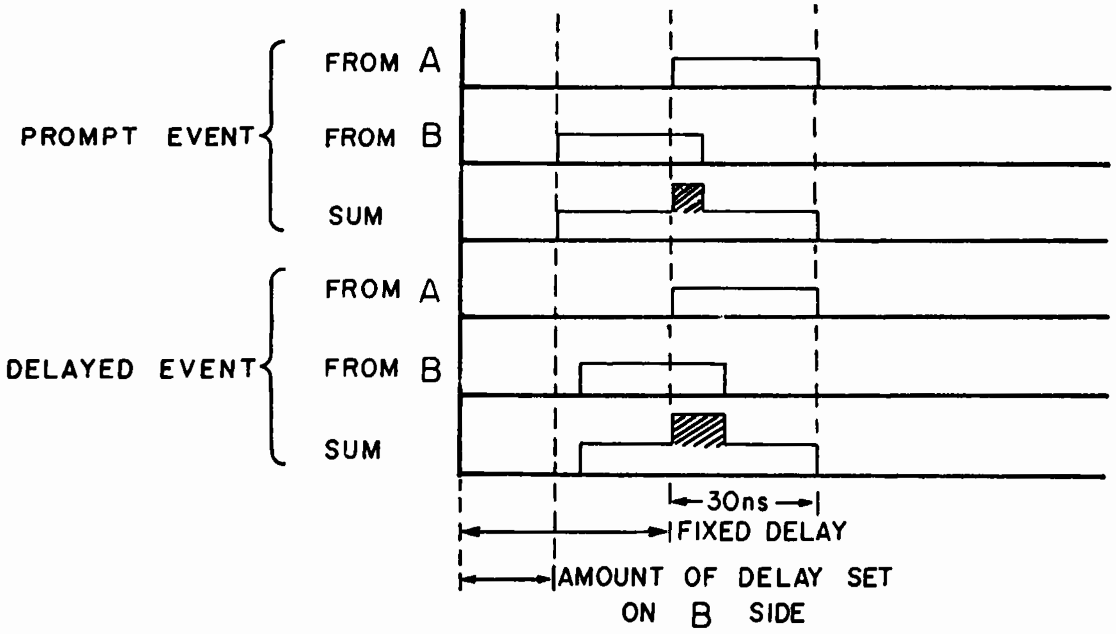


FIGURE 4

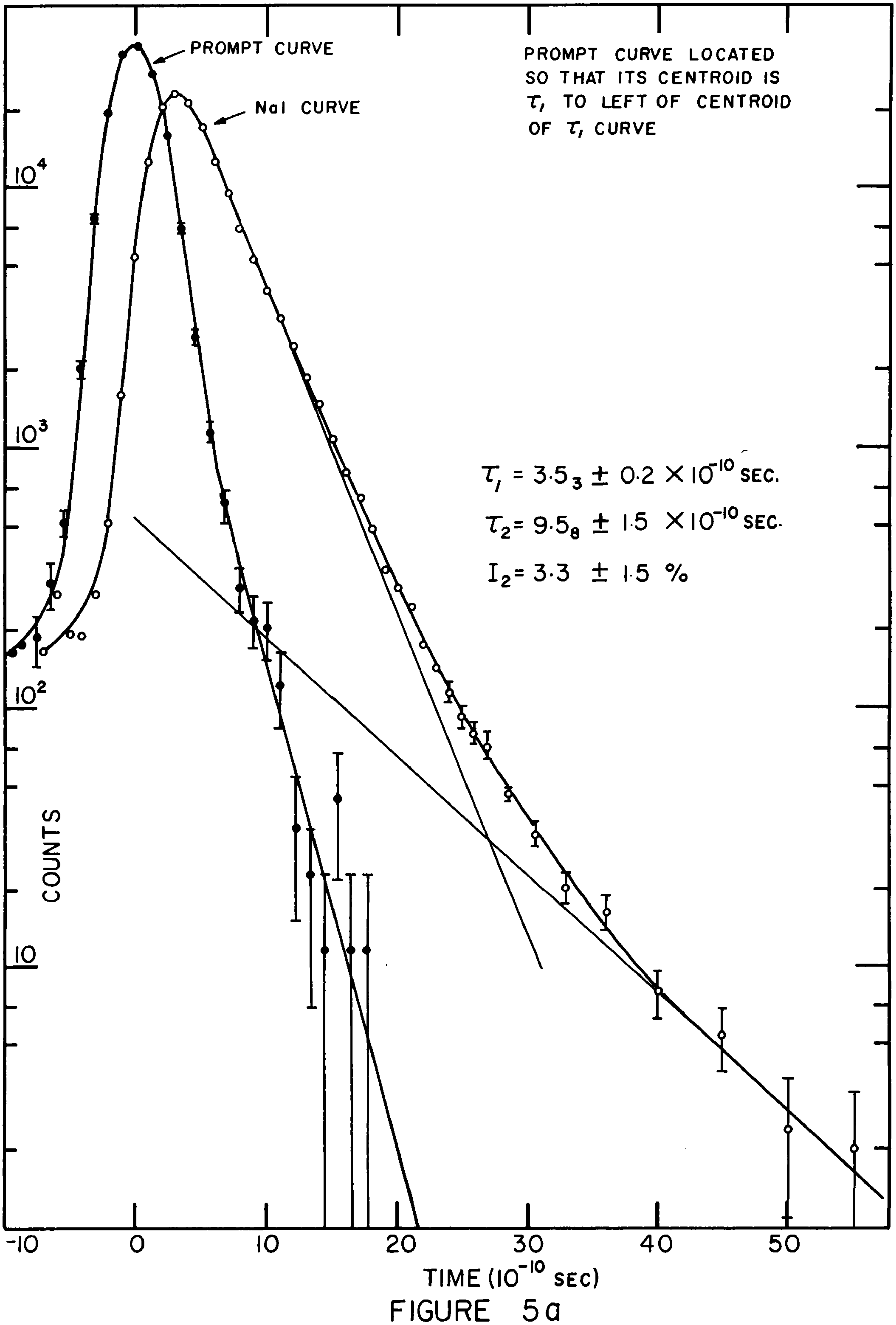

PROMPT CURVE
NaI CURVE
PROMPT CURVE LOCATED SO THAT ITS CENTROID IS τ_1 TO LEFT OF CENTROID OF τ_1 CURVE
$\tau_1 = 3.5_3 \pm 0.2 \times 10^{-10}$ SEC.
$\tau_2 = 9.5_8 \pm 1.5 \times 10^{-10}$ SEC.
$I_2 = 3.3 \pm 1.5$ %
10^4
10^3
10^2
10
COUNTS
-10
0
10
20
30
40
50
TIME (10^{-10} SEC)

FIGURE 5a

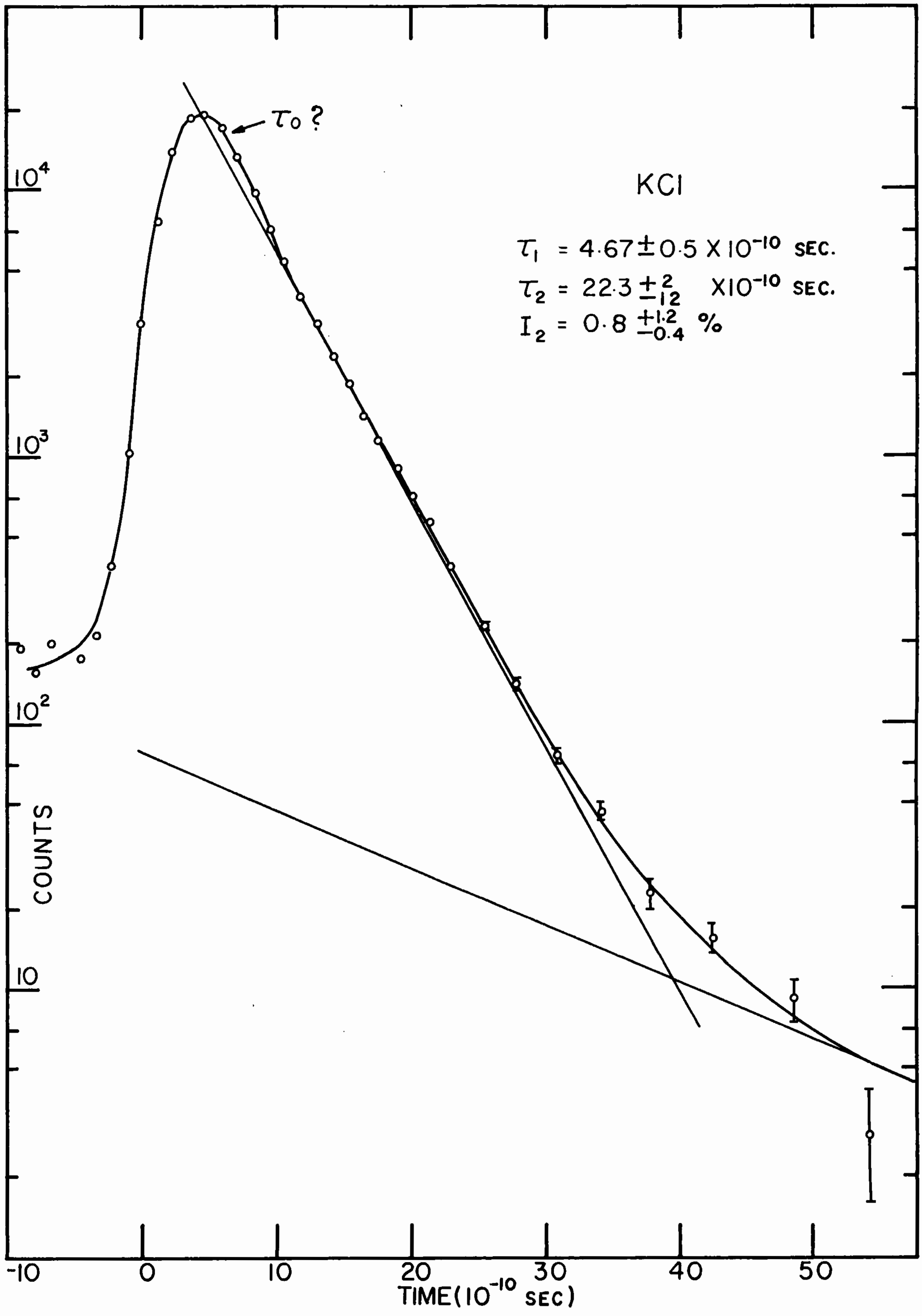

τ_0 ?
KCl
$\tau_1 = 4.67 \pm 0.5 \times 10^{-10}$ SEC.
$\tau_2 = 22.3 {}^{+2}_{-12} \times 10^{-10}$ SEC.
$I_2 = 0.8 {}^{+1.2}_{-0.4}$ %
10^4
10^3
10^2
10
COUNTS
-10
0
10
20
30
40
50
TIME(10^{-10} SEC)

FIGURE 5b

TABLE I

POSITRON LIFETIME RESULTS

MATERIAL	τ_1 (10^{-10} s·)	τ_2 (10^{-10} s·)	I_2(%)	REMARKS
NaF	3·46 ± 0·4	15·9 ± 4	$2{\cdot}2^{+2}_{-1}$	τ_0?
NaCl	3·42 ± 0·4	10·1 ± 4	$2{\cdot}5^{+3}_{-1{\cdot}8}$	
NaBr	3·44 ± 0·4	8·74 ± 4	$6{\cdot}7^{+7}_{-4}$	
NaI	3·53 ± 0·2	9·58 ± 1·5	3·3 ± 1·5	
LiCl	3·60 ± 0·4	11·4 ± 2	$0{\cdot}7^{+1}_{-0{\cdot}4}$	
NaCl	3·42 ± 0·4	10·1 ± 4	$2{\cdot}5^{+3}_{-1{\cdot}8}$	
KCl	4·67 ± 0·5	$22{\cdot}3^{+2}_{-12}$	$0{\cdot}8^{+1{\cdot}2}_{-0{\cdot}4}$	τ_0?
RbCl	3·92 ± 0·4	9·40 ± 2	8·5 ± 4	
CsCl	3·91 ± 0·4	7·50 ± 0·8	14 ± 7	τ_0? DIFFERENT CRYSTAL STRUCTURE

TABLE I

CHART OF POSITRON LIFETIME RESULTS