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A Search for V^0 Particles Produced by 450-Mev Protons*

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A search was made for high energy gamma-rays originating in vacuum close to a target bombarded by 450-Mev protons. The absence of a significant number of such gammas indicates that the cross section per nucleon is less than 7×10^{-33} cm^2 for production of unstable particles which decay into π^0 with a lifetime $\sim 2\times10^{-10}$ sec.

I. INTRODUCTION

THE last five years have brought conclusive evidence on the existence of particles of near-nucleonic mass and lifetimes of the order of 10^{-10} second.[1,2] There is some doubt as to the mode of decay. It is the current belief that the charged V's decay into pions. The neutral V particle, however, appears to decay frequently into a proton, a negative pion, and probably nothing else, although there remains the possibility of a light neutral particle.[3] On the assumption of a two-particle decay the mass of the neutral V is believed to be $1840+274+Q$ electron masses where Q is about 80.[1-3]‡

Thus, as far as energy requirements are concerned, one can produce a V^0 in a proton-neutron collision using the 450-Mev protons from the cyclotron at the University of Chicago. In the center-of-mass system one has an excess energy of 33 Mev above that required to transform the neutron into a V^0. Therefore, one would expect some production of V^0's in the collision of these protons with nuclei. The zero-point energy of the neutrons within the nucleus actually gives, with high probability, excess center-of-mass energy of the order of 100 Mev.

There are valid reasons and historical precedent for determining the threshold and excitation function for the production of V^0's. One has only to recall the clarification of spectroscopy brought about by the experiments determining the excitation energy required for the production of individual spectral lines. If one had first found artificial μ-mesons, the excitation function would have led immediately to the discovery of the π-meson. There is, accordingly, ample justification for the measurement of an excitation function in the case of the V^0.

In comparison with proper nuclear times the V particles have very long lives. It is not our purpose to refer to the various preliminary theories invented to account for this long life.[4,5] We need only mention that the long lifetime implies a very low cross section for the reconstruction of V particles from the decay products. This does not necessarily mean a low cross section for the production of V^0 in nucleon-nucleon encounters. Actually it is known that at high primary energy, of the order of 5 Bev, the production of V particles comprises a considerable fraction of the total cross section. It was also known at the time of this work that the cross section for producing V^0's by the action of 310-Mev bremsstrahlung on carbon is less than 5×10^{-32} cm^2 per steradian per Q per carbon nucleus.[6] In an attempt to determine the excitation function a very sensitive method was used to measure the cross section for the production of V^0's in proton-carbon collisions.

II. METHODS

The great sensitivity of the method to be described depends on an assumed sizeable branching ratio between the usual decay of a V^0, $V^0\rightarrow\pi^-+P$, and a postulated decay $V^0\rightarrow\pi^0+N$. It is entirely reasonable, but unfortunately not necessarily true, to suppose that the probabilities of these two decays are comparable. This may be argued on several grounds, the most obvious of which is that at the time of emission of the decay particles the π^-+P state is mixed with the π^0+N state by the observed charge-exchange process.[7] One can also argue on the matrix elements for a postulated decay process which leads one to believe that the relatively small mass difference between the π^- and the π^0 cannot account for more than a factor 2 in branching ratio, if the decay is limited by centrifugal barrier penetration, for instance. Be that as it may, there remains the possibility that the postulated mode of decay does not occur at all, or that a third particle is emitted in the decay. This experiment can be said to

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[1] G. D. Rochester and C. C. Butler, Nature **160**, 855 (1947).

[2] Armenteros, Barker, Butler, Cachon, and Chapman, Phil. Mag. **42**, 1113 (1951).

[3] K. A. Brueckner and R. W. Thompson, Phys. Rev. **87**, 390 (1952).

‡ *Note added in proof:* Two definitive investigations of V^0 particles have appeared since this paper was prepared. This work confirms the earlier data on natural V^0 and adds the information that V^0 are produced singly rather than in pairs. See Leighton, Wanlass, and Anderson, Phys. Rev. **89**, 148 (1953); Fretter, May, and Nakada, Phys. Rev. **89**, 168 (1953).

[4] A. Pais, Phys. Rev. **86**, 663 (1952).

[5] R. J. Finkelstein, Phys. Rev. **88**, 555 (1952).

[6] G. Cocconi and A. Silverman, Phys. **84**, 1062 (1951).

[7] Anderson, Fermi, Nagle, and Yodh, Phys. Rev. **86**, 793 (1952).

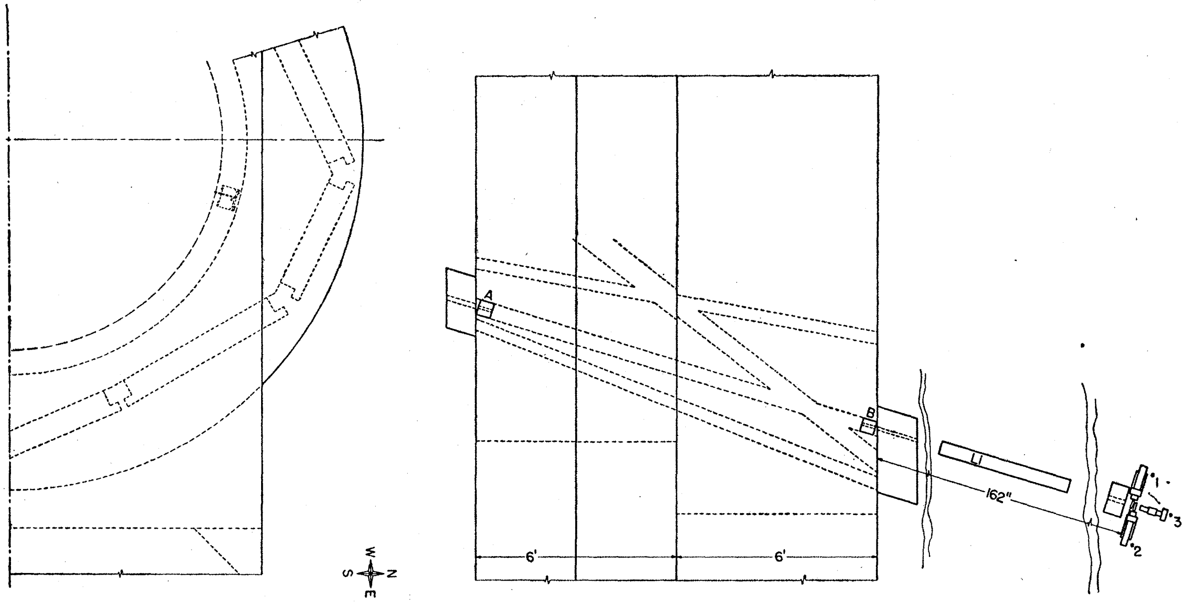

FIG. 1. Collimation and geometry. A is a 5 in. long lead block with hole $\frac{3}{8}$ in. wide $\times\frac{5}{8}$ in. high; B is a 5 in. long lead block with hole $\frac{3}{8}$ in. wide $\times 1$ in. high.

measure the cross section for the production of particles which decay into π^0's with a lifetime about 2×10^{-10} second.

It is obvious that this mode of decay would persistently escape detection in cloud-chamber observations. It is, however, the distinguishing property of the V^0 used here, for the V^0 is detected by the carrying of a π^0 some cm from its point of origin. The π^0 lifetime of $<10^{-14}$ second allows it to move only 10^{-3} cm before decaying. Thus the observation of decay gammas originating in vacuum some cm from a target bombarded by protons is conclusive evidence for the existence of an intermediate long-lived particle.

This experiment was designed to use the intense internal beam of the University of Chicago cyclotron to produce V^0's in a small graphite target, which is movable in azimuth by remote control from the experimental area. A highly discriminatory gamma-ray detector and a slit in the shielding wall restrict the origin of detected gamma-rays to a small region of space. The target can be moved through this region. When it is in the field of view of the collimator one obtains a high counting rate because one is looking directly at the π^0's produced in the target. An azimuthal motion of the target of one cm in either direction reduces the counting rate to a small fraction of its value at the peak. These counts in the wings arise by leakage of γ's and neutrons through the collimator, cosmic-ray background, as well as from V^0's. The experimental geometry is shown in Fig. 1.

Because of the motion of the center of mass the V^0's are emitted entirely in the forward hemisphere in the laboratory system, so that the curve of counting rate *vs* target position should be asymmetrical. Thus if one obtained a counting-rate *versus* target-position curve as in Fig. 2, one would expect that one was actually detecting V^0's. The strong possibility would remain that one was seeing only an asymmetry of the collimator instead. To resolve this point we have used almost radial observation of the target. Evidently then a reversal of the proton beam from east to west will not change the pattern at all if it is due to leakage through the collimator of gamma-rays from π^0's decaying in the target. On the other hand, gamma-rays from π^0's carried into space by V^0's will appear on the opposite side of the curve, so that by simple subtraction of the curves resulting from the east and west beam directions curve one obtains an antisymmetrical function which is just the V^0 observation (and its inverse).

There is somewhat of a problem in monitoring these

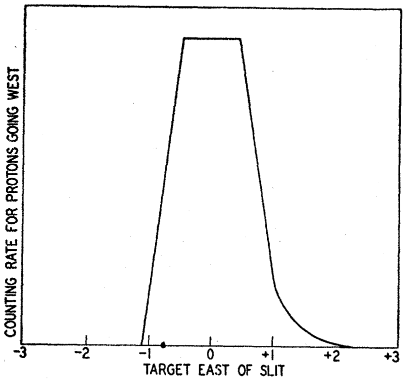

FIG. 2. Expected counting rate *vs* target position for a large production of V^0 particles.

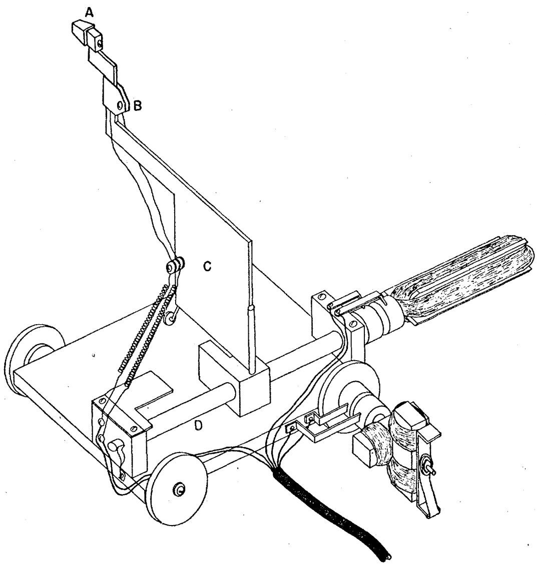

FIG. 3. Movable target. *A* is a graphite block $\frac{1}{4}$ in. high $\times\frac{3}{16}$ in. wide $\times\frac{3}{8}$ in. long; *B* is the calibrating heater and thermocouple hot junction; *C* is heat radiator and cold junction; *D* is the lead screw 13 threads per inch.

observations, since the target is moved inside the cyclotron as part of the experiment. We use two monitors here. One, a BF_3 counter, is exposed to the general neutron background, which does not vary much for centimeter motions of the target. This neutron monitor is used to reduce the counting rates for any one run to a constant beam intensity. There is usually a factor 2, however, between the response of the BF_3 counter to the eastbound and to the westbound beam. This factor is measured by the gamma-ray counts per monitor count in the peak for the two directions of beam. As a check we have also a thermocouple and computer measuring the power dissipated in the target.[8] This also gives an absolute measure of the proton beam in the target and is used to compute the cross section. It was not possible to obtain strict radial observation, the slot in the shield making an angle of 5 degrees with the radius. This is esthetically deplorable but practically does not affect the experiment, since the π^0 decay gamma-emission is a slowly varying function of the angle of emission.

III. EXPERIMENTAL PROCEDURES

The target, in the later stages of the work, was a small block of graphite $\frac{1}{4}$ in. high, $\frac{3}{16}$ in. wide, and $\frac{3}{8}$ in. in radial extent. It was verified that this target absorbed as much power from the beam as a graphite target 1 in. thick because of the multiple traversals of the target by the protons before they were scattered sufficiently to strike the dee. This power input was as much as 12 watts corresponding to 5×10^{11} nuclear collisions per second. The target is shown in Fig. 3. It can be moved in steps of $\frac{3}{4}$ in. by means of the coils attached to the wheels and in steps of 1/52 in. by the lead screw shown in the figure.

After some preliminary work the collimator of Fig. 1 was constructed. This collimator was designed to eliminate as much as possible the funneling of gamma-rays down the collimator which was observed to occur when a plain slot was used. There is a high probability of production of narrow-angle pairs by gamma-rays striking the wall of the collimator. Before undergoing much scattering these pairs radiated bremsstrahlung, again with a narrow angle, the result of which was the funneling effect. For a time this funneling limited the on-peak to off-peak ratio to 1000. The collimator of Fig. 1 is much improved in this respect since the detector does not see the wall at which most of the gamma-rays are absorbed. Indeed, the limiting ratio in this case is 5×10^4.

The counters consisted of a 1-cm thick $\times$2-in. diameter liquid scintillator[9] viewed by a RCA 5819 photomultiplier, followed by a second identical counter which was followed by a water Čerenkov counter[10] 2-in. diameter and 4 in. long. The arrangement is shown in Fig. 1. A $\frac{1}{4}$-in. space was left between the first and second counters. The counting rate at a given target position was determined with a 2 in. square $\times\frac{1}{4}$ in. thick lead plate immediately up-beam of the first counter ("front") or with this plate between the first and second counters ("in"). The first counter was connected in anticoincidence and the other two in coincidence by means of a circuit[11] of 4×10^{-9} second resolving time. Hewlett-Packard wide-band amplifiers were used in each channel.

Gamma-rays are detected by subtracting the "front" rate from the "in" rate. The neutron counting efficiency is very nearly independent of the position of the lead converter as is the charged particle efficiency, so that the simple "front"-"in" subtraction yields pure

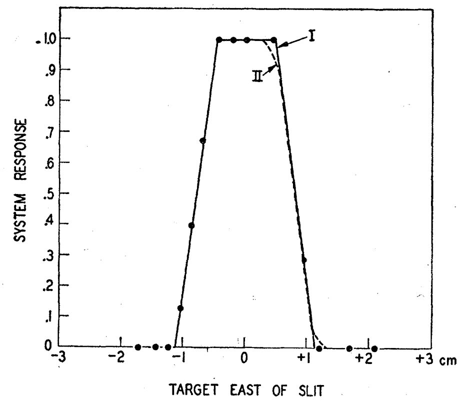

FIG. 4. System response to gamma-rays. I: point source; II: $\frac{3}{16}$-in. wide source.

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[8] R. L. Garwin, Rev. Sci. Instr. **23**, 681 (1952).

[9] R. L. Garwin, Rev. Sci. Instr. **23**, 755 (1952).

[10] R. H. Hildebrand, Rev. Sci. Instr. (to be published).

[11] R. L. Garwin, Rev. Sci. Instr. (to be published).

gamma-ray counts. With the target in the field of view of the collimator and absorbing 9 watts from the beam, the gamma-ray counting rate was $\sim 2\times 10^4$/min. Fast scalers were used to record the high counting rates produced by the 1 percent duty cycle of the cyclotron. The "front" rate under these conditions was $\sim$0.035 of the "in" rate. These "front" counts are almost all real gammas converted in the second counter. The off-peak count is very low because of the perfect discrimination of the Čerenkov counter against particles with energy less than 0.5 times their rest mass. Even the off-peak rate which is 2×10^{-5} of the on-peak rate is due almost entirely to leakage gammas as indicated by a small ratio ($\sim$0.2) of "front" to "in" counts.

Figure 4 gives the computed response of the collimator to a point source (sharp-cornered curve) or to a $\frac{3}{16}$-in. wide uniform source of gammas (round-cornered curve). The slope and half-width of this curve was repeatedly confirmed, but the tail never extended as far as the toe in the figure. Evidently this result is caused by the 5° inclination of the target to radial, which causes the protons to strike the corner of the graphite target. A more sensible method of insuring this effect is to use a wedge-shaped target.

Since the target is a source of high energy neutrons as well as of the more easily attenuated gamma-rays one must provide auxiliary attenuation for the neutrons. This was afforded by 20 in. of iron shown in Fig. 4. In addition, to reduce the counting rate induced by neutrons diffraction-scattered down the collimator itself, the experiment in its final form used a 140-cm lithium absorber just beyond the shield wall. This provides a relative attenuation of neutrons with respect to gamma-rays of 3.5. The importance of the lithium may be seen from the datum that, with the target 1.0 cm from the position of the peak counting rate, the "front" rate without Li was 45 per thousand monitor counts, the "in" rate 42 per thousand. With the Li the rate fell to 5.0±1.0 and 4.0±0.9, respectively. The geometrical cross section of Li gives an attenuation for neutrons of 5.5; for 70-Mev gammas the attenuation is 1.39 in the Li and 1.21 in the steel of its containers, giving a total attenuation of 1.69. Thus the Li improves the signal-to-noise ratio by >3.3 in actual practice. More Li should have been used.

IV. RESULTS

In all, 80 hours of cyclotron time were used, most of these in the preliminary stage of the experiment. The data of the last 8 hours are presented in Figs. 4 and 5. Points A are the counting rates as a function of position for protons going east. Points B are the same for protons going west. The lines $\bar{B}-\bar{A}$ are the difference of these averages. V^0's should show up as a positive contribution to the difference at the right-hand side and a negative contribution at the left. It may be seen that the difference is symmetrical within the statistical error of the points. The antisymmetrical difference, if any existed, should slope off quasi-exponentially on either side of the main peak. The rate of fall-off, when coupled with the estimated velocity of the V^0, would give the lifetime. It is evident that a long lifetime would allow us only poor sensitivity since only a small fraction of the V^0's would decay in the 1.6-cm field of view of the collimator. Similarly a very short lifetime means poor sensitivity as the V^0's would be lost in the penumbra from the target. The "off-peak" count is higher for protons going west than east because of scattered particles inside the cyclotron impinging on the vacuum tank in the field of view of the collimator.

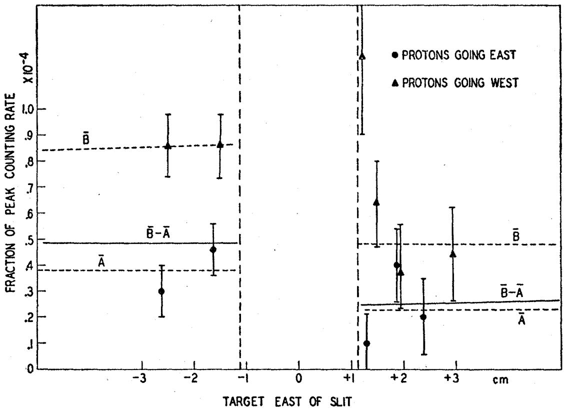

FIG. 5. Results for target out of field of view, $\bar{A}$ is drawn through the points for east-bound protons; $\bar{B}$ is drawn through the points for west-bound protons; $\bar{B}-\bar{A}$ are the difference in the averages.

Figure 6 shows the relation between the assumed value of the lifetime and the upper limit to the cross section established by this experiment. Counting rate ratios have been changed to cross sections by an estimated detector efficiency of 50 percent. The scintillator and Čerenkov particle efficiencies have been measured to be >98 percent so that the only estimate involves the converter. We find a total cross section of about 5.0×10^{-28} cm^2 for the production of the π^0's in the

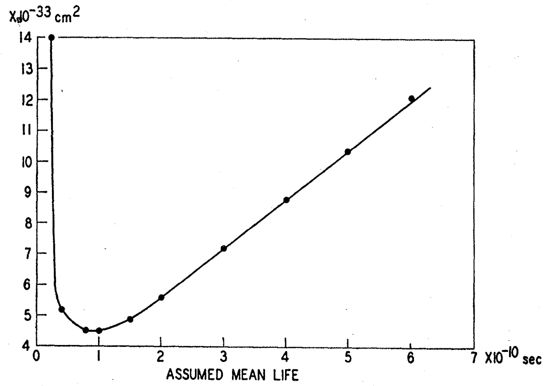

FIG. 6. Upper limit to production cross section per nucleon in carbon as a function of mean life.

collision of a 450-Mev proton with an average nucleon in carbon. This figure is reliable only to ±40 percent, most of the uncertainty being due to the difficulty of converting the measured differential cross sections for γ-production at 90° (4.0×10^{-29} cm^2 steradian) to a total cross section using a somewhat uncertain angular distribution. Adding to the uncertainty is the energy spread of the proton beam, which has been measured by A. H. Rosenfeld as 10 Mev and as 40 Mev at different times.

If one takes the currently popular V^0 lifetime of 3×10^{-10} second, this experiment establishes an upper limit of 7×10^{-33} cm^2 to the cross section for production of V^0's by 450-Mev protons on a nucleon in carbon.

V. CONCLUSION

It has been established with rather high probability that V^0 particles are produced in nucleon-nucleon collisions with a cross section which cannot be much greater than 10^{-32} cm^2 with an available excess center-of-mass energy of 100 Mev. Therefore, we think it possible that this energy is below the threshold for production of V particles. This probably means that they are decay products of some state which may contain two V-particles or which may contain just one particle which decays by the emission of a gamma-ray or a meson to the common V particles. Experiments at higher energy are required to investigate this problem further.

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Recombination Rate in Germanium by Observation of Pulsed Reverse Characteristic

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A new method for measuring recombination rates of minority carriers in germanium is described in which the decay of injected carriers is observed directly as a function of time. In this method the geometry is relatively unimportant as long as the sample is large in comparison to the diffusion length, and the method permits measurement of recombination rates too short to be measured with light beam methods. Data are presented which show excellent agreement between this method and a light beam method.

PREVIOUS methods for measuring recombination rates in germanium have consisted of injecting minority carriers by either a metal probe or by a beam of light, and of observing the decay of the carriers as a function of distance away from the injection probe.[1,2] These are essentially geometrical methods, measuring the diffusion length directly. As such, they have the advantage of offering a possibility for separating surface and volume effects. On the other hand, special geometries are generally required. In some cases it is advantageous to be free from restrictions on geometry, and the method to be described secures this freedom by measuring the decay of minority carriers as a function of time rather than distance.[3] Also, it will measure diffusion lengths too short to be easily measured by other means.

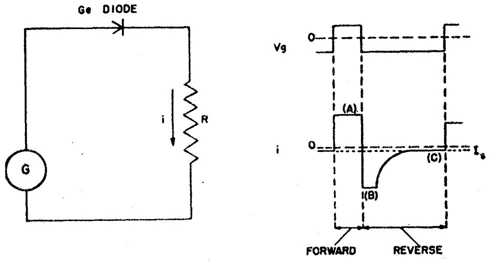

FIG. 1. Pulsed characteristic of Ge diode. The generator (G) supplies a square wave of voltage (V_G) which produces the current, i, through the circuit shown.

If a square wave of voltage is applied to a germanium diode, the resulting current will be as shown in Fig. 1, where the current at A and B is generally limited by series resistance (R) in the circuit. The current decays from the value at B to the reverse saturation current at C as the minority carriers which have been injected during the forward pulse disappear by diffusion and recombination. The shape of this decay curve can be used to determine the recombination rate.

To find the relation between the above decay curve and the recombination rate, the diffusion equation,

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[1] J. R. Haynes and W. Shockley, Phys. Rev. **81**, 835 (1951).

[2] L. B. Valdes and J. R. Haynes, Durham Conference on Electron Devices (June, 1951).

[3] The same results are obtainable more indirectly from the ac characteristic of rectifying junctions. See W. Shockley, *Electrons and Holes in Semi-conductors* (D. Van Nostrand and Company, Inc., New York, 1950), p. 317, and also Goucher, Pearson, Sparks, Teal, and Shockley, Phys. Rev. **81**, 637 (1951). A rough experiment by R. L. Pritchard of this laboratory indicates that the series resistance of the sample is more troublesome in the ac method than in the one described above. A recent article by Navon, Bray, and Fan, Proc. Inst. Radio Engrs. **40**, 342 (1952), describes another method for measuring τ directly, somewhat more complex in instrumentation than the above but not requiring a rectifying junction. See also M. C. Waltz, Proc. Inst. Radio Engrs. **40**, 1483 (1952), who describes a similar phenomenon in whisker diodes, but in this case considered it to be a transit time effect.