Title
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Publication Date
1978-06-01

LBL-7926 c.2
UC- 34a

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Prepared for the U. S. Department of Energy
under Contract W-7405-ENG-48

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by

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This work was done with support from the U. S. Department of Energy.

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A SEARCH FOR MASSIVE, LONG LIVED, FRACTIONALLY CHARGED PARTICLES PRODUCED BY 300 GeV PROTONS

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A search has been made for long lived (25μ sec $< \tau <$ 1 m sec), weakly interacting particles of rest mass greater than 5 GeV that come to rest and subsequently decay in the calorimeter portion of the CAL Tech-NAL neutrino detector.[a] The 253 meters of steel, 3 meters of Al, and 178 meters of earth in front of the detector allow singly charged particles between 415 GeV and 428 GeV to stop[c] in the calorimeter. Consequently, only particles of fractional charge 1/3e (between 46.1 and 47.5 GeV) and 2/3 e (between 184 and 190 GeV) could do so. No such particles were observed during a six-hour parasitic run[*] during which time 1.39×10^{16} 300 GeV-protons struck the 30 cm long aluminum target of the "single-horn" neutrino beam. The calorimeter electronics, whose energy threshhold was set at about 5 GeV, was gated off while the 20μ sec long burst of protons was striking the target and was gated on 75μ sec after the beginning of that burst for a duration of 14.925 milliseconds. As a control, another gate (10 milliseconds long) was opened two seconds before the arrival of the protons. We refer to these as the "Beam gate" and "Cosmic Ray gate", respectively. The electronic "dead time" was purposely set long enough so that no more than one event could be recorded per gate for each accelerator pulse. Only when the gating electronics sensed there was accelerated beam would it generate a "Beam gate" whereas a "Cosmic Ray gate" was formed every accelerator pulse. During this run there were 2097 "Beam gates" and

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[*] Cal Tech Run 1626, 22 Nov 1974 (17:27 to 22:58 hours)

2949 "Cosmic Ray gates," during which time the calorimeter electronics remained "alive" 2.6985 seconds and 3.8725 sec, respectively. Had there been no events, these times would have been 31.298 sec and 29.490 sec, respectively.

"Cosmic Ray" Time Distribution

The probability of a cosmic ray triggering the calorimeter in the time t is t/τ_o where τ_o^{-1} is the cosmic ray rate. Therefore, the probability that the electronics is still "alive" and capable of recording an event at that time is just the probability of getting zero events when $\bar{n} = t/\tau_o$ is expected, namely, $\exp(-t/\tau_o)$. Thus the Cosmic Ray distribution is,

$$\frac{\Delta N}{\Delta t} = R_o \exp(-t/\tau_o) \tag{1}$$

where,

$$\tau_o = (\text{CR live-time} = 3.8725 \text{ sec})/(\text{CR gates} = 2949)$$
$$= (1.313 \pm 0.024) \text{ milliseconds}$$

and

$$R_o = \frac{(\text{CR gates} = 2949)\ (\text{bin width} = 0.1 \text{ m sec})}{(\tau_o = 1.313 \pm .024 \text{ m sec})}$$
$$= 224.7 \pm 4.1 \text{ events}/0.1 \text{ m sec}$$

The first five milliseconds of the Cosmic Ray data are shown in Fig. 1a along with the expected curve, eq. (1).

"Beam Distribution"

The beam data are shown in Fig. 1b. The solid curve of the latter figure is the cosmic ray curve eq. (1) with R_o normalized to the number of "Beam gates".

$$R_o(\text{Beam})_{\text{pred via CR}} = \frac{(\text{Beam gates} = 2097)}{(\tau_o = 1.313 \pm .024 \text{ msec})}$$

$$= 155.2 \pm 2.8 \text{ events/o.1 msec}$$

The agreement is good except for the first 100 μsec bin. Fig. 2 is an expanded view of this interval, and shows that the entire excess of "Beam" events occurs at 25 μsec . This excess was caused by infrequent noise in the "Beam gate" triggering electronics. (It happened only 60 times during the entire run). Its effect was to start a beam gate 25 μsec before the arrival of the proton burst rather than 75 μsec after. As a consequence, the high instantaneous counting rate in the calorimeter during the beam burst caused the equipment to trigger on the first event near the beginning of the burst and thus to produce a "spike" of 60 events in a one-μsec wide bin at 25 μsec . After subtracting these 60 events from the "Beam" distribution and correcting the corresponding live time by subtracting 60 x 25 μsec from it, one can test the hypothesis that the "Beam" distribution is caused by only cosmic rays, and thus is of the form of eq (1); where,

$$\tau_o\ (\text{Beam}) = (\text{Live-time} = 2.6985\ \text{sec} - 60 \times 25\ \mu\text{sec})/(\text{Beam gates} = 2097-60 = 2037)$$

$$= (1.324 \pm 0.029)\ \text{msec}$$

and,

$$R_o(\text{Beam}) = \frac{(\text{Beam Gates} = 2037)}{(\tau_o = 1.324 \pm 0.029\ \text{msec})}\ (\text{bin width} = 0.10\ \text{msec})$$

$$= 153.8 \pm 3.4\ \text{events}/100\ \mu\text{sec}.$$

These numbers are consistent with the predicted ones, 1.313 ± 0.024 msec, and 155.2 ±2.8 events/0.1 msec.

Invariant Differential Cross section-Upper Limit (90%-confidence-level)

How large a "signal" could have been missed by statistical fluctuation? If there were B long-lived particles of life time $\tau = \lambda^{-1}$ that stopped in the calorimeter and decayed R fraction of the time so as to deliver more than 5 GeV to the calorimeter, one would expect the beam plus cosmic ray background distribution to be of the form,

$$\frac{\Delta N}{\Delta t} = \frac{G}{\tau_0}\left(1+\lambda\tau_0\frac{B\cdot R}{G}e^{-\lambda t}\right)\exp\left\{-\left[\frac{t-t_0}{\tau_0}+\frac{BR}{G}\left(e^{-\lambda t_0}-e^{-\lambda t}\right)\right]\right\} \qquad (2)$$

where G is the number of Beam Gates, t_0 is the beginning time of the gate relative to the beam burst*, and τ_0^{-1} is the cosmic ray background rate.

Figure 3 compares this distribution for some typical values of BR and τ with the first 1.4 milliseconds of the "Beam" distribution. The spurious 60 events at 25 μsec have been subtracted. For each value of τ one can form a chi-squared function and determine how large BR can be made before the chi-squared value reaches its 10%-probable value.† This value of BR, shown in Fig. 4A versus τ, enables one to establish an upper limit to the product of invariant differential cross section $E\frac{d^3\sigma}{dp^3}$ and "branching ratio" R, as a function of meanlife τ, by means of a relation of the following form,

$$R\cdot E\left.\frac{d^3\sigma}{dp^3}\right|_{\text{at 0 degrees}} = \frac{BR}{N_0 N_T f_{MS}\,\Delta\Omega\, P_B \Delta P_B} \qquad (3)$$

Here, N_0 is the number of incident protons, N_T the number of target nucleons per cm^2, $\Delta\Omega$ the solid angle subtended from the target by the calorimeter, P_B and ΔP_B the momentum and its interval of the fractionally charged particles that come to rest throughout the calorimeter. f_{MS} is the fractional loss caused by multiple scattering and is estimated

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* Here the beam is considered as a delta function in time.

† Account has been taken of the 20μsec width of the beam.

by assuming the production cross section varies as $e^{-6p_\perp^2}$.

The actual form of R E $\frac{d^3\sigma}{dp^3}$ is more complicated than eq. (3) because there are two targets, one the primary one (1 mean free path long Aluminum) located 944 meters from the calorimeter ($\Delta\Omega_1 = 2.52$ μ ster), the second one, the beam dump at the end of the neutrino beam decay tube located 544 meters from the detector ($\Delta\Omega_2 = 7.60$ μ ster). The protons that don't interact in the first target strike the second one with their full energy while some of the others emerge from the first target and stike the second one with reduced but still effective, energy. This phenomenon of "Thick targets" has been studied quantitatively in TM218[b] and applied to this case. For example, by assuming that each proton loses 1/3 of its energy each time it interacts, one estimates that the composition of the proton beam that strikes the second target consists of 37% at 300 GeV, 37% at 200 GeV, and 18% at 133 GeV. Furthermore, only the first mean free path of the second target (the beam dump) is considered as being effective for producing the weakly interacting particles that can come to rest in the calorimeter. The proton threshhold energies are 199 GeV and 65 GeV for producing stopping particles* of rest mass 5 GeV. Only one of such pair produced particles is detectable per event.

Table 1 summarizes the values of the quantities in,

$$\overline{R\cdot E\frac{d^3\sigma}{dp^3}}\Bigg|_{\text{at 0 degrees}} = \frac{B\cdot R}{P_B\,\Delta P_3}\left(N_0^{(1)}N_T^{(1)}f_{MS}^{(1)}\Delta\Omega^{(1)} + N_0^{(2)}N_T^{(2)}f_{MS}^{(2)}\Delta\Omega^{(2)}\right)^{-1} \quad (4)$$

that together with the BR values of Fig.4A allow one to determine the 90%-confidence level-upper limit of R.E $\frac{d^3\sigma(0^\circ)}{dp^3}$ vs τ.

This latter quantity is plotted in Fig. 4B,C and summarizes the results of the experiment.

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* 184 GeV/c (of charge 2/3e) and 46.1 GeV/c (of charge 1/3e)

Acknowledgements

I am grateful to Dave Buchholz, Frank Merritt, Barry Barish, and Franck Sciulli of the Cal Tech group who ran their detector for me during this brief six hour experiment.

References

a) B.C. Barish, et al PRL <u>31</u>, 180 (1973)
   "   "   " PRL <u>31</u>, 410 (1973)
   "   "   "   " <u>31</u>, 565 (1973)
   "   "   "   " Cal-Tech Report CALT-68-430 (to be published)

b) Targets for the Neutrino Beam, Concepts. M.L. Stevenson TM 218 (Feb. 15, 1970)

c) D. Theriot, Muon dE/dx and Range Tables: Results for Shielding Materials Using Collision Losses Only TM-260(1970)

This work was done with support from the U.S. Department of Energy.

Table 1

Charge	2/3 e	1/3 e
P_B	184 GeV/c	46.1 GeV/c
ΔP_B	5.8 GeV/c	1.4 GeV/c
$N_o^{(1)}$	1.39×10^{16} protons	1.39×10^{16} protons
$N_o^{(2)}$	1.02×10^{16} protons	1.02×10^{16} protons
$N_T^{(1)}$	5.0×10^{25} cm^{-2}	5.0×10^{25} cm^{-2}
$N_T^{(2)}$	5.0×10^{25} cm^{-2}	5.0×10^{25} cm^{-2}
$f_{MS}^{(1)}$	0.62	0.87
$f_{MS}^{(2)}$	0.62	0.87
$\Delta\Omega^{(1)}$	2.5×10^{-6} Ster	2.5×10^{-6} ster
$\Delta\Omega^{(2)}$	7.6×10^{-6} ster	7.6×10^{-6} ster
$P_B \Delta P_B$	1060 (GeV/c)^2	66.4 (GeV/c)^2
$(1) \equiv N_o^{(1)} N_T^{(1)} f_{MS}^{(1)} \Delta\Omega^{(1)}$	1.08×10^{36} cm^{-2}	1.51×10^{36} cm^{-2}
$(2) \equiv N_o^{(2)} N_o^{(2)} f_{MS}^{(2)} \Delta\Omega^{(2)}$	2.38×10^{36} cm^{-2}	3.35×10^{36} cm^{-2}
$P_B \Delta P_B[(1) + (2)]$	3.68×10^{39} cm^{-2} (GeV/c)^2	3.22×10^{38} cm^{-2} (GeV/c)^2

Figure Captions

Fig. 1a Cosmic Ray time distribution for first 5 msec (t_o = 75 μsec)

Fig. 1b "Beam Events" time distribution for first 5 msec (t_o = 75 μsec)

Fig. 2 Expanded time distribution of the first 100 μsec of "Beam" distribution.

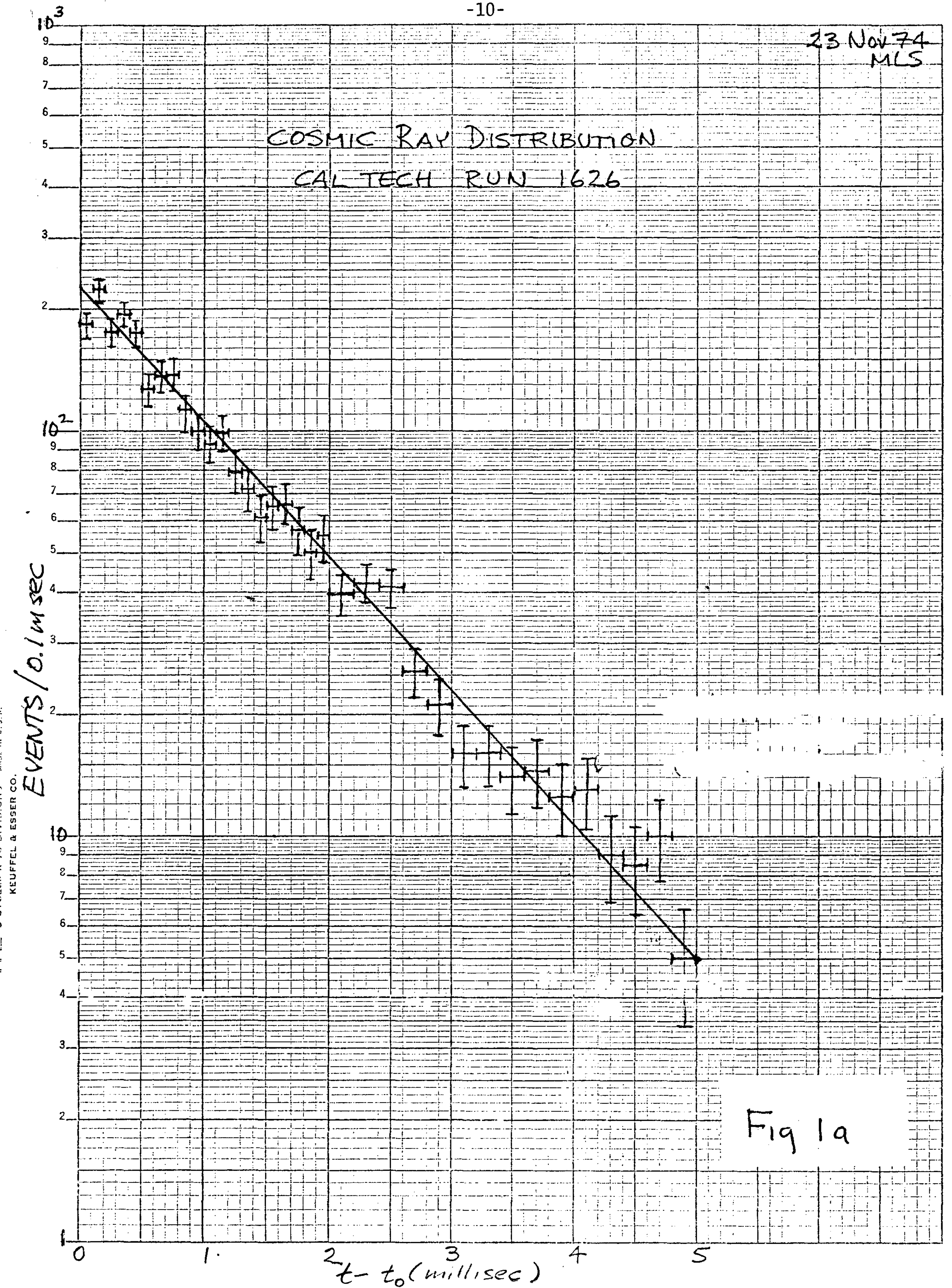
Fig. 3 Typical Expected time distribution for the number of long lived particles B (times their branching ratio R) compared with the first 1400 μsec of "Beam" data.

Fig. 4

A. The value of BR that gives a chi-squared value with a confidence level of ten percent versus mean life.

B. The 90%-confidence level-upper limit to the invariant cross section (times R), RE $\frac{d^3\sigma}{dp^3}$ (0^o), versus τ for 1/3 e charged particles of P_B = 46 GeV/c.

C. ...Ditto ... for 2/3 e charged particles of P_B = 184 GeV/c.



23 Nov 74
MLS

Fig 1a

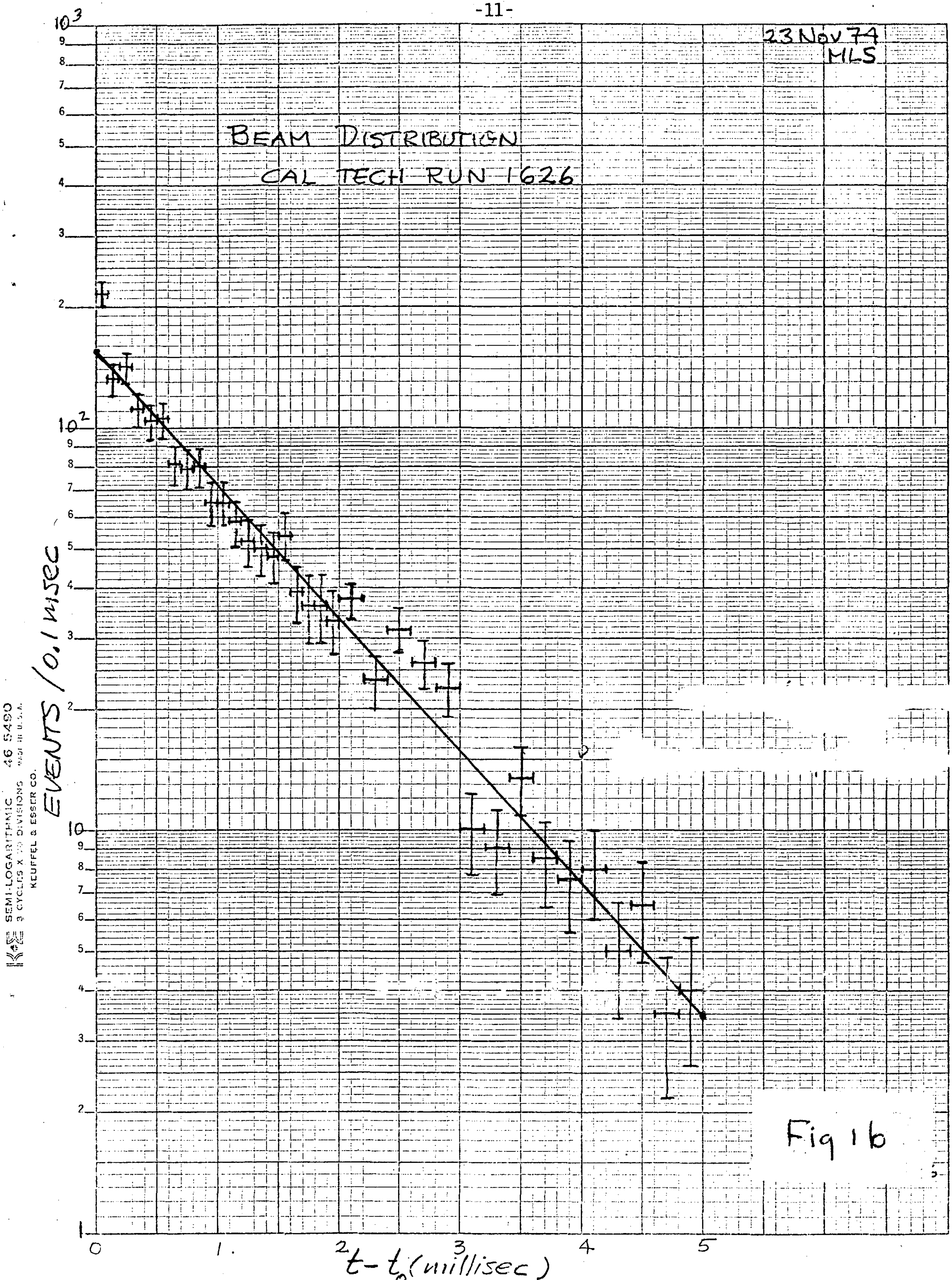


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Fig 1b

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BEAM DISTRIBUTION OF FIRST 100μSEC.
CAL TECH RUN 1626

$t_0 = 75\mu s$

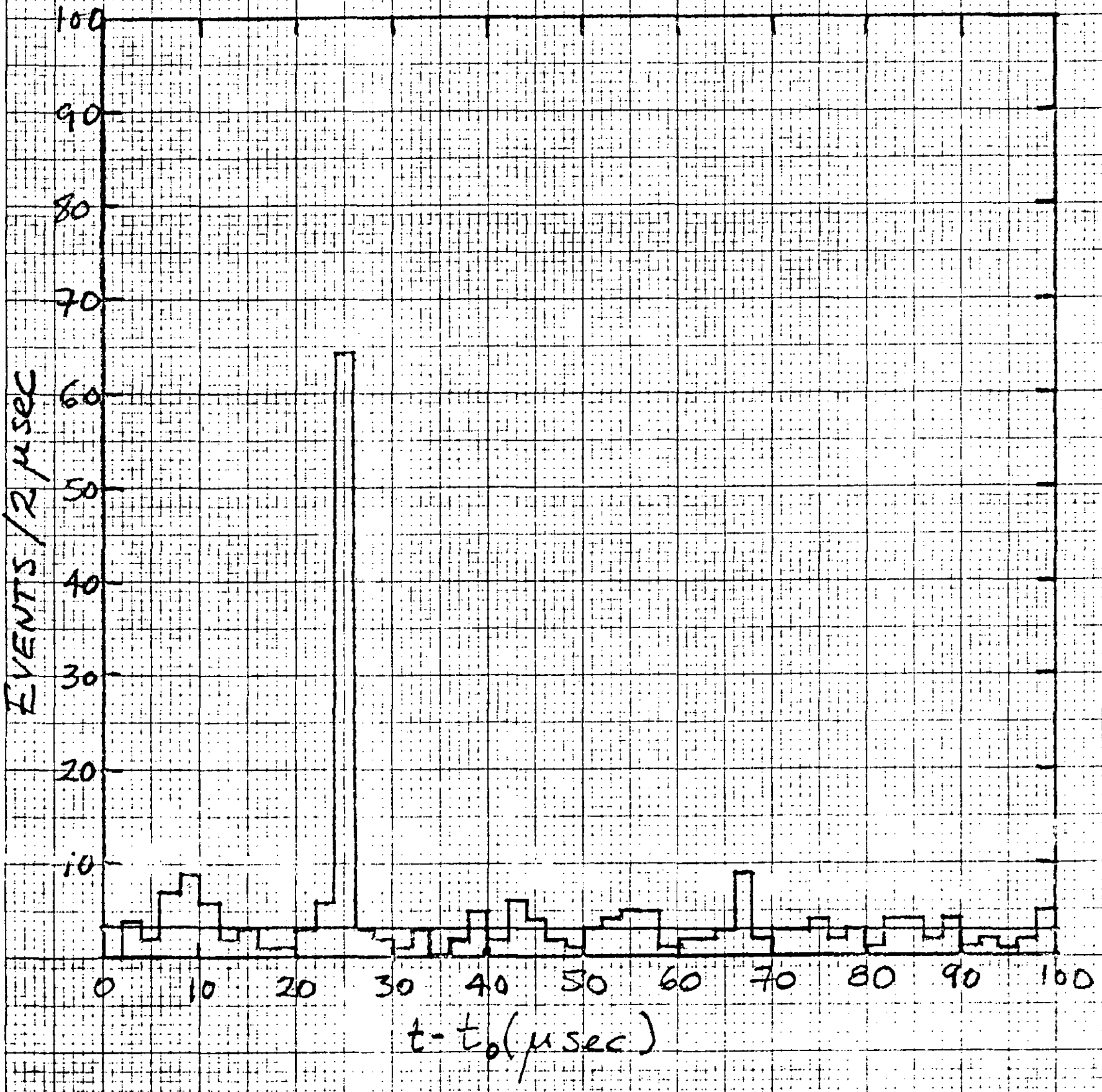

Fig. 2

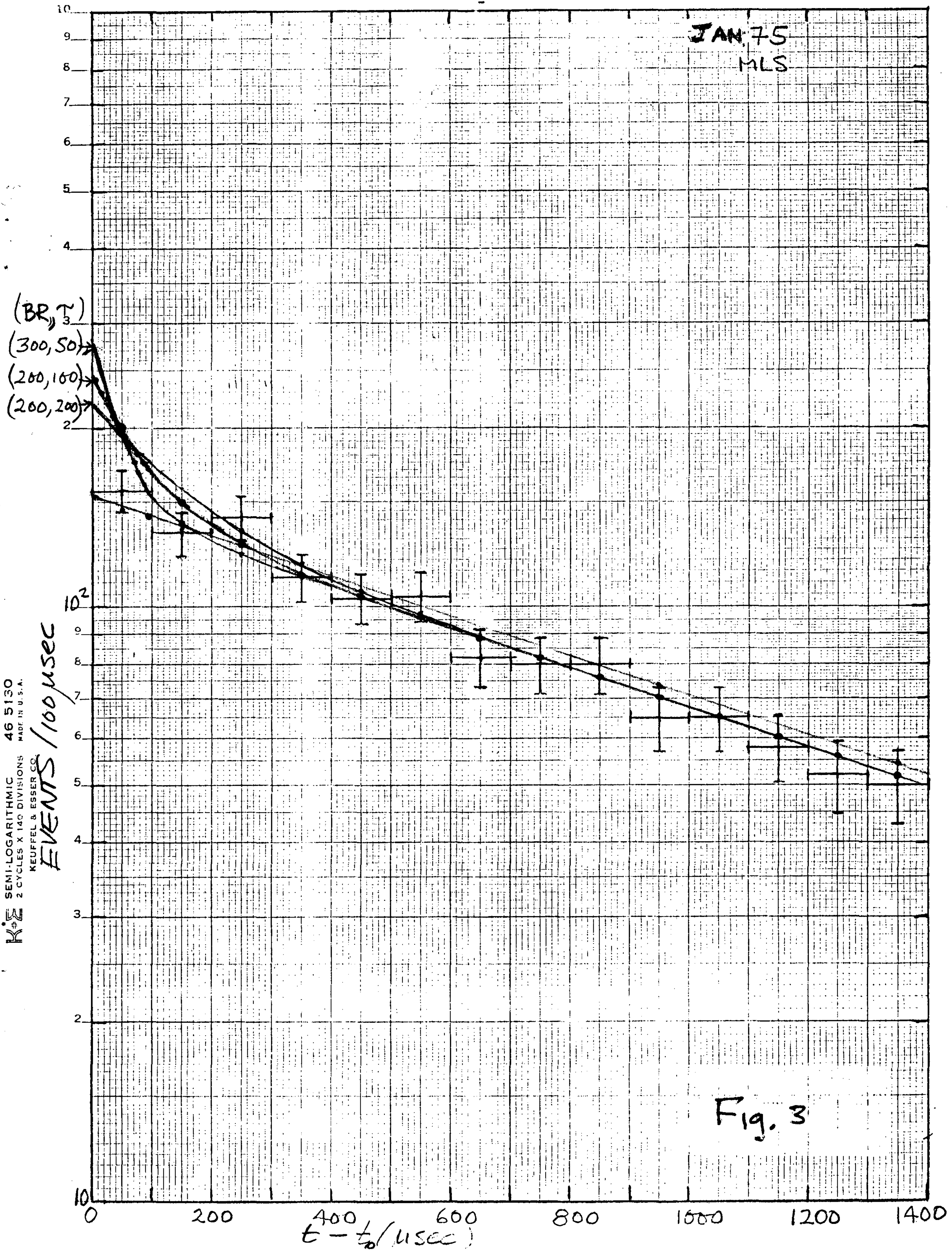
JAN 75
MLS
(BR, τ$_3$)
(300,50)
(200,100)
(200,200)
EVENTS/100 μsec
$t - t_0$ (usec)
10
9
8
7
6
5
4
3
2
10^2
9
8
7
6
5
4
3
2
10
0
200
400
600
800
1000
1200
1400
K+E SEMI-LOGARITHMIC 46 5130
2 CYCLES X 140 DIVISIONS MADE IN U.S.A.
KEUFFEL & ESSER CO.

Fig. 3

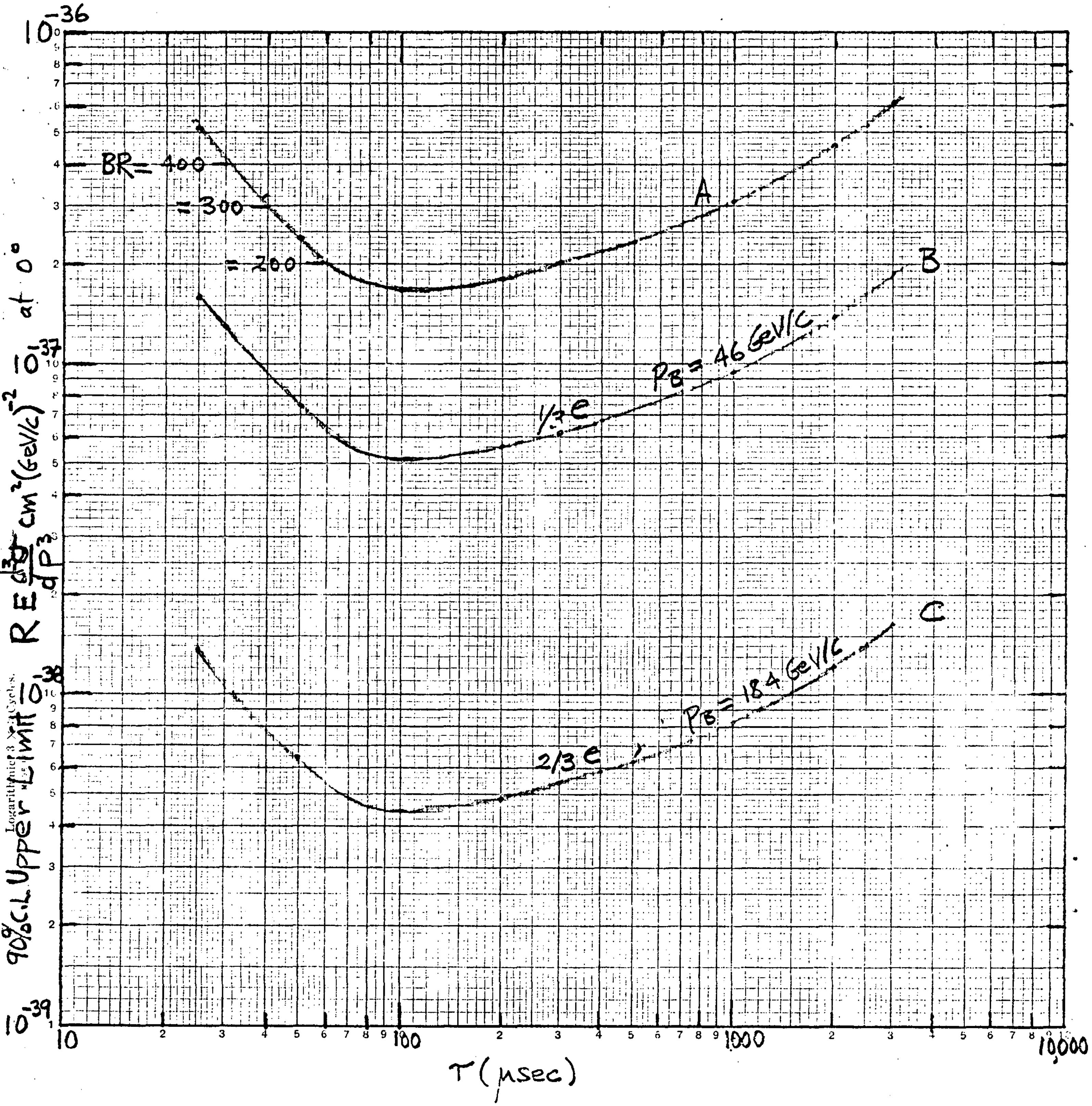
10^{-36}
BR = 400
= 300
= 200
A
B
$P_B = 46$ GeV/c
1/3 e
C
$P_B = 184$ GeV/c
2/3 e
10^{-37}
10^{-38}
10^{-39}
90% C.L. Upper Limit $R\,E\frac{d^3\sigma}{dp^3}$ cm^2(GeV/c)$^{-2}$ at 0°
Logarithmic 3 X 5 Cycles
10
100
1000
10,000
τ (μsec)

Fig 4.

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