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An Experimental Fable

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AN EXPERIMENTAL FABLE

Over the last two years, new phenomena have been observed with breathtaking frequency in high-energy collisions. In rapid succession have come the discoveries of neutral weak currents, of copious lepton production at large transverse momentum in hadron-hadron collisions, of unexpectedly large rates of hadron production in electron-positron annihilations, of the incredibly long-lived particles J(3095) and $\psi'(3684)$, of dimuon events in deeply inelastic neutrino-nucleon scattering, of a rich spectrum of states in the Psion family, of muon-electron events in electron-positron annihilations,[1] and of $K_S e^+ \mu^-$ events in neutrino nucleon collisons.[2] It is possible that all of these effects have a common origin, but the view that we are witnessing a number of new and distinct phenomena cannot be dismissed casually.

In the present communication, we shall not specifically discuss any of these noteworthy experimental findings. Instead we offer a fantastic account of the discovery[3] of the muon and pion, in the form of a yellowed letter which has recently fallen into our hands, apparently through the fortunate mistake of a postal clerk directing long-delayed mail.

FOOTNOTES

[1]It is inappropriate to record all the relevant original articles reporting on these discoveries. We suggest the forthcoming Proceedings of the Photon/Lepton Symposium at Stanford in 1975 as a comprehensive source book.

[2]J. Von Krogh, at Irvine Conference, December 5, 1975, and private communications with the Berkeley-Hawaii-Wisconsin-CERN collaboration. J. Blietschau, et al., CERN preprint D.Ph.II/PHYS 75-49.

[3]The account given below is apocryphal. The canonical history of the discovering of π and μ mesons and the attendant confusion is succinctly documented in R.E. Marshak, Meson Physics (McGraw-Hill, New York, 1952), Chapter VI.

Royal National Physical Laboratory
Batavia, Indonesia
December 31, 1937

My Dear Yukawa:

In the last few years, my associates and I, here at the Royal National Physical Laboratory, have been investigating the validity of the Quantum Mechanical version of Electromagnetic Theory as formulated by Dirac, Fermi and others. The name recently coined for this subject, "Quantum Electrodynamics" (as Fermi calls it "L'Elettrodinamica Quantistica"), seems most appropriate for brevity. I shall further save myself by abbreviating it to QED.

We are particularly intrigued by a prediction of relativistic QED, which has been worked out by our Indian colleague, Bhabha. According to his calculation, which has been repeated by a young theoretician at our Institute, scattering between an electron and a positron is quantitively different from that between two electrons. I understand that this difference arises from the Pauli exclusion principle applicable to two electrons (which is of course not applicable to an electron-positron system) and from the possibility that an electron and a positron can virtually annihilate into a light quantum. We have been trying to verify the Bhabha formula for scattering of very energetic electrons and positrons.

After two years of painstaking work, my colleagues and I are now convinced that above a certain energy, there is disagreement between the theoretical prediction and our experimental measurements. Since you have speculated in the past on the breakdown of QED, I am now reporting to you our experimental findings, and asking for your theoretical counsel. Our colleagues here are completely baffled by the findings. We are daily discussing various interpretations of the results, but we have not come to one which can explain all anomalies in our data.

Before telling you about our data, I must explain some aspects of the work we have carried out at our Laboratory in the past several years, which I trust you can keep in confidence. The Imperial Army Air Corps has been interested in detecting aeroplanes before they appear in sight, and commissioned the R. N. P. L., some years after the World War, to develop such a device by use of reflection of electromagnetic waves of certain wavelengths off metalic parts of hostile aeroplanes. State secrecy does not permit me to divulge all the details of this work, much less whether this idea works or not, but this endeavor did lead to a very remarkable means of accelerating electrons to very high velocities. The device is a long cylindrical electromagnetic wave "guide" loaded with metallic annular disks. With proper design, the speed of electromagnetic waves travelling downstream along the axis of the pipe can be increased, and electrons can be made to ride on the crest of the wave. In this way we were able to accelerate electrons to energies over 100 million electron volts!

At this point we learned also the possibility of producing positrons by colliding electrons with metallic elements. Positrons so produced may be collimated and refocused and accelerated to a desired energy by a wave guide. Since you are a theoretician, I shall spare you the technical details. In any case, the next step was to construct a ring of vacuum pipes in which to store accelerated electron and positron beams, well-separated and travelling in opposite direction. The storage ring consists of four semi-circular sections of 1 meter radius, and four straight sections connecting them.[a] The beam bending along the circular sections was accomplished by gigantic electromagnets of about 3 kiloGauss. The two beams, then, were steered to collide in one of the straight sections. This truly gargantuan undertaking was made possible by a Royal grant, amounting to several million guilders, no doubt with the timely intercession of our most enlightened Queen Mother, a dedicated patron of the sciences.

So much for the design of the colliding beam facility. Let me now describe our experimental results. We began our study from the energy of 50 million electron volts in each beam. The Bhabha formula can be reduced for extremely relativistic collisions to

$$\frac{d\sigma}{d\Omega} = \frac{r_o^2}{16}\left(\frac{m}{E}\right)^2\left\{\frac{2}{\sin^4(\theta/2)}\left(1+\cos^4\frac{\theta}{2}\right) - \frac{4}{\sin^2(\theta/2)}\cos^4\frac{\theta}{2} + \left(1+\cos^2\theta\right)\right\} .$$

We placed arrays of Geiger tubes on opposite sides of the beam pipe, 1 m. from the interaction point and subtending the angular interval $|\cos\theta| < 0.35$, $0 \leq \phi \leq \pi/2$ and $\pi \leq \phi \leq 3\pi/2$. We concentrated our measurements at wide angles, where the difference between the Møller and Bhabha formulas is most pronounced. Our angular resolution, although coarse, allowed a check of the collinearity of the scattered e^+e^- pair. Since we lacked the funds for analyzing magnets when we began our investigations, our data are folded about $\theta = 90^\circ$. Our detection apparatus also included small-aperture detectors near $\theta = 0^\circ$ and $\theta = 180^\circ$ for normalization. What we are able to test, therefore, is the angular distribution of scattered pairs predicted by Bhabha.

In Fig. 1 enclosed I plot the ratio of detected collinear pairs in the acceptance of our detector to the Bhabha prediction. The low- and high-statistics runs correspond to approximately 1,000 and 10,000 events. For these enormous numbers we are indebted to our tireless laboratory assistant, Mr. Ibrahim. You will notice that between the energies of 50 and 120 MeV per beam, our results are in excellent agreement with Bhabha's prediction, and very different from the well-known results for electron-electron scattering. So far as we can measure them, the angular distributions (see graphs a, b, c of Fig. 2) are in perfect agreement with the Bhabha formula. Thus, although we should prefer the statistics to be even greater, we have proved the θ-dependence of the Bhabha formula to our own satisfaction.

Starting at 125 MeV/c per beam, however, the situation is different and very confusing. The collinear-pair event rate begins to grow so that by 200 MeV/c per beam, there is an excess of about 10% over Bhabha's prediction.[b] You may be certain that our first reaction to these data was that some part of our apparatus was behaving poorly. We have kept these data to ourselves for more than a year while checking and rechecking for systematic errors, but we can find no explanation for this curious behavior.[c] Within our acceptance, the angular distributions are indistinguishible from Bhabha's prediction, provided we normalize to the observed number of events. [See the remaining graphs in Fig. 2.]

What can be made of these results? One of our most inventive young colleagues, Dr. Ashok, has observed that Bhabha's annihilation term interferes destructively with the photon-exchange term. He speculates (and I must confess I cannot follow his reasoning completely[d]) that at very high energies the annihilation term dies away because of the competition of many-photon final states. The contribution of the direct term, integrated over our acceptance, is $1.124 \times$ the full Bhabha formula, in excellent agreement with the trend of our data. While we cannot rule out this interpretation entirely, it runs into difficulty with another observation, which I shall now describe.

Having satisfied ourselves that the observed departure from the Bhabha formula is not merely an instrumental effect, we attempted to explore in detail the nature of the "extra" events. As I have already told you, the folded angular distributions appear to be rather uninformative. We attempted to unfold the angular distributions by placing a small magnet and a second plane of Geiger tubes outside the original planes. For energies below 125 MeV/c, the unfolded angular distributions agree fully with the Bhabha formula. Above this threshold energy, we find that when the analyzing magnet is turned on, the coincidences between the second Geiger tube plane and the opposite plane do not exceed Bhabha's prediction. In other words, the electrons or positrons in the excess events are swept out of our apparatus by the analyzing magnet!

Are we to conclude from this observation that low energy pairs are produced, in violation of the energy conservation law? It occurred to us that the energy conservation would be restored if there were neutral quanta produced in association. However this explanation seems to run afoul of the collinearity of pairs when the analyzing magnet is turned off.

We have noticed another effect which I hesitate to mention because we have not been able to rule out detector problems. It seems, however, to be genuine. At about 150 MeV/c per beam and above, we observe single counts with no accompanying count in the opposite detector.[e] Our observations are shown in Fig. 3. I stress again that this result is not yet on the same footing as our other data. Together with the preceding effect, however, it suggested another interpretation to us. The two-quantum process recently explored theoretically by Landau and Lifshitz and by E. J. Williams[f] would seem to call for the production of low-energy electron-positron pairs in addition to those which initiate the collision. Since our detector lacks any sensitivity for $|\cos\theta| > 0.35$, we cannot exclude the possibility that additional electrons are escaping down the beam pipe. We should be most grateful for your guidance in the matter of testing the two-quantum hypothesis.

I have saved for last the most bizarre, and most exciting, news. For part of our high-energy running we placed a cloud chamber outside the Geiger plane and triggered its expansions on collinear pairs in the electronic detector.[g] Nearly all the photographs showed throughgoing tracks, as expected. One, which I include as Fig. 4, was extraordinary. In fact we cannot explain the kink in the electron track, but one speculation is extremely tempting. We may have observed the production of a massive new object which decays into an electron and a neutral object (perhaps a photon?). I am embarrassed to admit that in our most unrestrained moments of speculation, we imagine that this may be the mediator of the nuclear force, your mesotron.[h]

This would also explain why excess events were swept away when we turned on the analyzing magnet. The mesotron pairs would carry very little momenta. However, our theoreticians keep reminding me of the implication of your paper that a mesotron cannot decay into an electron and a photon! Some suggested that the mesotron may decay into an electron and a neutrino of Pauli. Is it so?

These wild conjectures must reveal to you the depth of our confusion.

I appeal to you for ideas, either new interpretations or ways to test our own rather naive suggestions. My colleagues and I are certain of nothing except that we have exercised the greatest care of which we are capable in ensuring that the data are reliable.

Yours respectfully,

Raza Rahman

ANNOTATIONS BY BWL AND CQ

[a]We assume the storage ring was an isomagnetic type. The quantum fluctuation of the beam energy is estimated by us to be about 87 eV.

[b]We now recognize the onset of muon pair production. The modern reader may wonder why the 1^3S_1 and 2^3S_1 states were not seen. It is due to the fact that the width of the first is only 2×10^{-3}eV compared to the beam energy resolution of about 100 eV .

[c]We have been able to reproduce the essential results of this communication by a Monte-Carlo simulation.

[d]The Director of RNPL, Professor Dr. Raza ibn Yosif Rahman, clearly was not a theorist.

[e]These are due to the production and decay of pion pairs.

[f]The writer seems to refer to L. Laundau and E. Lifshitz "On the Production of Electrons and Positrons by a Collision of Two Particles" Physik Z. Sowjetunion 6, 244. (1934), and E.J. Williams "Correlation of Certain Collision Problems with Radiation Theory," Det. Kgl. Danske Videnskabernes Selskab. XII, 4 (1935). For modern views of this process, see S.J. Brodsky, T. Kinoshita and H. Terazawa, Phys. Rev. D4, 1532 (1971).

[g]We cannot help admiring the use, as early as in 1937, of a cloud chamber in a triggered mode.

[h]In fact this is an example of the decay $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$.

Without knowing how the confusion of present-day experimental results will be resolved, it is hard for us to draw the proper moral from our fable. The parallels of heavy leptons and new hadrons are of course self-evident, but these reflections on puzzles past suggest that there is a danger in not being bold enough in our speculations about new phenomena. It would be supremely ironic if the psions turned out to be bound states of heavy leptons and the charmed quark-antiquark bound state ϕ_c were still to be found.

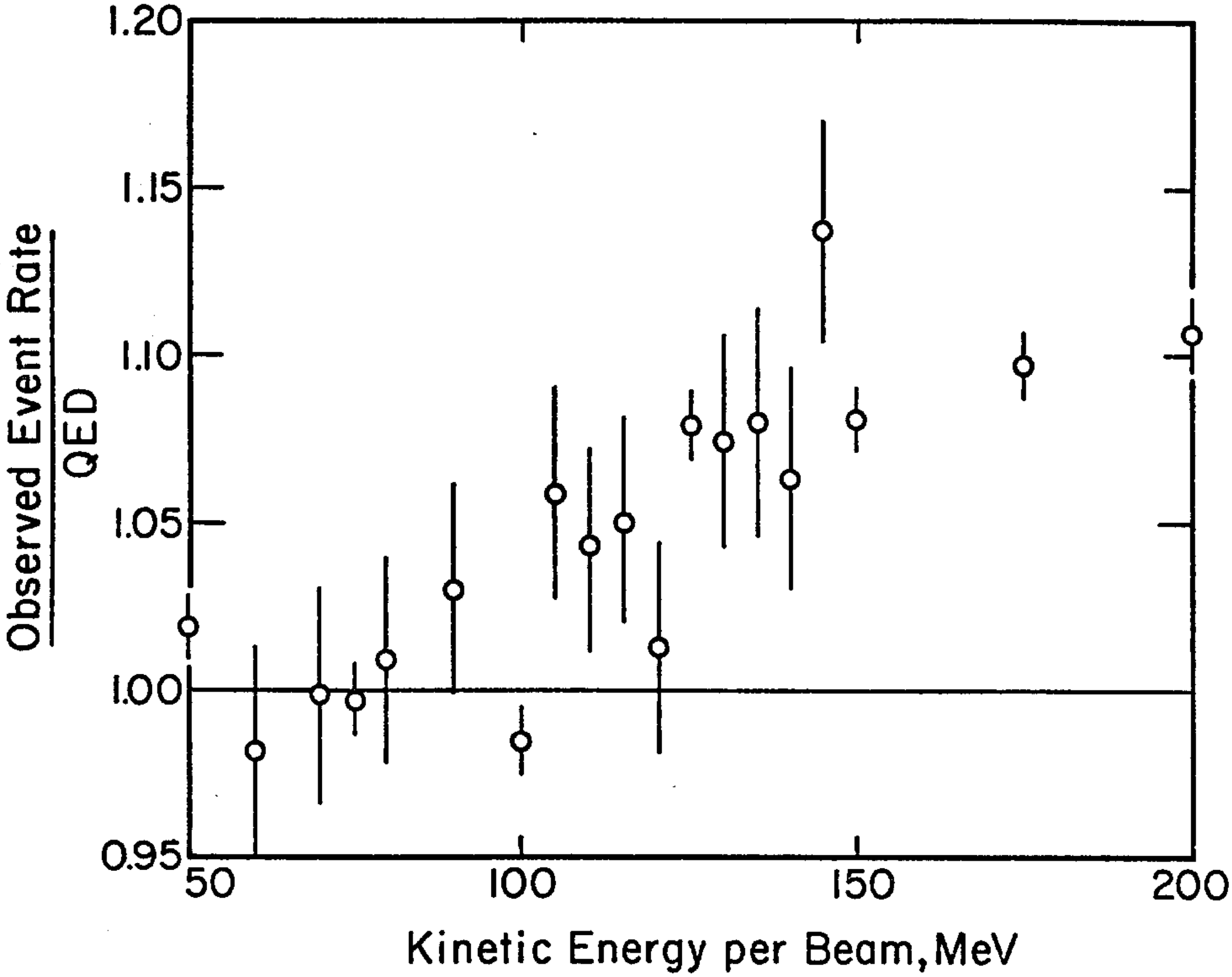

1.20
1.15
1.10
1.05
1.00
0.95
50
100
150
200
Observed Event Rate / QED
Kinetic Energy per Beam, MeV

FIG. 1

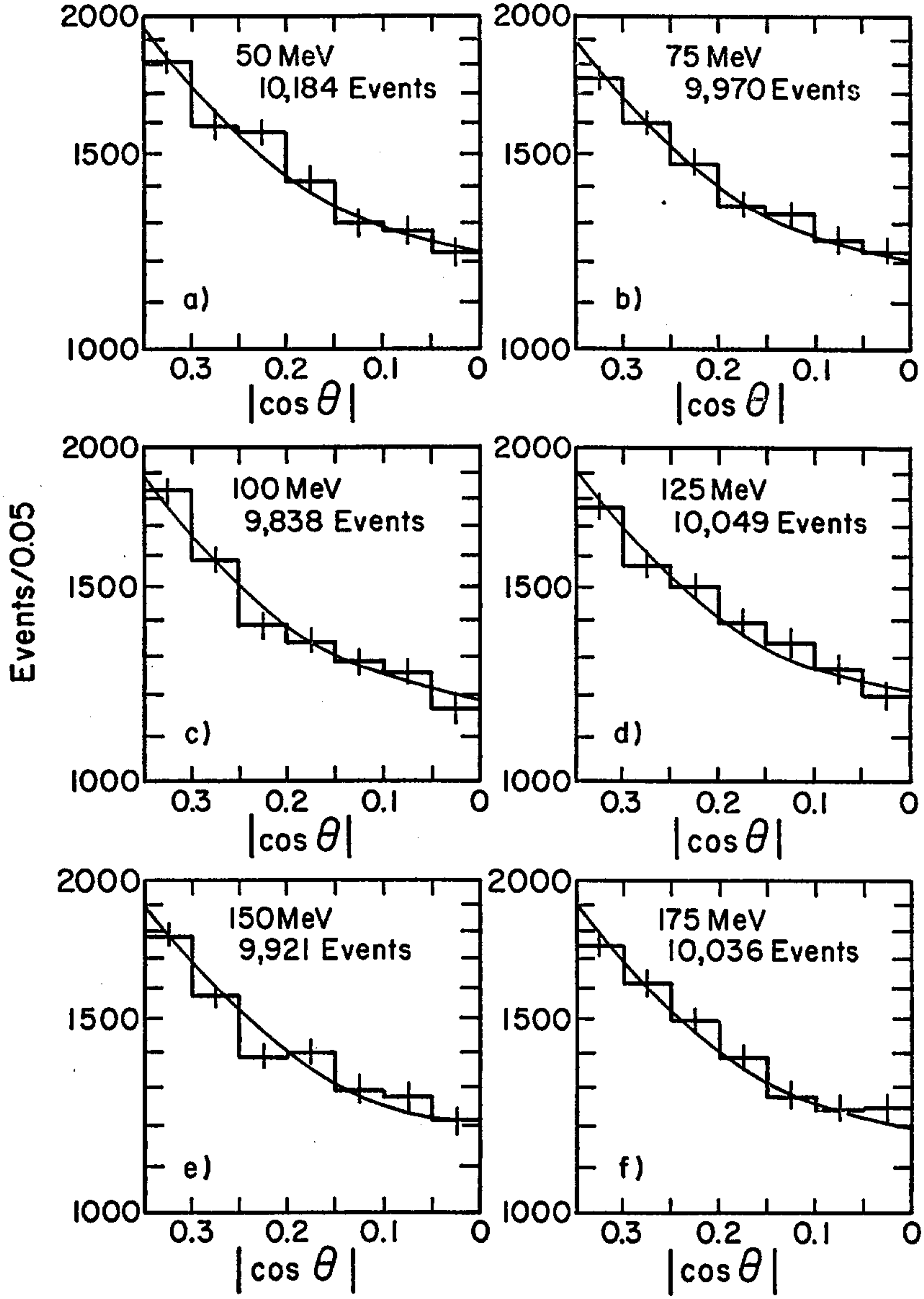

Events/0.05
50 MeV
10,184 Events
a)
75 MeV
9,970 Events
b)
100 MeV
9,838 Events
c)
125 MeV
10,049 Events
d)
150MeV
9,921 Events
e)
175 MeV
10,036 Events
f)
2000
1500
1000
0.3
0.2
0.1
0
|cos θ|

FIG. 2

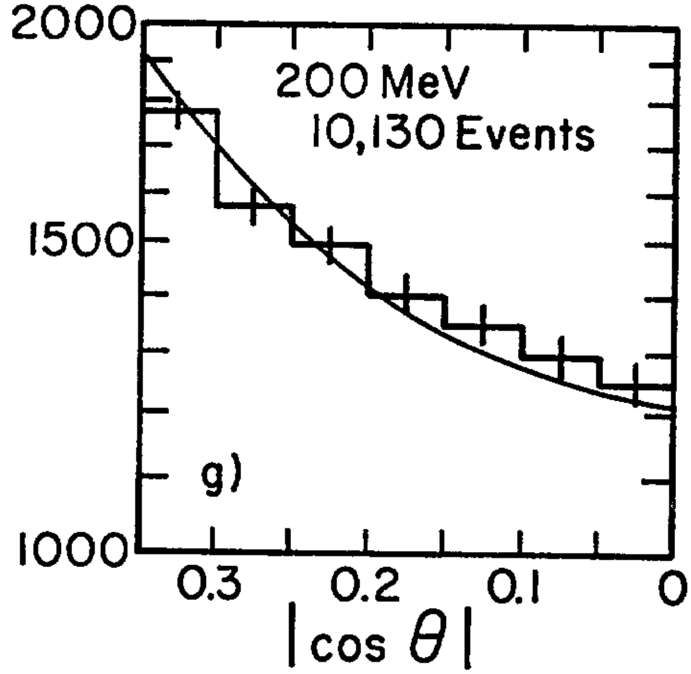


FIG. 2

(continued)

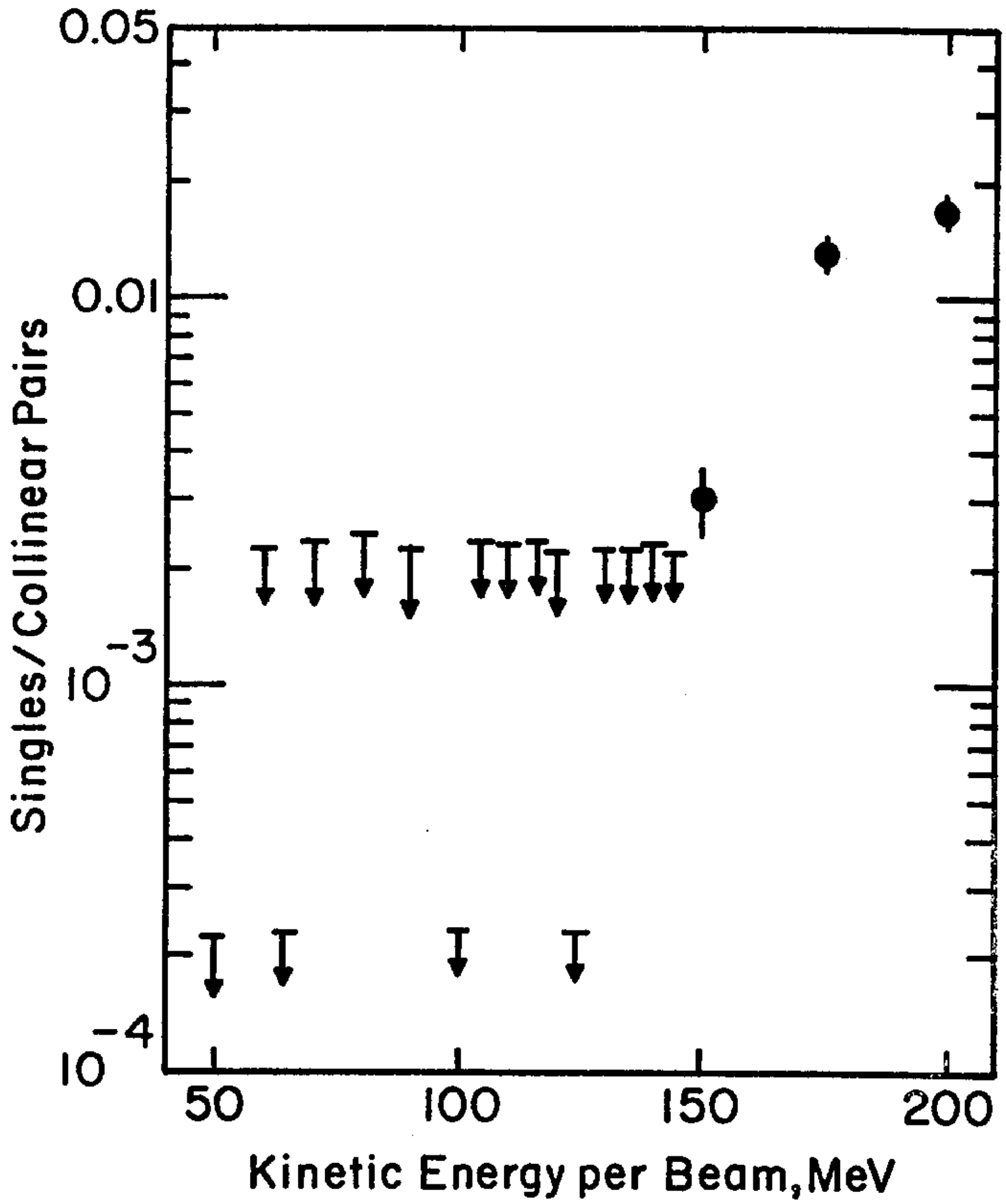

0.05
0.01
10^-3
10^-4
Singles/Collinear Pairs
50
100
150
200
Kinetic Energy per Beam, MeV

FIG. 3

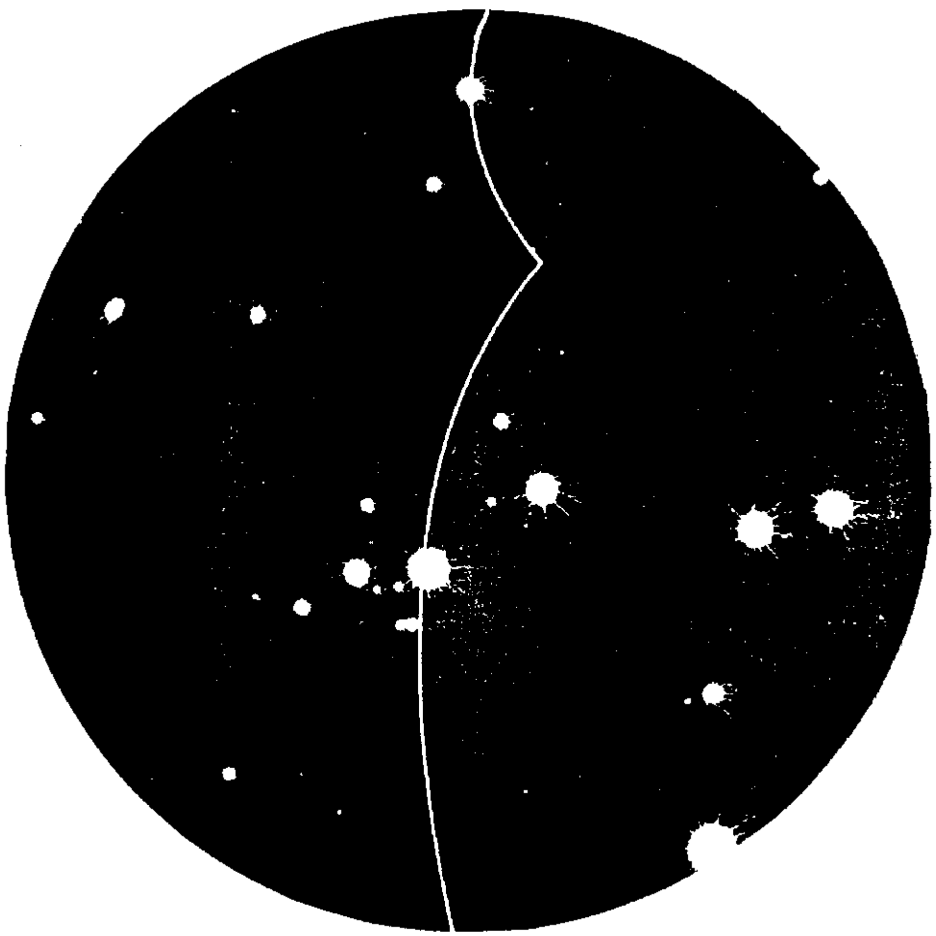
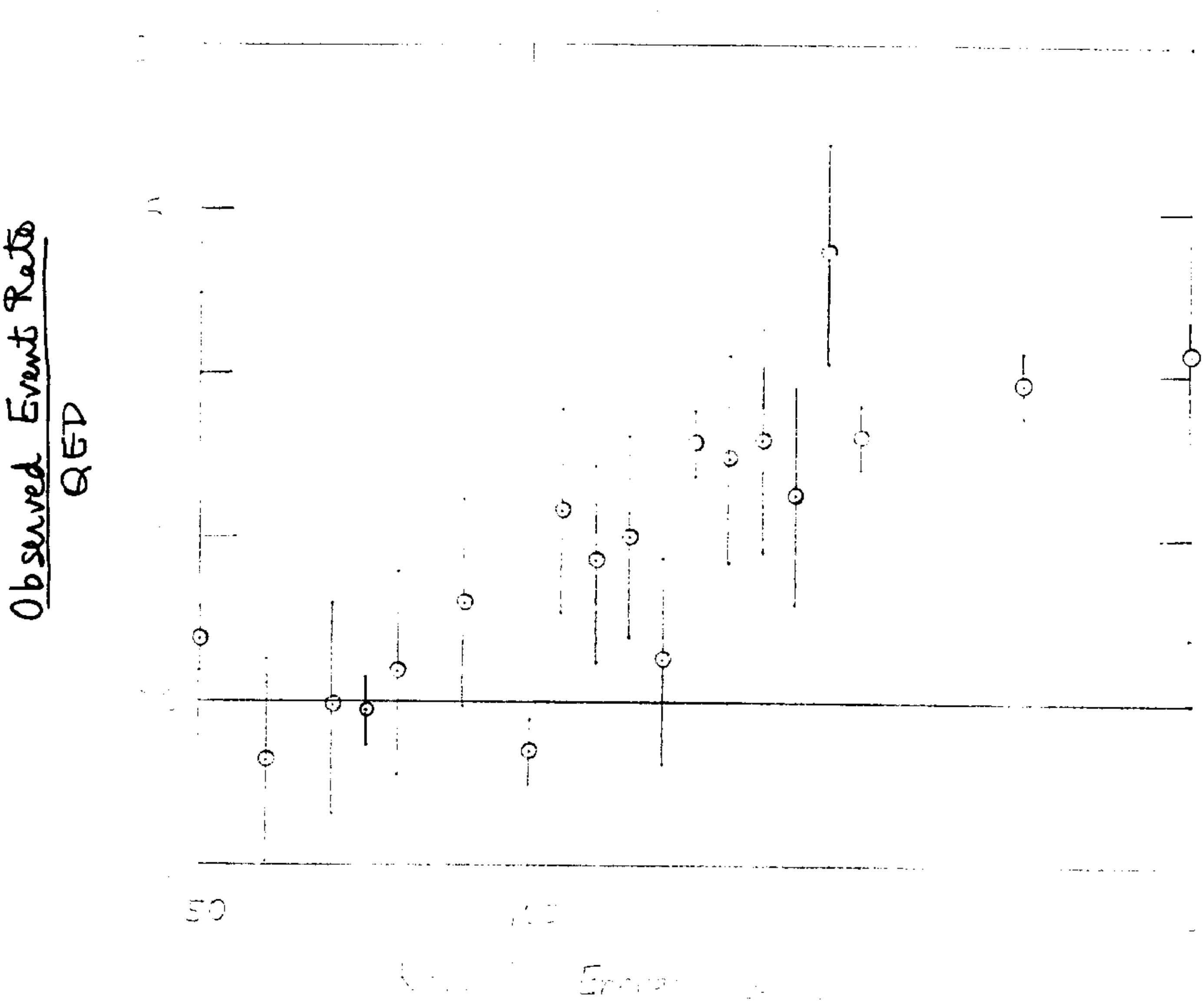


FIG. 4


Observed Event Rate
QED
50