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A Search for Short-Lived Particles Produced in an Electron Beam-Dump ‡

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Abstract

A search for short-lived neutral particles which decay to electron-positron pairs has been carried out using a beam of 275 GeV electrons incident on an active tungsten beam-dump. The experiment was sensitive to particles up to 10 MeV/c^2 in mass and down to 4×10^{-16} seconds in lifetime.

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The monoenergetic positron peaks seen in heavy ion collision experiments [1] at the Gesellschaft für Schwerionforschung (GSI) remain a puzzling phenomenon. It was proposed early on that this could be a signal for the production and subsequent decay into an electron positron pair of a new neutral boson X_0 with mass about 1.8 MeV/c^2 [2]. This suggestion was supported by the observation of coincident electron-positron pairs having equal lab energies ($E_{e^+} + E_{e^-} = 1.8$ MeV/c^2 - 2m$_e$) [3].

Dedicated searches for the X_0 in nuclear decay [4], in beam dump experiments [5,6,7] and in low energy bhabha scattering [8] have thus far all produced null results. The production of e^+e^- pairs by heavy ions in emulsion has, however, been presented [9,10] as direct evidence for new neutral bosons with masses less than 10 MeV/c^2 and lifetimes between 3×10^{-16} and 1.5×10^{-15} seconds.

While any simple model for the particles discussed in refs [9] and [10] would appear to be at odds with limits obtained from precision atomic physics experiments [11,12] all these phenomena have focussed attention on a region of mass and lifetime where short-lived neutral bosons could exist and yet would not have been observed. The most sensitive previous beam dump experiments [6,7], for example, are limited to lifetimes above 10^{-14} seconds.

In this letter, we report results from an electron beam dump experiment performed at Fermilab using a 275 GeV/c electron beam. An electron beam dump experiment is a direct way of searching for a neutral X_0 [7]. If the X_0 couples to the electron, it will be produced by interactions between beam electrons and high-Z nuclei of the beam-dump in a process analogous to bremsstrahlung [13]; it can then be detected by its decay in flight into an e^+e^- pair provided it exits the dump before decaying. If the X_0 decays predominantly into e^+e^-, its production rate is determined by a single coupling constant which is in turn fixed by the presumed mass and lifetime of the X_0.

The experiment was performed using the wide band electron beam [14] at Fermilab. The beam accepted by our apparatus had a mean momentum of 275 GeV/c with a spread of ±6% and was composed of 94% electrons and 6% hadrons. The apparatus (figure 1) included a set of beam-defining counters, the electron beam-dump (the target-calorimeter), and a pair of scintillation counters immediately behind the dump to veto events in which any charged particles emerged. A decay length of 7.25 meters downstream of the target-calorimeter was instrumented with 4 scintillation counters to detect and measure the multiplicity of charged particles produced by the decay in flight of neutral particles emerging from the dump. These counters were followed by the downstream electromagnetic calorimeter (the trigger calorimeter) and an hadronic calorimeter.

To maximize the sensitivity to short lifetimes, the target calorimeter was made as short as possible and consisted of two 28 radiation-length thick stacks of tungsten plates instrumented with scintillating fiber ribbons[15]; the overall target length, including veto counters, was 30 cm. Since the beam dump technique depends on the neutral particle emerging from the dump before it decays, the short dump length and the large Lorentz time dilation obtained at this energy played a major role in the sensitivity of the experiment. For example, 1.14 MeV/c^2 particles with lifetime 1.3×10^{-15} sec as described in reference [10] produced at 275 GeV would have an average path length of over 9 cm in the laboratory, and hence a substantial detection probability.

A typical beam electron deposited 98% of its energy in the first 28 radiation length section of the target calorimeter. The pulse height produced in the veto counters was less than 10% of minimum ionizing and no signals were seen in the downstream detectors. In contrast, an event in which a neutral particle was produced would be characterized by energy appearing in the downstream calorimeter.

The experiment trigger required an energy deposition in the downstream (trigger) electromagnetic calorimeter greater than 10% of the nominal beam energy in coincidence with a beam particle striking the target calorimeter and no signal from the veto counters immediately behind the dump. There was no requirement in the trigger on the signals from the counters in the decay volume, nor on the signals from the target-calorimeter or the hadron calorimeter.

The experiment operated at a typical intensity of 10^7 particles per 22 second beam pulse. The data described here represent a total of 0.52×10^{10} electrons on target, which produced a total of 1.6×10^5 triggers. The major sources of triggers were beam pions which passed through the target, were not registered by the veto counters, and then interacted in the downstream electromagnetic calorimeter, and kaons which interacted in the target to produce a leading neutral kaon which escaped the dump and decayed via $K_S^0 \rightarrow \pi^0\pi^0$ thus satisfying the trigger.

Since the bremsstrahlung production spectrum of a particle of mass > $2m_e$ is strongly peaked at high secondary energy [13], the evidence for a new particle would show as an excess of events with large electromagnetic energy deposition in the downstream calorimeter and signals corresponding to two charged particles in the decay volume scintillators. To identify such a signal, the backgrounds from conventional processes must first be identified and removed.

The primary reduction of the data consisted of three steps: the removal of events due to beam hadrons interacting in the target calorimeter or multiple beam particles, the classification of the event sample into bins of charge multiplicity, and the identification of the electromagnetic and hadronic final states for each multiplicity bin.

The first reduction was accomplished by three cuts. Events were removed from the data sample if the pulse height in the beam trigger counters indicated more than one beam particle, or if the sum of the calorimeter energies (target, trigger and hadronic calorimeter) deviated from the mean beam energy by more than 30%. Events in which the energy measurements were distorted by residual signal from previous interactions were rejected by examining ADC's setup with an early gate. Finally, to remove most hadron interactions in the target, events were removed from the sample if E $> 0.04 \times E_{beam}$ appeared in the second section of the target calorimeter.

The charge multiplicity distribution for the remaining events is shown in figure 2(a). Clearly visible are the expected peaks at multiplicity 0 for neutrals that failed to decay or decayed into neutral final states, and at 2 for neutrals that decayed into two charged particles. The prominent peak at multiplicity 1 is due to a small inefficiency of the veto counters (2×10^{-5}). It consists entirely of events in which a beam hadron passed through the target, failed to register in the veto counters, and interacted in the trigger calorimeter.

Hadronic and electromagnetic final states were distinguished by the fraction of the downstream energy appearing in the hadron calorimeter, $FHAD$. Figures 3(a-c) show the distribution of this fraction for multiplicity 0, 1, and

2 events. The peaks at low $FHAD$ in the multiplicity 0 and 2 plots are the electromagnetic neutral and electromagnetic two-charged particle final states respectively. The absence of any such peak in the multiplicity 1 plot shows the clear separation of electromagnetic and hadronic final states.

The electromagnetic sample is defined as the events with $FHAD < 0.16$. Figure 2(b) shows the multiplicity spectrum for events defined as electromagnetic. Compared to figure 2(a), the multiplicity 1 peak is strongly suppressed.

Given this sample of identified electromagnetic events, the distribution in the fraction of the total electromagnetic energy, $ZTRIG$, appearing in the downstream (trigger) calorimeter for charge multiplicity 0 and 2 is shown as the dashed curves in figures 4(a) and 4(b), respectively. Any signal for a new particle would appear as an excess of events at large $ZTRIG$ in figure 4(b). The remaining analysis is concerned with identifying and measuring the contamination from hadronic final state events and backgrounds from conventional electromagnetic processes, using the identified hadronic events and the multiplicity 0 (neutral) event spectrum.

Two corrections due to purely hadronic events must be applied to the raw spectrum of figure 4(b). The first is for single beam hadrons which passed through the target calorimeter, failed to register in the veto counters, were mismeasured to be multiplicity 2 *and* misidentified as electromagnetic in the downstream calorimeters. These events are the tail of the remaining multiplicity 1 peak in figure 2(b) which lies under the multiplicity 2 peak. Though there were few of these events, they typically were at large $ZTRIG$ and could thus simulate a real signal. The probability for a single hadron to be measured as multiplicity 2 (0.0135) and the probability for it to be misidentified as electromagnetic (2.9×10^{-3}) have both been determined from the data. The observed $ZTRIG$ distribution for multiplicity 1 hadrons was normalized by the combined probability (3.9×10^{-5}) and the result subtracted from the spectrum of figure 4(b).

The second correction was for multiplicity 2 hadronic final states, e.g. $K_S^0 \to \pi^+\pi^-$, which were misidentified as electromagnetic events. In this case the measured multiplicity 2 hadronic spectrum was multiplied by the probability that the event was misidentified as electromagnetic, (7.0×10^{-4}), and subtracted bin by bin from the multiplicity 2 electromagnetic spectrum of figure 4(b).

We now turn to the corrections on the multiplicity 0 spectrum, since this will be used to calculate the backgrounds in the electromagnetic multiplicity 2 spectrum. Again, the corrections for misidentified hadronic events must be made. As in the previous case, the $ZTRIG$ spectrum of hadronic final states with measured charge multiplicity 0 was multiplied by the misidentification probability (2.9×10^{-3}) and subtracted bin by bin from the multiplicity 0 electromagnetic spectrum. The corrected spectra are shown as the solid curves in figures 4(a) and 4(b).

The final step in the analysis was to subtract the background due to Dalitz pairs and conversions of photons from the multiplicity 2 electromagnetic event spectrum. We assume that the neutral electromagnetic event spectrum is dominated by events coming from the decay $K_S^0 \to \pi^0\pi^0$ where the K_S^0 was produced without an associated K_L^0 or Λ - most probably by a beam kaon. Pion induced events require an associated strange particle and will almost always result in a hadronic event since the K_L^0 decay probability is small, and Λ's or other strange baryons will always have a proton or neutron in the final state giving a large $FHAD$.

With this assumption, the expected spectrum of multiplicity 2 electromagnetic events from Dalitz decays and from photon conversions can be calculated directly from the corrected multiplicity 0 electromagnetic spectrum. The number of K_S^0 *produced* at any energy, E, is determined by dividing the electromagnetic energy spectrum *measured* by the decay probability for a K_S^0 of that energy; this production spectrum is then multiplied by the probability of the decay $K_S^0 \rightarrow \pi^0\pi^0$ upstream of the multiplicity measuring counters where *either* a π^0 decays with a Dalitz pair (probability $= 2 \times 0.0120 = 0.024$) *or* one of the 4 photons converts in the material before the multiplicity defining counters (probability $= 4 \times 0.009 = 0.036$).

The subtraction of this background from the multiplicity two electromagnetic spectrum is shown in figure 4(c). As can be seen, there are no excess events within the statistical precision of the plot. The 90% confidence level upper bound on the number of events with $ZTRIG > 0.3$ due to a neutral X_0 is 17 events or 3.26×10^{-9} events per incident electron.

This result constrains the interpretation of the e^+e^- events seen in emulsions [9] and [10]. For example, a spin zero X_0 with mass 1.14 MeV/c^2 and lifetime 1.3×10^{-15} seconds would yield 4700 events in figure 4(c) if it decayed primarily to e^+e^-. Such a particle can therefore exist only if its branching fraction into e^+e^- is less than 0.06.

Following previous beam dump experiments [6,7], we have calculated our yield of observed e^+e^- pairs as a function mass and lifetime, assuming a unit branching fraction into e^+e^- . For a spin 0 particle of mass 1.14 MeV/c^2, we find that the lifetime must be less than 4×10^{-16} seconds (in which case it would decay unobserved inside the beam dump) or greater than 4.5×10^{-12} seconds (in which case it would pass through the decay space before decaying). Figure 5 shows the regions of mass and lifetime excluded at 90% c.l. for four different assumptions about the spin and parity of the hypothetical neutral boson. Longer lifetimes are already ruled out by previous beam dump experiments (for example ref 7, quoted for P only). Shorter lifetimes are constrained[11] by bounds obtained from agreement between theory[17] and experiment[16] for the anomalous magnetic moment of the electron (g-2). Our data, in conjunction with the g-2 limit, rule out a scalar particle with a mass less than 5.0 MeV/c^2, a pseudoscalar with mass less than 4.8 MeV/c^2, a vector particle with mass less than 4.1 MeV/c^2, or an axial vector with mass less than 5.8 MeV/c^2. It has been pointed out[11] that bosons of opposite parity contribute to g-2 with opposite signs. Hence, for the case of *more than one new boson*, the g-2 limit could be violated due to cancellation. As can be seen from figure 5, our result extends by about an order of magnitude the precision required of such a cancellation to allow particles to exist below our quoted mass limits.

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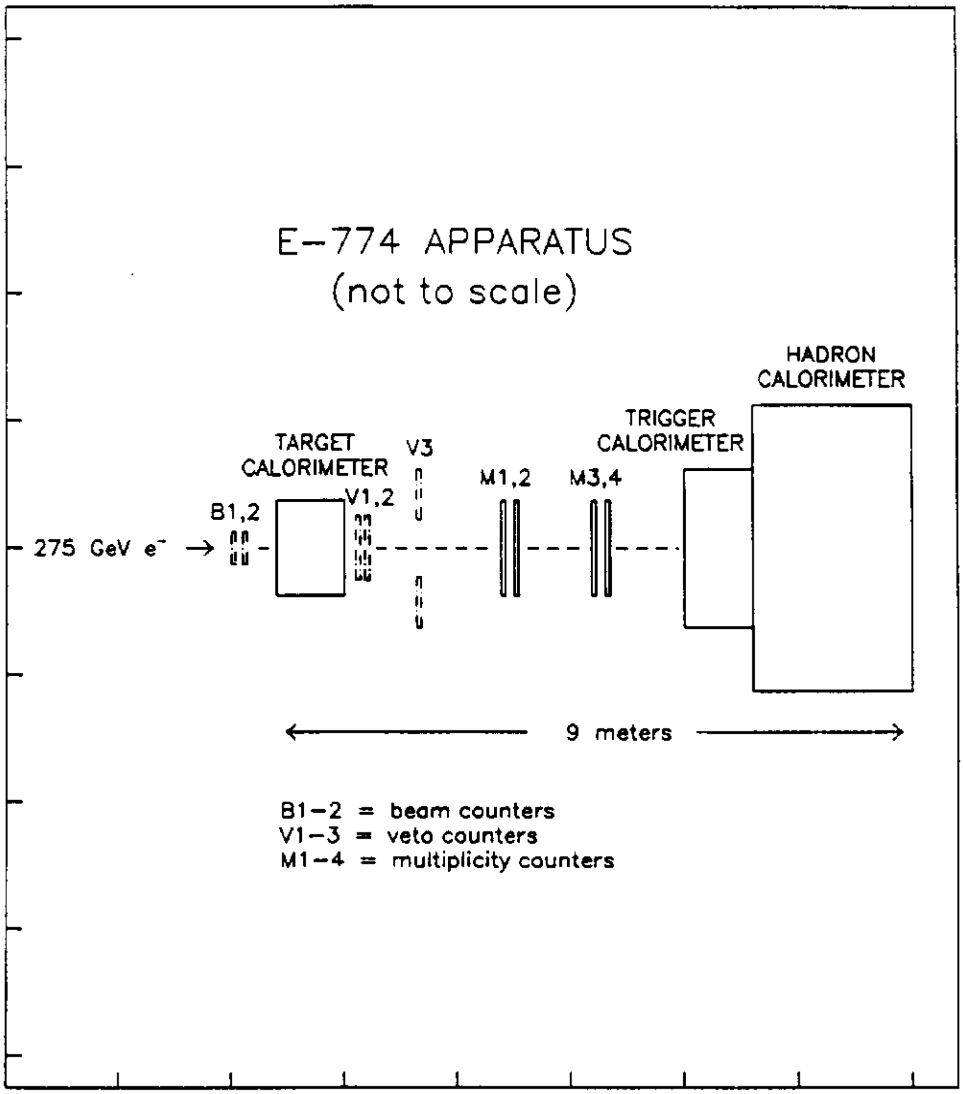
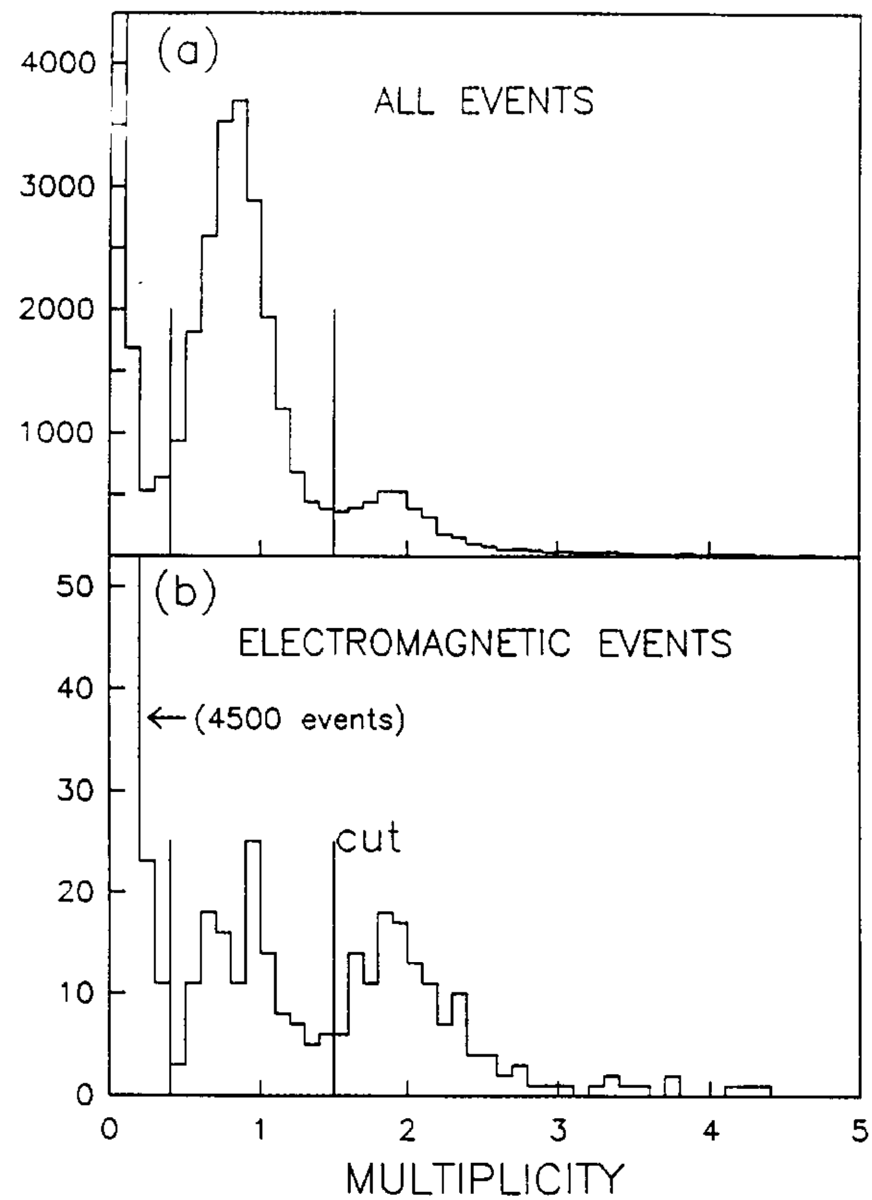

E-774 APPARATUS
(not to scale)
HADRON CALORIMETER
TRIGGER CALORIMETER
TARGET CALORIMETER
V3
M1,2
M3,4
V1,2
B1,2
275 GeV e⁻
9 meters
B1-2 = beam counters
V1-3 = veto counters
M1-4 = multiplicity counters

Figure 1



(a)
ALL EVENTS
4000
3000
2000
1000
(b)
ELECTROMAGNETIC EVENTS
50
40
30
20
10
0
←(4500 events)
cut
0
1
2
3
4
5
MULTIPLICITY

Figure 2

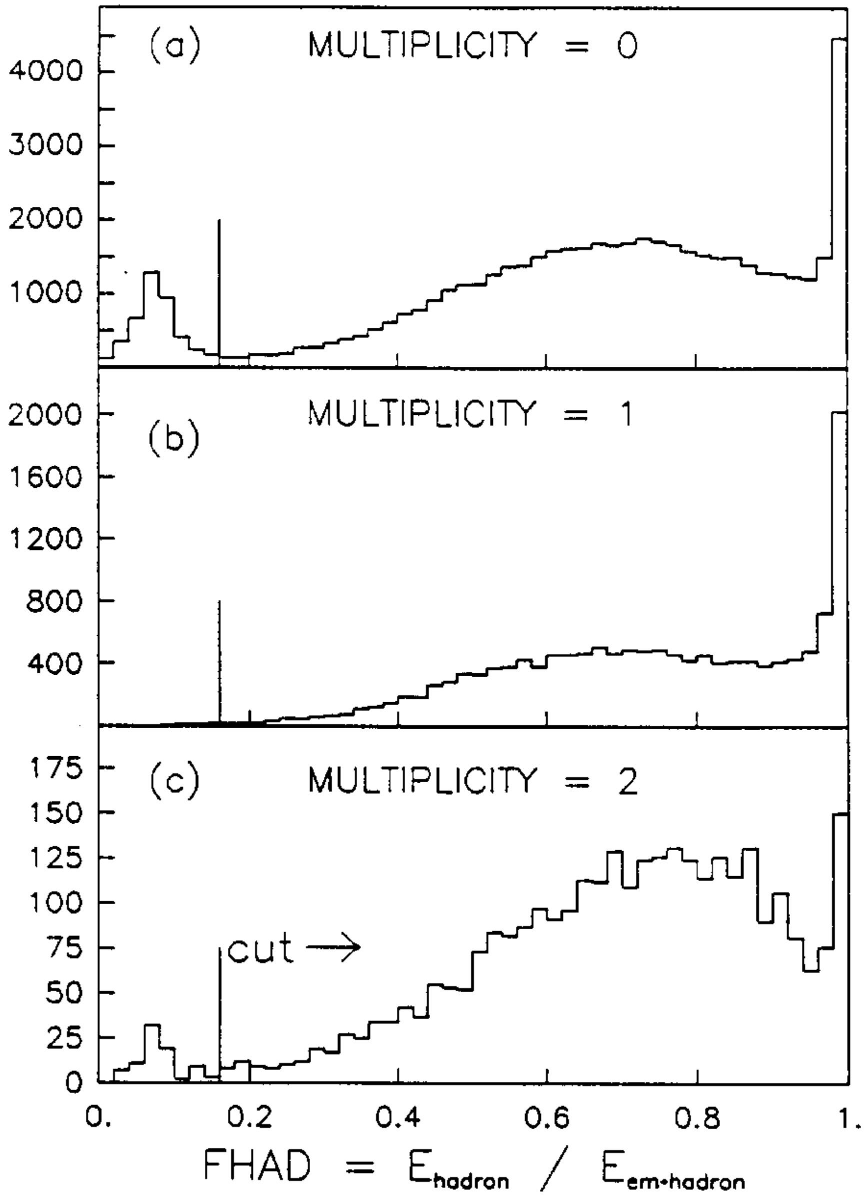

(a)
MULTIPLICITY = 0
4000
3000
2000
1000
MULTIPLICITY = 1
(b)
2000
1600
1200
800
400
(c)
MULTIPLICITY = 2
175
150
125
100
75
50
25
0
cut →
0.
0.2
0.4
0.6
0.8
1.
FHAD = E_hadron / E_em+hadron

Figure 3

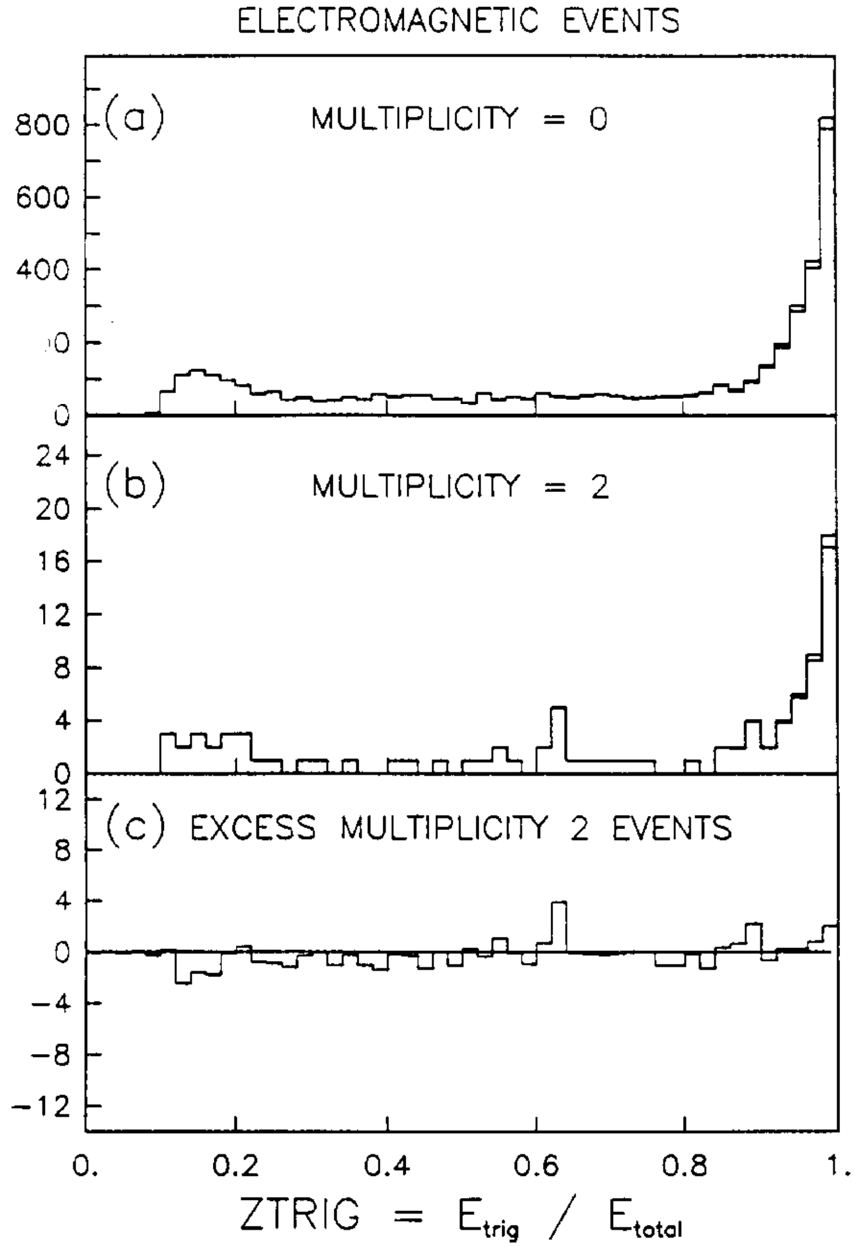
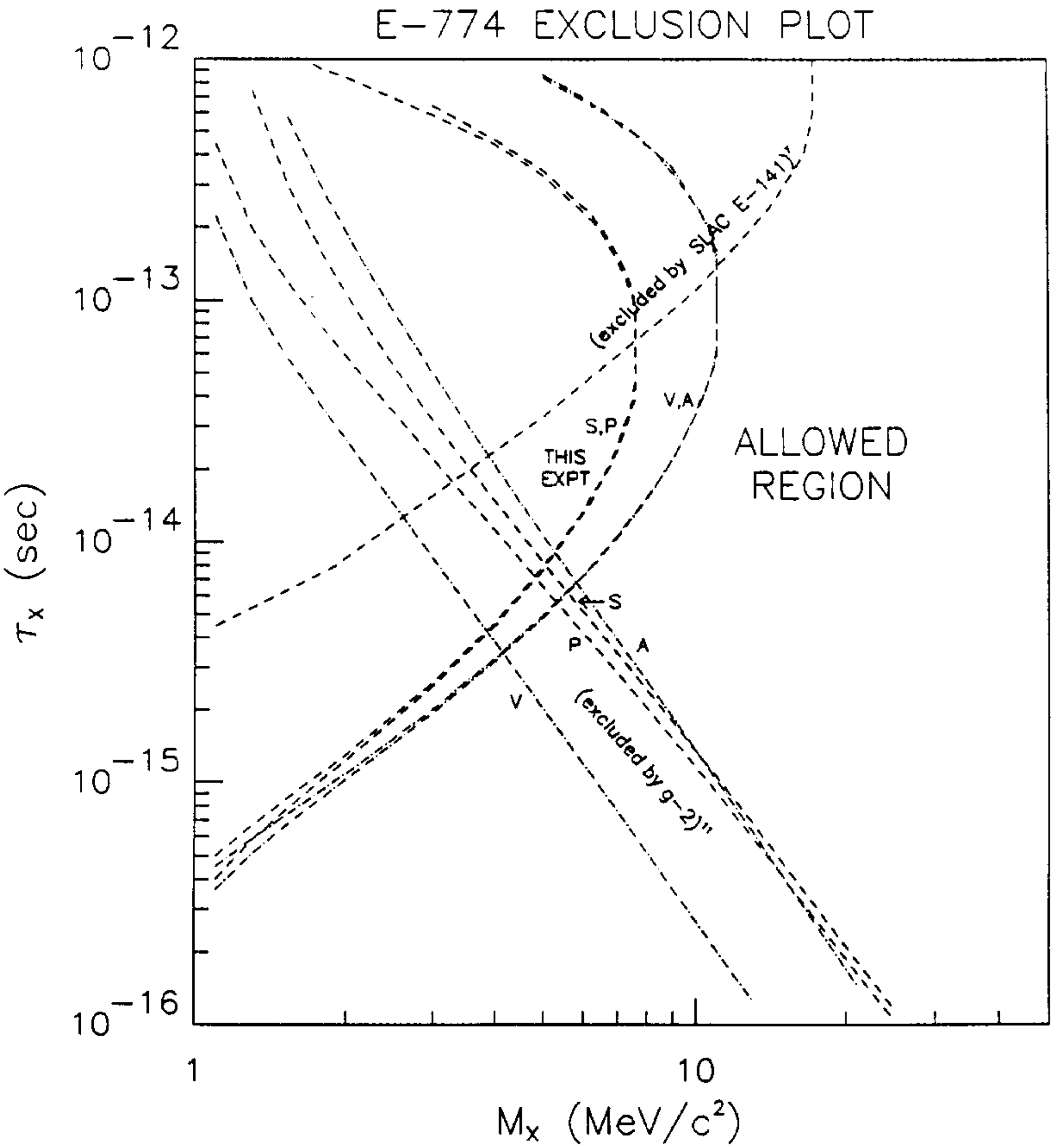

ELECTROMAGNETIC EVENTS
(a) MULTIPLICITY = 0
800
600
400
0
(b) MULTIPLICITY = 2
24
20
16
12
8
4
0
(c) EXCESS MULTIPLICITY 2 EVENTS
12
8
4
0
−4
−8
−12
0.
0.2
0.4
0.6
0.8
1.
ZTRIG = E_{trig} / E_{total}

Figure 4



E-774 EXCLUSION PLOT
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
τ_x (sec)
1
10
M_x (MeV/c^2)
(excluded by SLAC E-141)
S,P
THIS EXPT
V,A
ALLOWED REGION
S
P
A
V
(excluded by g−2)

Figure 5