upon t is reasonable because the pitch angle, θ, is quite small in this spectrometer; the large dependence upon s is a result of the occultation effect.

The source brightness B (observed density of muon decays per unit source area) is obtainable from the data since the trajectory of each event is known, and B, in fact, is already a very good approximation to W. That B is not identical to W is due to the fact that $\Omega(x;s,t)$ is somewhat larger for source points nearer the detector; these points appear brighter on an illumination plot normalized to the local muon stop rates. B was obtained by observing events in the range $0.43\leq x\leq 0.57$, for which $\gamma=1$. This range contains about one-half of the total events. Using this B, the source was then divided into three equally bright vertical strips, and the centroids of these strips were found. These centroids were then subjected to a 0.02-in. horizontal displacement (toward the outside of the source) to account for the fact that $(1/\Omega)\partial\Omega/\partial s=-0.043$/in. in the above momentum range. The correction to ρ to account for neglecting the shape of the stops distribution in the vertical is estimated to be $\Delta\rho=-0.0002$. The correction needed because three instead of an infinite number of strips were used is estimated to be 0.0004.

A plot of $\Omega(x)$ is given in Fig. 5.

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Search for Fractionally Charged Particles*

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A search was made for fractionally charged particles produced by 12-GeV electrons incident on a copper target. No such particles were detected. Comparison with calculations on photoproduction of pairs of these particles enable lower limits to be placed on the masses of such particles if they exist. Particles of the type discussed in this paper (pure spin-$\frac{1}{2}$ Dirac particles with no strong interactions) do not exist with masses below these limits. These limits are dependent on the charge and lifetime assigned to the particle. For lifetimes $\geq 10^{-7}$ sec, the lower limit varies from 0.2 GeV for $0.04e$ charge, to 1.5 GeV for $0.7e$ charge. For lifetimes $\geq 10^{-8}$ sec and $0.7e$ charge, the lower limit is 1.1 GeV.

INTRODUCTION

THERE have been a number of experiments[1–8] designed to detect fractionally charged particles since the idea of quarks was introduced by Gell-Mann[9] and Zweig.[10] Experiments at proton accelerators have failed to find quarks with production ratios, compared to pions of the same momenta of $\sim 5\times 10^{-9}$ for charge $e/3$, and $\sim 4\times 10^{-8}$ for charge $2e/3$. Cosmic-ray experiments place limits of $\sim 10^{-8}$ of the muon flux for charge $e/3$ or $2e/3$ particles. Foss *et al.*[8] have searched for fractionally charged particles with charges from $e/3$ to $2e/3$ using the Cambridge electron accelerator. This experiment, which was similar in concept to ours, used a 6.0-GeV bremsstrahlung beam incident on a carbon target. They found no fractionally charged particles. Using the Bethe-Heitler pair production cross section they were able to show that no particles exist with

$$[\text{charge } e/3] \text{ and } [0.5\text{ MeV}\leq\text{mass}\leq 780\text{ MeV}],$$
$$[\text{charge } 2e/3] \text{ and } [2.0\text{ MeV}\leq\text{mass}\leq 840\text{ MeV}].$$

These limits are for non-strongly-interacting particles with relatively long lifetimes.

The high-energy, high-intensity electron beam at the Stanford linear accelerator center offers the opportunity

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to produce fractionally charged particles electromagnetically, and for a given mass and charge, the yield of such particles may be calculated. The higher energy and greater intensity of this new accelerator, compared to the Cambridge electron accelerator, provides the opportunity to increase substantially the sensitivity of the search, to raise the lower mass limits found by Foss *et al.*, and to look for particles with *less* than one-third of the electronic charge. Further, the sensitivity to particles with very small charges was considerably enhanced by using large sodium-iodide crystals to detect the particles.

In the next section the method of calculation of the photoproduction of these particles will be summarized. Measurement of the yield of muons at 0° has confirmed the validity of such calculations for the pair production of muons. Thus, using the muon beam described by Barna *et al.*,[11] tuned to 12.5 GeV/c, and a primary target of 10 radiation lengths of copper, followed by 6 ft of beryllium, it may be calculated that 10^{18} electrons at 12 GeV incident in this target would yield, for example, 500 particles of charge $2e/3$ and mass 1 GeV transmitted by the beam. Furthermore, with detectors sensitive to very low ionization loss, such an irradiation, for instance, would yield 100 particles of charge $e/25$ and mass 0.1 GeV detected at the final focus of the beam.

It was therefore decided to search for fractionally charged particles in this beam, not limiting the system to detect only $2e/3$ and $e/3$ particles, but to search also at the limit of the apparatus available for possible particles with charge as low as $e/25$.

PRODUCTION THEORY

The production of pairs of charged particles occurs in the following manner: An electron beam of energy E_0 is incident on a target. In our case, the target consisted of 10 radiation lengths of copper followed by 6.3 radiation lengths of beryllium. The electron produces a photon flux in the target by the bremsstrahlung process. Tsai and Whitis[12] have given detailed formulas for thick-target bremsstrahlung and their equations were used in the calculations. The higher-energy portions of the bremsstrahlung spectrum attenuate as the photons pass through the target. By the end of the 10-radiation-length copper portion of the target, there are insufficient high-energy photons (or secondary electrons) left to produce particles in the beryllium.

The photons produce pairs of charged particles by photoproduction on the nuclei and nucleons of the target. The production cross section is given by generalizing the Bethe-Heitler process to take account of coherent and incoherent production and of form factors. A general discussion of the method of extension is given by Tsai.[13] The coherent production is photoproduction with the nucleus as a whole, and the nucleus remains in its ground state after the reaction. A nuclear form factor must be included. The incoherent production takes place on individual nucleons, primarily protons in the nucleus and here the nucleon form factors must be used. The nuclear and nucleon form factors used were those given by Hofstadter.[14] Finally, the effect of the Pauli principle on the incoherent production must be included, namely, a recoiling proton must be given sufficient energy to go to an unoccupied state in the nucleus.

The pair-production cross section is sharply dependent on the masses of the produced particles. For example, for each muon produced at 0° with 8-GeV/c momentum by a 12-GeV/c electron beam on our target, we would obtain 3×10^{-5} particles of unit charge and mass 0.5 GeV, 5×10^{-7} particles of unit charge and mass 1.0 GeV, and 3×10^{-9} particles of unit charge and mass 1.5 GeV. Thus the production cross section decreases by a factor of almost 10^9 in going from a particle of mass 0.105 GeV to a particle of mass 1.5 GeV. This very sharp dependence on the mass comes from two factors. Primarily it comes from the effect that only the smallest values of q, the four-momentum transfer to the target, are important in the pair production process. There is a q^4 in the denominator of the production cross section; and, as the masses of the produced pair increase, the minimum value of $|q|$ increases. The second effect is the result of form factors which add polynomials in q^2 to the denominator of the production cross-section formula and further intensify the first effect.

The pair production cross section is dependent on the particle charge e' as $(e')^4$. Therefore, a particle with a muon mass but with $e'=e/10$ would have 10^{-4} of the muon cross section. Therefore, there is a lower limit on the charge, below which the production cross section would be too small to measure in this experiment.

The production cross section is *not* strongly dependent (with one exception) on the other properties of the produced particles. All the calculations presented in this paper are for pure Dirac-type particles with spin $\frac{1}{2}$. Only the mass and charge have been varied. There may be other types of fractionally charged particles. One type might have spin 0. The production of pairs of spin-0 particles has also been calculated. For particles of mass near the muon mass, the ratio of production of spin-0 to spin-$\frac{1}{2}$ particles of identical mass and charge is $\frac{1}{5}$. This $\frac{1}{5}$ factor increases as the mass increases to be about 1/2.5 at a mass of 1.5 GeV. The limits set on spin-$\frac{1}{2}$ particle production in this paper then also apply to spin-0 particle production when this factor of $\frac{1}{5}$ to

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[11] A. Barna, J. Cox, F. Martin, M. L. Perl, T. H. Tan, W. T. Toner, T. F. Zipf, and E. H. Bellamy, Phys. Rev. Letters **18**, 360 (1967); **18**, 526(E) (1967).

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1/2.5 is taken into account. If one goes the other way and considers particles of spin$>\frac{1}{2}$, or adds in the anomlous magnetic moments or further electromagnetic interactions, the pair production cross section is *greater* than spin-$\frac{1}{2}$ particle production. Therefore, all limits on spin-$\frac{1}{2}$ particle existence apply to particles with higher spins or, further, non-Dirac electromagnetic interactions.

The one particle property besides mass and charge which can drastically change the production cross section is related to a form factor of the newly produced particles themselves. This form factor could substantially decrease the production. If the particles are strongly interacting, the usual assumption is that they have a form factor. But in the case of quarks or other fractionally charged particles, the conditions of particle existence are already so strange, that there is no necessary connection between their strong interactions. and their form factor. Therefore, we shall only state that if the particles have a form factor, the production rate is lower. If the particles have no form factor, the primary production cross section is independent of whether or not they have strong interactions. However, if they do have strong interactions, their final flux will be somewhat reduced due to attenuation in the beryllium portion of the target.

More detailed discussion of pair photoproduction of heavy-mass particles is contained in a paper by Barna *et al.*[15] on unit-charge particles. The detailed calculations were carried out by Tsai and Whitis[16] for this paper.

EXPERIMENTAL METHOD

The detectors consisted of five NaI(Tl) crystals. The first (counter A), 3 in. long and 3 in. in diameter, was placed at the second focus of the μ beam. The other four (counters 1–4), 5 in. thick and 11 in. in diameter, each viewed by four photomultipliers, were placed behind the third or final focus, about 50-m downstream of A. Reading along the direction of the incident particles, 1 and 2 were placed close together; then after a gap of 8 ft, 3 and 4 were placed together.

The dynode pulses were amplified and their leading edges used to generate logic pulses. The logic pulse from counter A was 64 nsec long and those from counters 1–4 were each 32 nsec long. The amplified analog pulses from the five counters were suitably delayed, mixed, and displayed on a double-beam oscilloscope. Simultaneously, those from counters 1–4 were digitized and recorded using a typewriter. A-1-3, or A-2-4, or 1-2-3-4 coincidences were used to trigger the oscilloscope, and the gate for the four analog-to-digital converters (ADC's). Some typical results are shown in Table I.

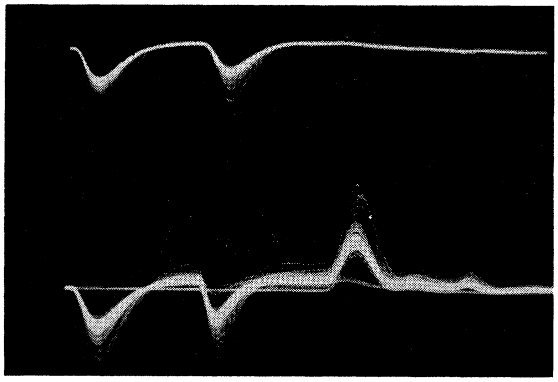

FIG. 1. A display of several muons traversing the five NaI(Tl) counters during one of the 18-GeV/*c* checks.

Since the energy losses, in passing through a crystal, of particles of charges $e/25$ and e are in the ratio of 1:625, which is greater than the useful dynamic range of either ADC's or oscilloscope, this complete range was covered, for the first 50% of the running time, in three overlapping sections, by varying both photomultiplier voltages and amplifier gains. At all three settings, however, the triggering rate turned out to be low (of order 10 per hour), and for the second 50% of the running time, the counters were operated at their most sensitive settings. The discriminator levels at these settings were <75 keV for counters 1–4 and 25 keV for counter A. These levels were determined by triggering an oscilloscope with the output from the trigger circuit on each crystal in turn, using a low-energy γ-ray source, and observing the γ-ray spectrum. The whole of the required dynamic range was covered during this second 50% of the running time by using not one, but two double-beam oscilloscopes, with relative gains set in the ratio 25:1. Equal irradiation with both positive and negative settings of the beam were used. The resolution of all counters at 1 MeV was better than ±5%. In the

TABLE I. The second column shows the number of muon counts during a typical run with incident electrons of 18 GeV/*c*. These runs were carried out periodically to ensure that the counters, electronics, and beam magnets were functioning correctly. The third column shows the results of a typical "search" run with incident electrons of 12 GeV/*c*. In each case the muon beam is tuned to 12.5 GeV/*c*.

Electron energy (GeV)	18.0	12.0
Number of electrons	$\sim 1.5\times 10^{12}$	1.2×10^{17}
Machine gates	30 000	1 000 000
Single counts		
A	2713	28 266
1	2768	159 378
2	2728	104 579
3	2578	209 956
4	2598	75 556
Coincidences		
13	2418	1253
24	2421	273
A13	2343	1
A24	2364	1
1234	2341	6
A13A24	2301	0

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[15] A. Barna, J. Cox, F. Martin, M. L. Perl, T. H. Tan, W. T. Toner, and T. F. Zipf (to be published).

[16] T. S. Tsai (private communication).

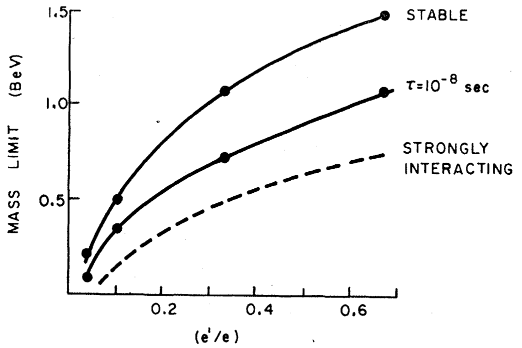

FIG. 2. Lower mass limits imposed by these results, as a function of charge, assuming electromagnetic production and a stable particle, or a lifetime of 10^{-8} sec.

5-in. counters, the most probable energy loss of a particle traversing the counter was $(e'/e)^2 \times 70$ MeV, where e' is the charge of the particle and e is the electron charge.

The electron beam incident on the target was set at 12.0 GeV/c and the beam itself was tuned to 12.5 GeV/c to avoid flooding the detection system with particles of unit charge. Under these conditions, particles of charge e' and momentum $(e'/e) \times 12.5$ GeV/c would be transmitted by the beam. The electron energy was periodically raised to 18 GeV and the intensity reduced so that single muons traversing the beam could be counted. Under those conditions, 85% of the single counts in counter A were recorded as 5-fold coincidences. (See Fig. 1.) Therefore, the efficiency of the five-crystal system was 85%, at least for beam particles which enter the first crystal.

During the first 20% of the running time, 2×10^{17} electrons were incident on the target at each of the three settings described above and a total of twenty 5-fold coincidences was recorded. None of these was a possible candidate for a fractionally charged particle, the pulse heights in the different counters in each case varying by large amounts. On the setting at lowest gain, it was apparent that in these coincidences, several hundred MeV were lost in some of the counters, suggesting electron showers. We realized that there were a relatively large number of electrons in the beam even after the 16 radiation lengths of target and these might cause an electron-photon-electron cascade down the beam and be the cause of the background. As described by Barna *et al.*,[11] the electron contamination can be radically reduced by placing a lead radiator at the first focus of the beam. For the rest of the runs, on both positive and negative beam settings, 2 cm of lead were placed at the first beam focus. This effectively reduced these background coincidences.

RESULTS

We found *no* further 5-fold coincidences. That is, no fractionally charged particle was ever recorded. Only 4-fold coincidences 1-2-3-4 and lower-order coincidences were found. The remaining background of 1-2-3-4 coincidences, was consistent with muons which penetrated the shielding and were originating in the machine before the beam target. In all, for each of the three settings a total of 10^{18} electrons were incident on the target. This number of electrons would produce 10^{10} muons at 7 GeV/c transmitted by the beam if the latter were tuned to that value.

We first consider the limits which can be placed on the existence of non-strongly-interacting fractionally charged particles. If the particle is stable, which is a very reasonable situation for a fractionally charged particle, we obtain the following limits. For charge $2e/3$, *no such particle exists* with a mass less than 1.5 GeV; for $e/3$, less than 1.0 GeV; for $e/10$, less than 0.5 GeV; and for $e/25$, less than 0.2 GeV. This variation of mass limit with charge is shown in Fig. 2. If we consider an unstable particle, the mass limit depends on the lifetime. As an extreme case we consider a particle lifetime of 10^{-8} sec. Taking into account the effects of time dilatation, we find that for charge $2e/3$, *no such particle exists* with a mass less than 1.1 GeV; for $e/3$, less than 0.75 GeV; for $e/10$, less than 0.35 GeV; and for $e/25$, less than 0.1 GeV. Again Fig. 2 gives the complete limits. These quoted limits are for 95% confidence. The production cross section increases so rapidly with decreasing mass, that a few percent decrease in the mass gives 99.9% confidence limits.

Definite conclusions cannot be reached regarding strongly interacting particles owing to the unknown attenuation in the beryllium. If one assumes that the cross section for scattering these out of the beam is the same as for other strongly interacting particles, i.e., about 25 mb/nucleon, then the attenuation will be about 300 and the corresponding mass limits are

$$2e/3, \quad 0.75 \text{ GeV};$$
$$e/3, \quad 0.50 \text{ GeV};$$
$$e/10, \quad 0.15 \text{ GeV}.$$

These limits are calculated assuming that the particles have no form factor and also that there is no contribution to the production cross section from strong interactions.

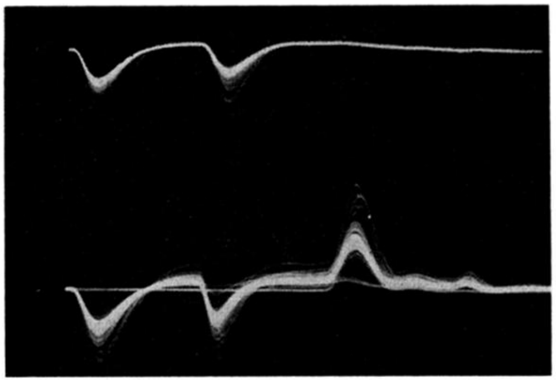

FIG. 1. A display of several muons traversing the five NaI(Tl) counters during one of the 18-GeV/c checks.