Search for the Production of μ-Meson Pairs by a 345-Mev Synchrotron Beam*

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Observations made at 45° and 90° to a 345-Mev bremsstrahlung beam failed to indicate the production of pairs of μ^+-μ^- mesons from targets of Be and Al. From the run on Be at 45°, $\sigma(\mu \text{ pair}) < (4\times10^{-32}/16\pi^2)$ cm^2 (steradian)$^{-2}$ proton^{-1}. This upper limit is twenty times the value predicted by the Bethe-Heitler theory for a purely electromagnetic interaction. The result would seem to preclude any interaction between pairs of μ mesons and nucleons which is as large as 10^{-3} of the strength of the interactions of π mesons and nucleons.

I. INTRODUCTION

THERE is an increasing amount of quantitative evidence which shows that μ mesons are essentially heavy electrons.[1,2] Thus μ mesons do not appear to interact with other particles except through the electromagnetic field[3–5] or through a Fermi type of interaction (i.e., an interaction accompanied by the emission or absorption of neutrinos). From such experiments as those of Amaldi and Fidecaro[6] on the scattering of μ mesons, and those of Fitch and Rainwater[5] on μ mesonic atoms, it is possible to estimate that if there is a nonelectromagnetic interaction of *single* μ mesons with nuclei, its strength is less than 10^{-3} of the strength of the interaction of π mesons with nuclei.

The question arises as to what one can conclude concerning the possible interactions between nucleons and μ-meson *pairs*. Before the war, there was a considerable amount of theoretical work published on meson pair theories.[7,8] Several of these authors[8] showed that if there exists a nucleonic interaction of meson pairs, that the scattering of a single meson depends upon the type of coupling involved. Specifically, Jauch showed that one would not expect meson scattering if the pair was coupled by a pseudoscalar interaction. Therefore, from the data on the lack of scattering of mesons one can only say that if there is a μ-pair interaction (greater than 10^{-3} of the π interaction) it would have to be with pseudoscalar coupling.

After the war, Wentzel[9] and Tannenwald[10] explored theoretically some of the consequences of a pair theory model of π mesons. In Wentzel's model a charged π meson consisted of a charged muon bound to a neutral nuon, and the neutral π meson consisted of a pair of charged muons or neutral nuons.

One of the consequences of such a model is that from sufficiently excited nuclei one should observe the emission of μ mesons and of pairs of μ mesons. Peterson, Gilbert, and White[11] found that with a 322-Mev bremsstrahlung beam hitting a carbon target the number of μ mesons produced was 0.02 ± 0.02 of the total production of π mesons. Wolff,[12] using Wentzel's model, calculated that for the spectrum employed in the experiment of Peterson *et al.*, they should have found the μ meson production was 6 percent of the total π-meson production. Mather, Martinelli, and Jarmie[13] looking for μ pairs found the production of such pairs was less that 6 percent of the production of π mesons. Therefore, there seems to be no experimental support for Wentzel's pair model of π mesons.

From the aforementioned data which set an upper limit on μ-meson production,[12,13] one can draw a more general conclusion, namely, if there is a nucleonic interaction with μ pairs, it is not commensurate with (and probably not even 10 percent of) the strength of the π-meson interaction. However, from these data, and in view of the ambiguity in interpreting the scattering data, one could not rule out the remote possibility that there is an interaction of μ-meson pairs with nucleons which is the order of several percent of the strength of the π-meson interaction. The present state of the π-meson theory of nuclear forces is certainly not sufficiently quantitative to rule out such a possibility. The experiments described here were undertaken to establish whether or not there was a nucleonic interaction of μ-meson pairs which was greater than 10^{-3} of the strength of the π-meson interaction.

It was mentioned at the very outset that μ mesons seem to be essentially heavy electrons. If they are simple Dirac particles, μ^+-μ^- meson pairs should be produced in a manner similar to the production of electron-positron pairs. The Bethe-Heitler[14] theory suitably

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1 For a general discussion of the evidence up to 1951 see R. E. Marshak, *Meson Physics* (McGraw-Hill Book Company, Inc., New York, 1952), Chap. 6,
2 Also see B. Rossi, *High Energy Particles* (Prentice Hall, Inc., New York, 1952), Chap. 4.
3 W. D. Walker, Phys. Rev. **90**, 234 (1953).
4 F. E. Driggers, Phys. Rev. **87**, 1080 (1952).
5 V. L. Fitch and J. Rainwater, Phys. Rev. **92**, 789 (1953); L. N. Cooper and E. M. Henley, Phys. Rev. **92**, 801 (1953).
6 E. Amaldi and G. Fidecaro, Phys. Rev. **81**, 339 (1951).
7 For the literature up to 1945, see W. Pauli and N. Hu, Revs. Modern Phys. **17**, 267 (1945).
8 For calculations on scattering, see R. Marshak and V. Weisskopf, Phys. Rev. **59**, 130 (1941); J. Weinberg, Phys. Rev. **59**, 130 (1941); J. M. Jauch, Helv. Phys. Acta **15**, 221 (1942).
9 G. Wentzel, Phys. Rev. **79**, 710 (1950) and Progr. Theoret. Phys. (Japan) **5**, 584 (1950). The latter contains a survey of literature up to 1950.
10 L. Tannenwald, Phys. Rev. **86**, 332 (1952).
11 Peterson, Gilbert, and White, Phys. Rev. **81**, 1003 (1951).
12 P. A. Wolff, Phys. Rev. **81**, 1056 (1951).
13 Mather, Martinelli, and Jarmie, Phys. Rev. **82**, 973 (1951).
14 W. Heitler, *The Quantum Theory of Radiation* (Oxford University Press, London, 1949), second edition, Chap. IV, pp. 194 ff.

modified for the heavier mass of the μ meson should give the cross section for the purely electromagnetic production of such pairs in the Coulomb field of a proton.[15] There is the interesting question of whether or not μ mesons have some complexity which reduces the probability of these particles being materialized in a purely electromagnetic field. From this point of view it would be extremely desirable to measure the purely electromagnetic production of μ^+-μ^- pairs. Unfortunately, the cross section predicted by the modified Bethe-Heitler formula is extremely small. Mather *et al.*[12] say that their result shows that the production of μ pairs is not greater than 10^5 times the cross section given by the Bethe-Heitler theory.

Although the experiments described here were undertaken as a search for a nucleonic interaction with μ pairs, it was felt that such a study would clarify the problems involved in trying to observe μ pairs from the purely electromagnetic interaction.

II. EQUIPMENT

A. Experimental Arrangement

A 345-Mev bremsstrahlung beam from the M.I.T. synchrotron was sent through a series of collimators and a clearing magnet. At the target the beam had a width of $\frac{3}{4}$ in. and was 2 in. high. The beam was monitored by two ionization chambers, one of which was in front and the other in back of the target. Targets of beryllium and aluminum metal were employed which were 4 in. and 1 in. long, respectively. One arrangement of the target, detectors, and their shielding is shown in Fig. 1.

Two detectors of the type shown in Fig. 2 were constructed especially for these measurements. The detectors consist of two tanks filled with cyclohexylbenzene containing 3 g of terphenyl and 18 mg of diphenylhexatriene per liter. The external tank (E) developed from a desire to have a detector that did not have a direct view of the target, but which would observe the electrons following the decay of a μ meson in the central tank (C). Mu mesons were identified by the process $\mu^{\pm}\rightarrow e^{\pm}+2\nu$ with a mean life of about 2 μsec. It was required that the decay electron be observed in both the C and E detectors delayed relative to an event in C (see Sec. IIB).

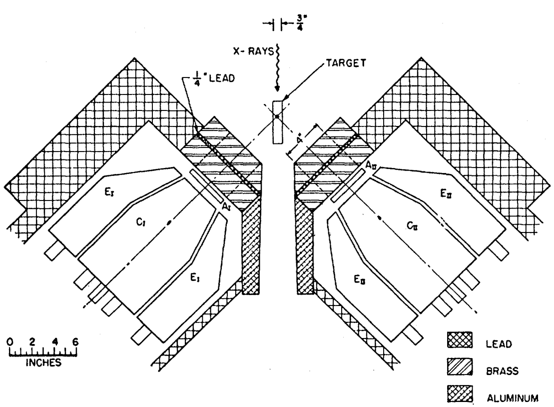

FIG. 1. μ^+-μ^- pair experimental arrangement. Detectors are at 45° to x-ray beam.

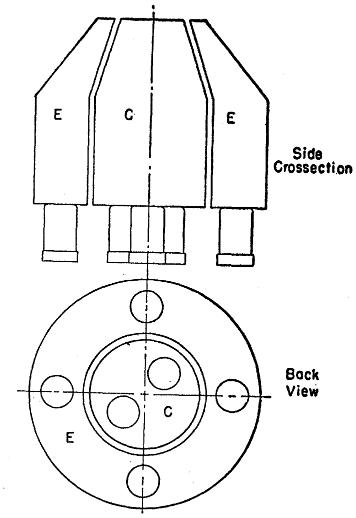

FIG. 2. μ-meson detector. Photomultipliers are RCA 5819.

The peculiar shape of these detectors arose from an attempt to optimize their efficiency and the solid angle they subtended at the target. The efficiency of these detectors was measured by counting the mesons arising from $\gamma+p\rightarrow\pi^++n$. The efficiency for detecting μ mesons that entered detector C was determined and found to be 60 percent, which checked the estimated design value.

In front of each special detector was a thin plastic scintillator (A) (Fig. 1) which was larger in diameter than C. The detectors A served dual purposes. Firstly, it was required that A and C be in coincidence (see Sec. IIB) for the incoming μ meson, and secondly, A had to be in anticoincidence with E and C at the time the decay electron was observed.

In order to decrease the spurious counting rate caused by scattered γ rays, a $\frac{1}{4}$-in. lead radiator was placed in front of detector A. With the above arrangement of the apparatus, and the biases employed on counters C, μ mesons which had a range of energies from 35 to 108 Mev were detectable.

B. Electronic Circuitry

The electronics can be looked upon as being separable into so-called fast electronics and conventional electronics. By fast electronics we mean coincidence circuits (and associated amplifiers, etc.) with resolving times of the order of 10^{-8} second; the conventional electronics was about ten times slower. Figure 3 shows a block diagram of the fast electronics. The circuitry was arranged so that counters AI and AII were in coinci-

[15] For the case of $Z>1$, one has to consider the coherence in the production of the μ-meson pairs. This is discussed in the section on form factors under the heading of "Calculation of the Cross Section."

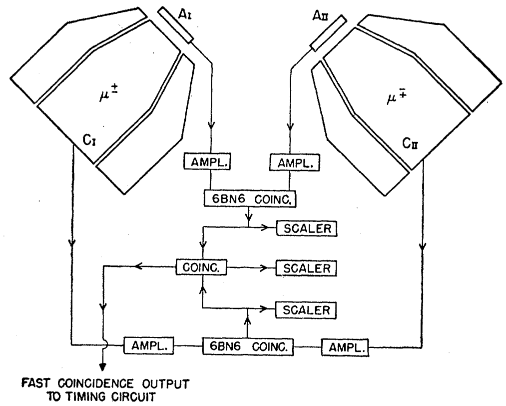

FIG. 3. Schematic of circuits for fast coincidences between μ mesons 200-ohm cable and distributed amplifiers are used.

dence and counters CI and CII were in coincidence. The resultant coincidences (AI and AII) and (CI and CII) were then put into fourfold coincidence. A pair of μ mesons would have triggered this fourfold coincidence circuit. The fast fourfold coincidence output was then sent through appropriate timing circuits to observe coincidences with delayed events. The operation of the fast fourfold coincidence circuitry and detectors was checked with electronically generated pulses and with the pulses arising from the conversion of the two γ rays from the decay of π^0 mesons.

The decay electron from a μ meson produced, as mentioned earlier, a coincidence of the type (EI+CI−AI). If such an event occurred in detector I and was delayed relative to a fourfold coincidence [(AI+AII)+(CI+CII)], it was recorded in one of five delayed channels. There was a similar five-channel delay circuit for such events from detector II. The first four of each of these sets of five channels were about 1.4 μsec long, and the fifth channel was about 10 μsec long.

If, following a fast fourfold coincidence, there were delayed events in both detectors I and II, then such an eightfold coincidence was recorded in one of a set of five delayed channels (see Fig. 4). The delay channel was determined by the time of arrival of the last of the two delayed events. With such an arrangement, the number of (spurious) accidental events increases linearly with delay time. One therefore obtains a large lever arm on the accidental events by using a delay as long as 20 μsec in the last channel. The first four channels were about 1.4 μsec long. If there were real μ-pair events, they would have appeared almost entirely in the first three channels.

III. DATA

The measurements were made over a rather long period of time, and the complexity of the equipment made frequent checking desirable. The individual scintillators had associated radium or cobalt standard. The timing of the circuits was checked by triggered synchroscopes and delay cables.

The most inclusive check on the proper functioning of the equipment was obtained by observing the $\mu^+ \rightarrow e^+$ decays from the π^+ mesons produced in the targets. The number of $\mu^+ \rightarrow e^+$ decays from the Be (or Al) target was measured about overy six hours during a long run. This standard checked the overall operation of everything except the two fast coincidence circuits. These latter were checked by the γ rays from a Co^{60} source.

Three separate measurements were made, each consisting of several runs lasting about eight to twelve hours each. With both detecting systems set at 90° to the beam and a Be target, no (eightfold coincidence) events were observed in a total of about 1.6×10^{11} equivalent quanta.[16] Similarly, with an Al target at 90°, no (eightfold coincidence) events were observed in a total of about 10^{11} equivalent quanta passing through the target. With the detecting systems set at 45° to the beam and a Be target and for a total of 5×10^{11} equivalent quanta, four (eightfold coincidence) events were observed in the first three delay channels (the channels where μ-pair events would appear). It can be estimated from the counting rates in the fourth and fifth delay channels (which arise from spurious accidental counts) that there should have been about 5.6 accidental counts in the first three channels, where we observed four. *Thus all events observed are attributable to an accidental (spurious) counting rate.* A check on this can be had from calculating the accidental counts that should have occurred in each of the eightfold delay channels from the registered events in the individual delay channels of detectors I and II. Such a calculation is based on the

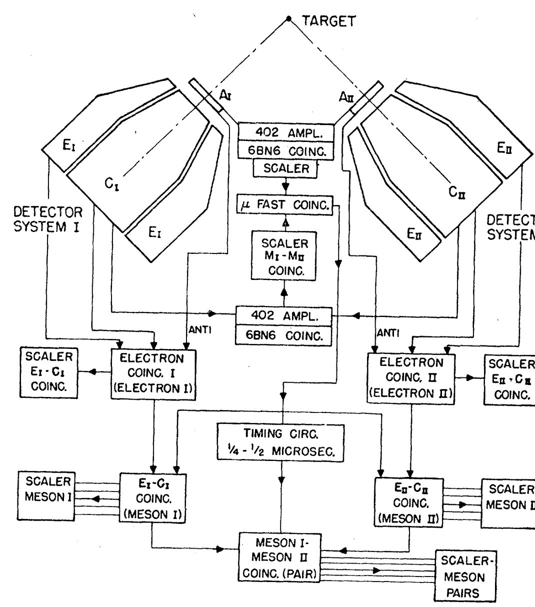

FIG. 4. Electronics for μ-pair detection. Five lines to scalers indicate five scalers for delay channels.

[16] The number of equivalent quanta, Q, in a beam is the energy in the beam divided by the maximum photon energy. Thus, for a $1/E$ spectrum, the number of quanta of energy E is $dN=QdE/E$.

TABLE I. Events observed in various delay channels and the estimated accidental events from the runs on Be at 45°.

Number of equivalent quanta	1 Observed	1 (Estimated accidental)	2 Obs	2 (Est.)	3 Obs	3 (Est.)	4 Obs	4 (Est.)	5 Obs	5 (Est.)
0.91×10^{11}	0	(0.05)	1	(0.25)	0	(0.43)	0	(0.48)	6	(7.1)
0.91×10^{11}	0	(0.36)	1	(0.27)	1	(0.40)	0	(0.38)	2	(3.0)
0.31×10^{11}	0	(0.05)	0	(0.06)	0	(0.04)	0	(0.17)	2	(1.7)
0.91×10^{11}	0	(0.18)	0	(0.40)	0	(0.51)	1	(0.70)	4	(4.4)
0.82×10^{11}	0	(0.15)	0	(0.40)	0	(0.72)	0	(0.65)	7	(4.8)
1.14×10^{11}	0	(0.27)	0	(0.47)	1	(0.63)	1	(0.69)	3	(3.4)
Total 5×10^{11}	0	(1.1)	2	(1.8)	2	(2.7)	2	(3.1)	24	(24.4)

assumption that all delayed events observed are purely random and that the fourfold fast coincidence arose from some real event such as two γ rays from a π^0 or a proton and π^- in coincidence. (The above assumption was corroborated by studies of counting rates as a function of beam intensity.)

Table I lists the events observed in various portions of the Be run at 45° and the calculated number of accidental events; the estimated accidental counts are in parentheses.

IV. CALCULATIONS OF CROSS SECTIONS

A. Cross Section per Atom

If we had observed any real events, the relationship between the cross section and the counting rate would have been given by

$$\text{counts/monitor unit} = (\Delta\omega)^2\epsilon^2\delta^2 N\int_{E_T}^{E_{\max}} \sigma\phi(E)gdE, \quad (1)$$

where $\Delta\omega$ is the solid angle subtended by each of the detecting systems; ϵ is the efficiency for counting the decay electrons from μ mesons that stop in the central tank; $(1-\delta)$ is the fraction of decay electrons which decay before the first delay channel goes on. N is the number of atoms per cm² in the target. σ is the double differential cross section which is a function of both angles. $\phi(E)$ is the number of photons of energy E (per monitor unit) which impinge on the target. E_T is the threshold energy and $E_{\max}$ is the maximum bremsstrahlung energy. g is the fraction of μ pairs that would be observable. All μ pairs are not observable because only a limited range of μ-meson energies (i.e., 35–105 Mev) are accepted by the detecting system. There is a broad spread of energies for the individual mesons even from monoergic photons because the pair production process is essentially a three-body reaction. (The recoiling nucleus or nucleon is the third body.)

We had an effective observational threshold of 290 Mev (i.e., $g\equiv0$ for $E<290$ Mev) even though it is energetically possible to produce μ-meson pairs as low as 220 Mev. Estimates of g were made on the assumption that the division of energy between the μ^+ and μ^- would be the same as the division of energy between e^+ and e^- as given by the Bethe-Heitler theory suitably scaled for the masses. A calculation of the integral in (1) was also performed with g evaluated on the assumption that all distributions of energy between μ^+ and μ^- were equally probable. This assumption leads to a value of the integral of half of the value calculated on the basis of the Bethe-Heitler theory.

The quantity g increases with energy from 0 at 290 Mev to about 0.75 at 345 Mev. The value of the other parameters in expression (1) are: $\Delta\omega=0.12$ steradian, $\epsilon=0.60$, $\delta=0.79$, $N=1.5\times10^{24}$ atoms/cm².

It is to be noted that the product $(\Delta\omega)\epsilon\delta$ was determined experimentally for each counter by measuring the number of π^+ mesons from the previously studied process $\gamma+p\rightarrow\pi^++n$.

In expression (1), the cross section of interest is contained in an energy integral. The integral was evaluated in two ways: one way was to assume that σ is a constant over the energy interval 295 to 345 Mev; the other way was to assume that σ varied as[17]

$$[(k-2)/k]^3,$$

where k=photon energy divided by the rest energy of the particle. The value of the integral calculated on these two different assumptions differed by about 30 percent.

On the basis of the data previously described and summarized in Table I, it cannot be concluded that any μ-pair events were observed. Under the circumstances, all that one can do is set an upper limit on the cross section. The last column of Table II lists the values of the cross sections we would have obtained had we seen one real event in each of the 90° cases or one and a half

TABLE II. Summary of experimental results.

Angle of detectors	Target	Number of equivalent quanta	Number of events observed	Estimated accidental events	Upper limit to cross section[a] cm² sterad⁻¹ atom⁻¹
90°	Be	1.6×10^{11}	0	0	5×10^{-33}
90°	Al	1.0×10^{11}	0	0	20×10^{-33}
45°	Be	5×10^{11}	4	5.6	6×10^{-33}

[a] These upper limits are based on the assumption that there is no angular correlation in the emission of the two mesons.

[17] P. V. C. Hough, Phys. Rev. 73, 266 (1948). This paper gives a convenient approximation for the Bethe-Heitler formula in the region where $\hbar\omega\lesssim3mc^2$.

real events at 45°. (This latter comes from the experimental result -1.6 ± 3.1 events.)

B. The Cross Section per Proton and the Question of Coherent Production

It is of interest to try to convert the above values into upper limits on the cross section *per proton*. If we assume that there is no spin flip of a nucleon involved in producing a μ pair, and that only protons contribute, we find the cross section per atom from a nucleus of Z protons is given by

$$\sigma_A(\theta)=\sigma_p(\theta)[Z+Z(Z-1)F(KR)], \qquad (2)$$

where $\sigma_A(\theta)$ is the cross section per atom (for angle θ), σ_p is the cross section per proton, Z is the number of protons, and F is a form factor that depends on R, the nuclear radius, and K, which is the difference between the momentum of the incoming photon and the resultant momentum of the outgoing mesons.

As usual with form factors, F falls off very rapidly for $KR>2$ and is relatively independent of the charge distribution. For the runs at 90°, F is the order of 10^{-2} or less. For the run with Be at 45°, F has an average value of about 0.5 for the observable μ-meson energies. Therefore, if the production is coherent, the Be run at 45° is the most significant one. Using this value for the form factor, and assuming only the protons contribute, one obtains an upper limit to the cross section for the production of μ pairs at 45° of 6×10^{-34} cm^2 (sterad)$^{-2}$ proton^{-1}. This value appears misleadingly small because of the fact that it is the double differential; it is perhaps seen in better perspective when written in the form $(4\times10^{-32}/16\pi^2)$ cm^2 (sterad)$^{-2}$ proton^{-1}.

If the process involved in the production of μ pairs was an incoherent one (e.g., one that flipped the spin of a nucleon), one might look a little more closely into the kinematics. For incoherent production it is to be anticipated that a single nucleon probably takes up the entire recoil, and the rest of the nucleus would play a very minor role. For such processes, with the detectors at 90°, a single nucleon would have to take 50 Mev to balance momentum. As the maximum energy of the bremsstrahlung was at 345 Mev and the observational threshold for the μ meson was 290 Mev, there was very little probability for us to observe incoherent production at 90°. Measurements at large angles at such energies are therefore of very little significance in trying to detect μ-pair production; unfortunately, going to higher energies raises the possibility of π-meson pair production.

At 45°, if the production process were an incoherent one, the single nucleon would have 15 Mev of recoil energy. This reduces slightly the fraction of the spectrum from which production is observable. [The $Z(Z-1)$ term of expression (2) is zero for incoherent processes.] If the process were completely incoherent and if only the protons contributed, the upper limit to the cross section would be about $(1.5\times10^{-31}/16\pi^2)$ cm^2 (sterad)$^{-2}$ proton^{-1}. However, it would be very surprising if the neutrons, as well as the protons, did not contribute to a spin-dependent production process; in this case, the last value should be divided by approximately two.

V. DISCUSSION

A. Nuclear Forces

The upper limit obtained above is several orders of magnitude lower than those discussed in the introductory section. The first conclusion that one can draw is that the μ-pair model of pions[9] is not a correct one.

One can also set a crude upper limit on the contribution to nuclear forces that can arise from an interaction between μ pairs and nucleons. The upper limit for nuclear forces comes from comparing the upper limit for μ-pair production,

$$(4\times10^{-32}/16\pi^2)\ \text{cm}^2\ (\text{sterad})^{-2}\ \text{proton}^{-1}$$

to the cross section for π-meson production [about $(2\times10^{-28}/4\pi)$ cm^2 sterad^{-1} proton^{-1}].[18] From these values it seems safe to say that if there is any contribution of μ-meson pairs to nuclear forces it is less than 10^{-3} of the strength of the π-meson interaction.

B. Electromagnetic Pair Production

As mentioned earlier, if μ mesons obey the Dirac theory, they should be produced in pairs according to a modification of the Bethe-Heitler theory. For the two detectors set at 45°, and for energies which were observable in our measurements, the Bethe-Heitler (modified for mass) predicts an average cross section of $(2\times10^{-33}/16\pi^2)$ cm^2 (sterad)$^{-2}$ proton^{-1}. Our upper limit of $(4\times10^{-32}/16\pi^2)$ cm^2 (sterad)$^{-2}$ proton^{-1} means that if we wished to study the electromagnetic production of μ-meson pairs, we would have to reduce our accidental counting rate by a factor of at least twenty.

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[18] G. S. Janes and W. L. Kraushaar, Phys. Rev. 93, 900 (1954).