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Radiation Laboratory
Berkeley, California

Contract No. W-7405-eng-48

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February 27, 1956

Printed for the U. S. Atomic Energy Commission

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ABSTRACT

Using the 1.19-Bev/c antiproton beam recently discovered at the Berkeley Bevatron of the University of California, we have measured the attenuation cross section in beryllium and copper. These cross sections are compared to attenuation measurements made with the same geometry using positive protons of the same incident energy (497 Mev).

The measurements were made at cutoff angles θ_c of 12.7° for copper, and at 18° for beryllium. For <u>both</u> copper and beryllium the measured attenuation cross section for antiprotons is twice that for positive protons, with a statistical error of ±15%. In addition, for both elements, more than half the attenuation events resulted in one or more fast charged secondary particles ($\beta \gtrsim 0.75$)--probably indicating that annihilations had taken place.

The cross section results are: for copper at $\theta_c = 12.7^\circ$, $\sigma_{\overline{p}} = 1.58 \pm 0.22$, $\sigma_{p^+} = 0.780 \pm 0.069$; and for beryllium at $\theta_c = 18^\circ$, $\sigma_{\overline{p}} = 0.365 \pm 0.059$, $\sigma_{p^+} = 0.178 \pm 0.013$, where the units are 10^{-24} cm^2. For copper and beryllium, respectively, the average energies in the absorbers were 430 and 455 Mev.

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INTRODUCTION

The first experiments done with the recently discovered 1.19-Bev/c antiproton beam[1] at the Berkeley Bevatron were primarily concerned with confirming the identification of the antiproton.[2,3] We have now started to study those properties of the new particle that are not immediate consequences of its identity. As a first step we have performed a counter experiment to measure the antiproton attenuation, both in copper and in beryllium.

Antiprotons, certified as to their nature by the system of counters described in Reference 1, were allowed to impinge on an absorber. Two additional counters were used to determine how many passed through the absorber. One of these counters was a scintillation counter that was sensitive to all charged particles passing through it. These charged particles were (a) "pass-through" antiprotons, by which we mean those that failed to have a nuclear interaction or at most were scattered through an angle smaller than θ_c (where θ_c is the half angle subtended by the counter at the center of the absorber); and (b) charged secondaries resulting from the annihilation of an antiproton with a nucleon. In order to determine the cross section correctly it was necessary to recognize these charged secondaries, since they would otherwise simulate pass-through antiprotons and thereby cause the measured cross sections to be too small. For this purpose we used as a "guard" counter a water Cerenkov counter that counted only those particles with a velocity greater than $\beta = 0.75$ ($\beta = \frac{v}{c}$). Since the incident antiprotons had a velocity of $\beta = 0.75$ before entering the attenuator, they were not counted in this guard counter. Therefore, in order that a pulse in the detector counter represent a pass-through antiproton, we have added the stipulation that there must be no count in the Cerenkov guard counter.

The antiproton cross sections were compared with those for protons by an experiment in which the currents in the analyzing magnets (M1, M2) and focusing magnets (Q1, Q2) were reversed. It was also necessary to change the position of the target slightly in order to allow the protons to pass through the fringing field of the Bevatron into the orbit defined by the magnets and counters. For these runs the Bevatron internal beam was accelerated to 1.1 Bev. There was no meson contamination of this 1.19-Bev/c proton beam because mesons of this momentum could not be produced by 1.1-Bev protons.

EXPERIMENTAL

Figure 1 shows both the beam-selecting apparatus described in Reference 1, and the attenuation apparatus. The energy of the antiprotons at counter S3 was 497 ± 10 Mev, and the beam had a rms angular divergence of $\pm 3^{\circ}$, due mainly to multiple Coulomb scattering in counters C1 and C2.

Table I gives the specifications of the three counters S3, C3, and S4. S3 and S4 were plastic scintillation counters, whereas C3 was the water Cerenkov guard counter mentioned earlier. At the suggestion of Bruce Cork it was placed directly behind the attenuator, rather than behind the detector S4, because it thereby subtended a larger solid angle at the absorber and thus had a better efficiency for counting annihilation events. However, by placing counter C3 between counters S3 and S4, we increased the amount of absorbing material through which the beam had to pass. The copper equivalent of counter C3 (water plus tube and base) was about 22 g/cm^2 Cu. In order to correct for the attenuation in this additional absorbing material it was necessary to take data with the primary attenuator out as well as in place. It should also be noted that it was very unlikely that an annihilation pion produced in the primary absorber could traverse the water without having sufficient energy to emit Cerenkov radiation in so doing.

The three pulses from counters S3, C3, and S4 were displayed on an oscilloscope trace and photographically recorded. Another camera was simultaneously photographing the pulses from counters S1, S2, and C1. These latter traces were used only for recognition of the antiprotons (as discussed in Reference 1). The traces of the two films were then correlated and the S3, C3, and S4 pulses recorded for antiproton traces. All double sweeps (two or more sweeps sometimes occured within the 50-millisecond duration of the beam pulse) were discarded because their inclusion might intorduce a systematic error.

Table I

Counter Specifications				
Counter	Type	Diameter (in.)	Thickness (in.)	Remarks
S3	Plastic Scintillator	4	1	
S4	" "	7	0.5	Used only in copper experiment.
S4	" "	13	1	Used only in beryllium experiment
C3	Water Cerenkov	7.5	3.5	

The extremely low counting rate (an average of one antiproton every 15 minutes) limited our measurements to only two elements; we have chosen copper and beryllium. The thickness of the copper absorber was 68 g/cm^2, the beryllium 37.5 g/cm^2.

A schematic drawing of the experimental arrangement is shown in Fig. 2 for the copper geometry, and in Fig. 3 for the beryllium geometry.

The angle subtended by the pass-through counter S4 at the center of the attenuator is conventionally called the cutoff angle θ_c. However, the divergence of the incident beam and the thickness of the attenuators introduced an uncertainty in the real cutoff angle, especially in the copper geometry. For this reason it was desirable to choose an angle for which the cross section is not strongly dependent on θ_c. Thus, the cutoff angle was chosen larger than the angle at the first minimum of the diffraction pattern for protons, so that the detector S4 counted nearly all antiprotons that had suffered only diffraction and multiple Coulomb scattering. Hence the quoted cross sections include only negligible amounts of diffraction scattering. This has been verified by calculation. In Figs. 2 and 3 the incident divergent beam is shown with dashed lines, and the rms angle δ of multiple Coulomb scattering is indicated. The cutoff angles were $\theta_c = 12.7^\circ$ for copper, and $\theta_c = 18^\circ$ for beryllium.

An incident particle must always count in S3. In the remaining two counters, C3 and S4, there are only four possible different combinations of responses. These will be labeled (C3, S4), ($\overline{C3}$, S4),(C3, $\overline{S4}$), and ($\overline{C3}$, $\overline{S4}$), where a bar indicates that the corresponding counter did not count.

For the purposes of computing cross sections we interpret these four possible combinations of responses as follows:
First, we will assume that all ($\overline{C3}$, S4) events represent pass-through particles. Indeed, pass-through particles cannot count in the Cerenkov counter, C3, but will count in the detector, S4. This combination of counts could also be obtained, however, if an interaction occurred in which only slow secondaries were produced in the forward direction with one of them counting in S4. As we have pointed out earlier, such an event is unlikely; nevertheless, the assumption made above may result in a low value for the attenuation cross section.
Second, we will assume that all annihilations produce a fast charged particle ($\beta \gtrsim 0.75$) into the cone of acceptance of counter C3. Thus, we interpret the events (C3, S4) and (C3, $\overline{S4}$) as representing annihilations. This allows us to estimate the partial cross section for annihilation.
Finally, combination ($\overline{C3}$, $\overline{S4}$) is interpreted as an event in which an antiproton was scattered through an angle θ_c without giving rise to fast charged secondaries into the cone of acceptance of C3. Of course, these events again may not give a true value for the scattering cross section, since this particular combination ($\overline{C3}$, $\overline{S4}$) could also result from annihilations in which no fast charged particle is produced in the forward direction and no charged particle traverses S4.

In summary we list the four types of events and their interpretations:

(1) ($\overline{C3}$, S4)--a pass-through particle,

(2) (C3, S4)--an annihilation event,

(3) (C3, $\overline{S4}$)--an annihilation event,

(4) ($\overline{C3}$, $\overline{S4}$)--a scattering event.

For measurement of the attenuation cross section for protons the above interpretation of the events was altered. Protons of 497 Mev are too slow to count in C3. Except for single-meson production, the protons cannot produce fast charged particles that count in C3. In fact, the very absence of counts in C3 when protons were attenuated lends strong support to the assumption that counts in C3 were due to annihilations when antiprotons were used.

RESULTS

In Table II we have summarized the number of events of each type, together with cutoff angle. The data were taken with the absorber in and out, for both protons and antiprotons.

The formulas used for computing the total attenuation cross section σ and the statistical standard deviation $\Delta\sigma$ are:

$$\sigma = \frac{1}{N} \ln \frac{I_0}{I} \frac{I'}{I'_0} , \quad \Delta\sigma = \frac{1}{N} \sqrt{\frac{1}{I} - \frac{1}{I_0} + \frac{1}{I'} - \frac{1}{I'_0}} ,$$

where I_0 and I'_0 are the numbers of incident particles with the absorber in and out respectively; I and I' are the numbers of pass-through particles with the absorber in and out respectively; and N is the thickness of the attenuator in atoms/cm^2. If we let I_s (and I'_s) be the number of scattered particles = ($\overline{C3}$, $\overline{S4}$), and I_a (and I'_a) be the number of annihilation events = (C3, S4) + (C3, $\overline{S4}$), then the partial cross sections for scattering, σ_s, and for annihilation, σ_a, are given by

$$\sigma_s = \frac{1}{1 + \alpha} \sigma , \quad \sigma_a = \frac{\alpha}{1 + \alpha} \sigma ,$$

where

$$\alpha = \frac{I_a I' - I'_a I}{I_s I' - I'_s I} .$$

I_0, I, I_s, and I_a are also summarized in Table II. The resulting cross sections and statistical errors are given in Table III.

The errors listed in Table III represent only standard deviations due to counting statistics. It was not possible to obtain better statistical results because of the low counting rate. Some of the partial cross sections listed in Table III may not be very meaningful because of the large statistical errors.

A source of error, other than statistical, may be annihilation events in which no fast charged secondary passes through C3. This effect would indicate that the partial annihilation cross sections given in Table III are too low, but would not affect the measured total attenuation cross sections as long

Table II

Experimental Results. I_0 is the number of incident particles, I is the number of unattenuated particles, I_s is the number of scattered particles, and I_a is the number of annihilated particles.

Attenuator	Incident Particle	Cutoff Angle	$S4\ \overline{C3}$	$\overline{S4}\ \overline{C3}$	$S4\ C3$	$\overline{S4}\ C3$	I_0	I	I_s	I_a
8 in. Be	$\bar{p}$	18^o	26	32	16	17	91	26	32	33
none	$\bar{p}$	18^o	43	5	8	4	60	43	5	12
8 in. Be	p^+	18^o	518	392	1	3	914	519	395	-
none	p^+	18^o	619	76	2	4	701	621	80	-
3 in. Cu	$\bar{p}$	12.7^o	44	40	16	58	158	44	40	74
none	$\bar{p}$	12.7^o	51	6	4	5	66	51	6	9
3 in. Cu	p^+	12.7^o	447	448	-	-	895	447	448	-
none	p^+	12.7^o	211	45	-	-	256	211	45	-

Table III

Cross-section Results. The quantity σ is the measured attenuation cross section; σ_a and σ_s are the partial cross sections for annihilations and scattering, respectively. The errors shown are standard deviations due to counting statistics.

Attenuator	Incident Particle	Cutoff angle	σ (in 10^{-24} cm^2)	σ_s (in 10^{-24} cm^2)	σ_a (in 10^{-24} cm^2)	$\frac{\sigma_{\bar{p}}}{\sigma_{p^+}}$
8 in. Be	$\bar{p}$	18^o	0.365 ± .059	0.19 ± .07	0.17 ± .06	
8 in. Be	p^+	18^o	0.178 ± .013	-	-	2.05 ± .36
3 in. Cu	$\bar{p}$	12.7^o	1.58 ± .22	0.53 ± .11	1.05 ± .22	
3 in. Cu	p^+	12.7^o	0.780 ± .069	-	-	2.02 ± .33

as there were no slow charged secondaries passing through counter S4. As it is very unlikely that a slow charged particle can get through counter C3, the latter source of error should have very little effect on the total attenuation cross sections. For the copper experiment counter C3 subtended an average solid angle of π steradians at the absorber. Crude kinematical estimates indicate that probably no more than 20% of the annihilations fail to produce a fast charged particle into this solid angle. On the other hand, in the beryllium experiment counter C3 subtended an average solid angle of only $\frac{\pi}{2}$ steradians. In this case counter C3 may have failed to detect about 30% of the annhilation events. Therefore the values quoted for the cross sections for annihilation represent lower limits.

For both copper and beryllium the measured cross sections for antiprotons are twice those for protons, within the statistical errors of ± 15%. For copper with ($\theta_c = 12.7^o$): $\sigma_{\bar{p}} = 1.58 \pm 0.22 \times 10^{-24} cm^2$, $\sigma_p = 0.78 \pm 0.069 \times 10^{-24} cm^2$. For beryllium with ($\theta_c = 18^o$): $\sigma_{\bar{p}} = 0.265 \pm 0.059 \times 10^{-24} cm^2$, $\sigma_p = 0.178 \pm 0.013 \times 10^{-24} cm^2$. The cross section we obtained for protons on copper is about 14% greater than that obtained by Chen, Leavitt, and Shapiro[4] at Brookhaven ($0.68 \times 10^{-24} cm^2$) with a similar geometry at a somewhat higher energy (860 Mev). Our beryllium cross section for protons is almost 37% greater than that obtained at Brookhaven ($0.130 \times 10^{-24} cm^2$). This apparent discrepancy could be due to the differences in energy and in geometry between the two experiments.

It is also interesting to note that in 65% of the antiproton interactions in copper, each was accompanied by a fast charged particle in the cone of acceptance of counter C3. For beryllium 51% of the interactions resulted in a count in C3. If we assume that these fast particles result from annihilations then we conclude that the most probable inelastic event that can befall the antiproton is annihilation.

We may attempt to explain our results by assuming either that the antiproton has a "larger radius" than the proton when interacting with matter, or that the potential representing the nucleus is different for antiprotons and protons (assuming that the proton and antiproton have the same "size"). The assumption of a "bigger" antiproton leads to a different ratio of $\frac{\sigma_{\bar{p}}}{\sigma_p}$ for copper and beryllium, but this possibility is not conclusively ruled out on the basis of our experiment.

Duerr and Teller,[5] on the basis of a model of the nucleus first proposed by Johnson and Teller,[6] predicted an antiproton cross section for copper that is consistent with our experimental result. This model is characterized by a velocity-dependent term in the Hamiltonian describing the interaction of the incident particle with the nucleus.

CONCLUSION

The results of this experiment show two features of particular interest:

(a) The attenuation cross sections of antiprotons in beryllium and copper are approximately twice those of protons.

(b) The most probable inelastic event for antiprotons in beryllium and copper is annihilation with a nucleon.

We wish to thank Dr. Edward J. Lofgren and the staff of the Bevatron for their continuous cooperation and help.

This work was performed under the auspices of the U. S. Atomic Energy Commission.

FOOTNOTES

1. Chamberlain, Segrè, Wiegand, and Ypsilantis, Phys. Rev. 100, 947 (1955).
2. Brabant, Cork, Horowitz, Moyer, Murray, Wallace, and Wenzel, Phys. Rev. 101, 498, (1956).
3. Chamberlain, Chupp, Goldhaber, Segrè, and Wiegand, and Amaldi, Baroni, Caltagnoli, Franzinetti, and Manfredini, Phys. Rev. (in press) and Nuovo Cimento (in press).
4. F. Chen, C. Leavitt, and A. Shapiro, Phys. Rev. 99, 857 (1955).
5. H. P. Duerr and E. Teller, Phys. Rev. 101, 494 (1956).
6. M. Johnson and E. Teller, Phys. Rev. 98, 783 (1955).

FIGURE CAPTIONS

Fig. 1. Schematic diagram of the experimental arrangement. (For details see Reference 1 and Figs. 1 and 2. therein.)

Fig. 2. Schematic diagram of copper attenuation apparatus. See text for details.

Fig. 3. Schematic diagram of beryllium attenuation apparatus. See text for details.

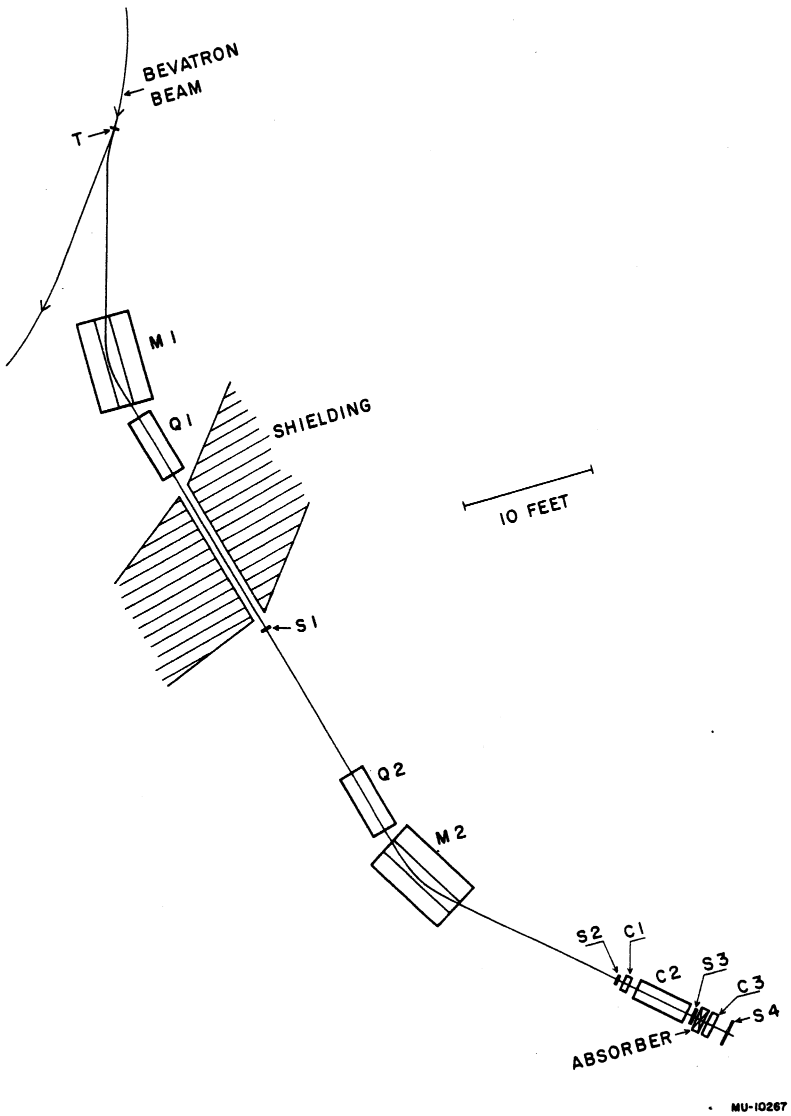
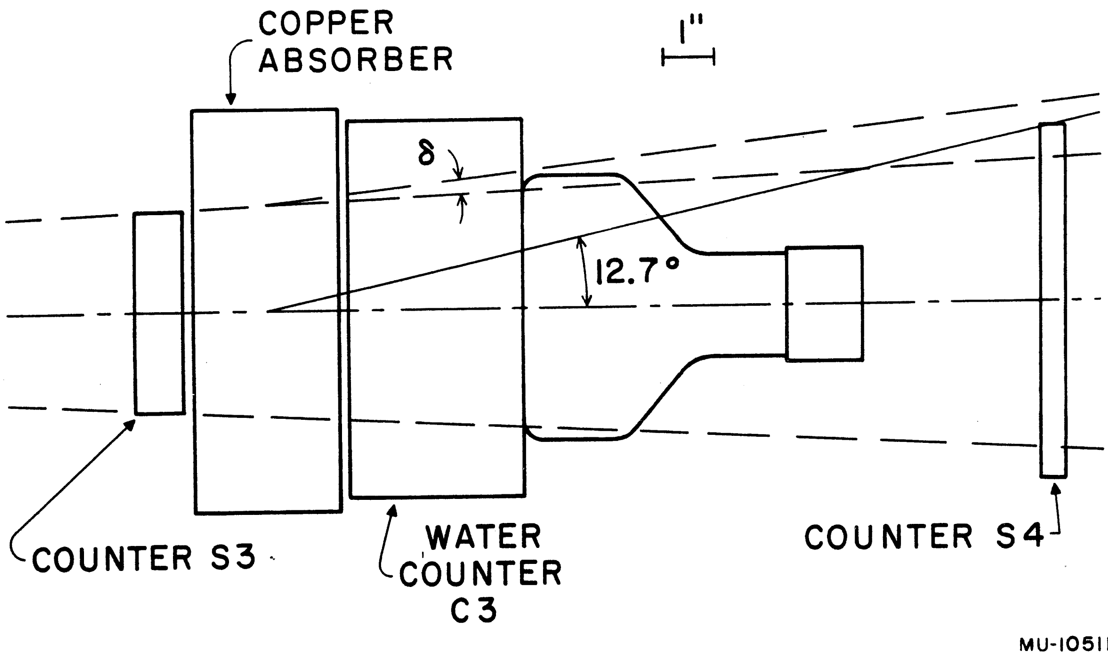

BEVATRON
BEAM
T
M 1
Q 1
SHIELDING
10 FEET
S 1
Q 2
M 2
S 2
C 1
C 2
S 3
C 3
S 4
ABSORBER
MU-10267

Fig. 1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δ
12.7°
COUNTER S3
WATER COUNTER C3
COUNTER S4
MU-10511

Fig. 2

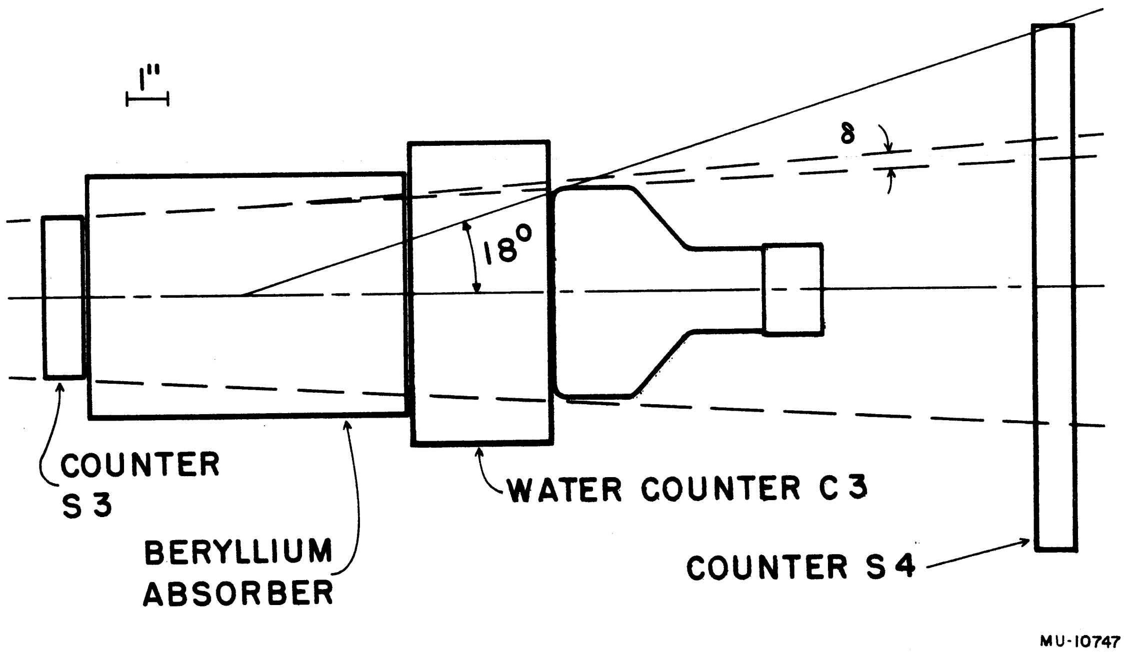
1"
8
18°
COUNTER
S 3
BERYLLIUM
ABSORBER
WATER COUNTER C 3
COUNTER S 4
MU-10747

Fig. 3