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NEUTRON YIELDS FROM THICK TARGETS BOMBARDED BY 24-Mev DEUTERONS AND 12-Mev PROTONS

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ABSTRACT

The gross yields of neutrons produced by 24-Mev deuterons bombarding Be, Cu, Ta, and U and by 12-Mev protons bombarding Be, Cu, and Ta were measured by detecting the neutrons in a solution of $MnSO_4$ that surrounded the targets. The yields were (in neutrons per μcoulomb): 24-Mev deuterons: Be, 1.85×10^{11}; Cu, 0.55×10^{11}; Ta, 0.52×10^{11}; U, 0.73×10^{11}; 12-Mev protons: Be, 4.1×10^{10}; Cu, 0.61×10^{10}; Ta, 0.15×10^{10}.

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I. INTRODUCTION

Shielding requirements for high-energy particle accelerators are based upon attenuation of the neutrons produced by nuclear reactions in the targets and other materials, but little information on the production of neutrons by high-energy particles has been published. The work presented here is concerned with the production of neutrons by 24-Mev deuterons and 12-Mev protons. Although of primary interest for determining shielding requirements, the data are also useful for the design of intense neutron sources and of interest in connection with nuclear reaction theory; any comparison with theory, however, would be unsatisfactory because of the small number of elements investigated. The data may be useful in estimating the importance of neutron background when accelerator experiments are designed.

For determination of the yield of neutrons from particles incident on thick targets, the number of particles striking the target and the number of neutrons emitted from the target must be measured independently. The number of particles was measured by placing the targets in a faraday cup, and the neutrons that escaped from the target were detected by counting the Mn^{56} activity in a solution of $Mn\ SO_4$ that surrounded a cavity that contained the targets.

Gross yields for 10-Mev deuterons and 30-Mev alphas have been measured by Smith and Kruger[1] using this method, and the fast-neutron yields for 15-Mev deuterons have been measured by Allen et al.[2] by a different

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[1] L. W. Smith and P. G. Kruger, Phys. Rev. 83, 1137 (1951).

[2] Allen, Nechaj, Sun, and Jennings, Phys. Rev. 81, 536 (1951).

method. Recently Cohen[3] has used threshold detectors to obtain yields for 23-Mev protons and Tai[4] has used the $MnSO_4$ tank detection method to measure yields for 32-Mev protons from the linear accelerator at this laboratory. The yields of neutrons from targets bombarded by deuterons and protons in the energy region of hundreds of Mev have been measured during the past several years and have recently been declassified.[5]

The source of the charged particles was the 60-inch cyclotron of the Crocker Laboratory of the University of California. Beam currents of the order of microamperes were used in a strong-focused external beam.[6]

II. EXPERIMENTAL PROCEDURE

A. Beam Extraction and Characteristics

The general problem of extracting the beam from the 60-inch cyclotron and the strong-focusing system has been described by Ellis.[6] The same method was used for our experiment, but in order that the $MnSO_4$ tank could be in a region of low neutron background, a steering magnet was placed just outside the cyclotron shielding tanks (see Fig. 1) and the beam deflected approximately 15°. The entire system was connected to the cyclotron tank in order to maintain a vacuum.

The beam position and shape at the target position were observed by permitting the beam to pass through a 0.001-inch stainless steel foil and strike a fluorescent screen. The steering- and focusing-magnet currents were adjusted, and the faraday cup positioned, so that the beam was contained in a small spot in the center of the target position. The current hitting the brass tube leading from the steering magnet to the faraday cup could be measured; the steering magnet current was varied to cause the beam to hit first one, then the other side, and the magnet current was finally adjusted so that the beam would not wander onto the brass pipe. No data were taken until the beam was accurately positioned and no current could be detected on the brass pipe (a current of less than 0.01 μamp could have been detected). Some of these

[3] B. L. Cohen, Phys. Rev. 98, 49 (1955).

[4] Y. K. Tai, to be published.

[5] W. E. Crandall and G. P. Millburn, Total Neutron Yield from Targets Bombarded by Deuterons and Protons, UCRL-2063, (decl. March 1956).

[6] R. E. Ellis and L. Schecter, Phys. Rev. 101, 636 (1956).

precautions were not necessary for the proton bombardment (see Sec. F). The steering-magnet current was regulated to within 0.1%.

Typical currents on the target were 0.1 to 1.0 μamp for deuterons and 0.7 μamp for protons. A maximum beam of a few microamperes was available at the target. The beam at the target was contained within a circle of 1-in. diameter and the targets were 4 in. in diameter, except for the proton bombardments (see Sec. F).

B. Beam Monitoring

The targets were placed in a faraday cup formed by a brass cylinder 6 in. long and 4 in. in diameter (see Fig. 2). A 1-in. section holding the targets could be insulated from the remainder of the cylinder and the currents on each section measured separately. The negative current (from secondary electrons produced in the target and stopping in the isolated section of the cylinder) amounted to approximately 10% of the recorded positive current from the target, and was roughly independent of the target material.

The total net charge collected by the faraday cup (target and cylinder) in a bombardment was placed on a low-leakage condenser connected to the inputs of a 100% inverse-feedback integrating electrometer. The electrometer signal was measured and recorded on a Leeds and Northrup Speedomax that was automatically calibrated against a standard cell before each bombardment. The condensers were compared with a condenser calibrated by the National Bureau of Standards to within 0.1%, and the electrometer scale factors were calibrated to within 1%. Thus the charge could be measured to within 1%, but because of possible leakage of the secondary electrons, we have assigned a standard error of 3% to the measurement of the number of particles striking the target.

C. Neutron Detection

The targets were placed near the center of a large aluminum tank (5 by 4 by 4 ft) that had a 1-by-1-by-5-ft tunnel passing through the center. The rear of the tunnel was filled with a removable plug approximately 14 in. deep, and solution was pumped continuously between the plug and the tank. A layer of $MnSO_4$ solution at least 18 in. thick surrounded the tunnel. Neutrons that escaped from the target were moderated by the water, and some of them were finally captured by Mn^{55} to form radioactive Mn^{56}. When the Mn^{56}

activity was to be measured the solution was stirred manually with a pair of large paddles suspended in the tank and a small sample was drained off. An accurately measured volume of the sample was placed in a container and five Geiger counters were immersed in the sample to count the Mn^{56} activity. The mixing and sampling techniques were tested and found to give results consistent to within 1%. The above technique permitted the bombardments to proceed without the delay that would have resulted from immersing counters directly in the tank.

The detection efficiency of the solution and counters was determined by placing a 0.5-g Ra-Be source at the target position with the brass pipe, faraday cup, and target holder in position. The source was left in place for several hours and the saturation activity determined. The source was calibrated by the National Bureau of Standards to a standard error of 3%.

Several possibilities for error are inherent in this method of detecting neutrons. Probably the most important is a difference between the energy spectra of neutrons from Ra-Be and from the targets. However, 98% or more of the neutrons from the Ra-Be source are captured before they escape from the tank,[7] and the majority of the neutrons emitted from the target are probably of lower energy than the mean energy of the Ra-Be neutrons.

Another cause of error would be an extreme difference between the angular distributions of neutrons from the source and from the target. This is not expected to give rise to any large error.[1]

Variations in the height of the solution in the tank would also change the specific activity because the outer layers of solution, which are in a region of very low neutron density, tend mainly to decrease the over-all specific activity. However, the height of solution is easily controlled and does not introduce any appreciable error.

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[7] J. H. Rush, Phys. Rev. 73, 271 (1948).

D. Counting Procedure

Two sets of Geiger tubes were used to count the samples from the tank, and a solution of Co^{60} was used throughout the course of the experiment to check the reliability of the tubes. Five Tracerlab TGC-5 glass-walled tubes were connected in parallel (isolated by crystal diodes) and immersed in the solution samples. The depth of the solution in the sample holders was determined so that a variation of 1/32 in. caused less than 1% variation in the counting rate. The depth of the solution was always carefully adjusted with syringes and could be accurately reproduced to within 1/64 in.

The counters performed satisfactorily and the Co^{60} standard solution gave counting rates reproducible to within counting statistics (about 1%).

The measured counting rates were corrected for normal background, Mn^{56} activity present in the solution at the start of the bombardment, decay during and after the bombardment, and dead time of the counters. The beam current was assumed to be constant, but fluctuations would have introduced a negligible error because the longest bombardment was only about 10% of the mean life of the Mn^{56} activity.

The counting rates were always kept low enough so that the dead-time correction amounted to less than 3%. In order to do this, some samples were counted with only one Geiger tube and the ratio between counting rates with one and five tubes was determined (it was typically 4.9). It was also necessary at times to dilute the $MnSO_4$ sample with water; this was done by filling the sample holders with water and adding an accurately measured volume of $MnSO_4$ solution. Yields from Be were measured by all counting techniques and gave results consistent to within 3%. When dilution was necessary, the sample holders and tubes were carefully rinsed with water and dried to remove the $MnSO_4$ remaining from the previous sample. The ratio between diluted and undiluted activities was typically 15.9 x 4.92 = 78.3, where 15.9 is the ratio for a diluted sample counted with five tubes to the undiluted sample counted with one tube, and 4.92 is the ratio between the counting rate from five tubes and one tube. All counting rates were normalised to that rate which would have been measured with five tubes.

The number of neutrons emitted during the bombardment could then be caluclated. If A' is the saturation activity of the solution induced by a neutron source emitting N neutrons per minute, then $f = N/(\lambda A')$ is the

number of neutrons per unit counting rate (λ is the decay constant of Mn^{56} = $1/224\ min^{-1}$).[8] Then the number of neutrons added during a bombardment is $n = fA$ if A is the net activity at the end of bombardment (corrected for decay during bombardment).

E. Targets

The targets were 4 in. in diameter and at least 20% thicker than the range of a 25-Mev deuteron. They were made of stock material.

The targets were chosen to represent various parts of the periodic table, and in particular to withstand the high heat load from the beam without special cooling devices.

F. Background

The background from neutrons produced elsewhere than in the target could not be directly determined for the deuteron bombardments, but various limits could be assigned. The deuteron beam was stopped in carbon at position A inside the cyclotron shielding (see Fig. 1) and found to give a negligible activity in the $MnSO_4$ tank (the activity added by 1000 μcoulombs of deuterons was 110 ± 70 counts per minute, or $(1.5 \pm 1.0) \times 10^7$ neutrons per μcoulomb). The deuteron beam was also stopped in carbon at position B outside the cyclotron shielding, and gave rise to an activity corresponding to $(6 \pm 1) \times 10^8$ neutrons per μcoulomb. Both these background sources are negligible compared with other sources of error. A more serious background source would arise from neutrons produced in the brass pipe leading from the magnet to the faraday cup, but since the current hitting the brass pipe was always less than 1% of the current hitting the target, and since copper has a low yield, this source may also be neglected.

The energy of the protons is well below that needed for neturon production in carbon, so a background could be taken with a carbon target for the proton bombardments. This measurement gave a "yield" of $(3.1 \pm 0.3) \times 10^9$ neutrons per μcoulomb. This relatively high background should probably be explained. Molecular H_2^+ ions are accelerated in the cyclotron and--rather than assume that no stripping occurred in the collimators or elsewhere--we introduced a 1/4-mil Al foil at position B to strip all the H_2^+ ions to atomic H^+ ions. The resultant scattering spread out the beam so that the ratio of current striking the target to that striking the brass pipe was only 3:1.

[8] Hollander, Perlman, and Seaborg, Revs. Modern Phys. 25, 469 (1953).

III. RESULTS

A. Yields

The yields of neutrons from 24-Mev deuterons bombarding Be, Cu, Ta, and U and from 12-Mev protons bombarding Be, Cu, and Ta are given in Table I. For comparison we have also listed the yields of 10- and 15-Mev deuterons,[1,2] and 32-Mev protons.[4]

B. Errors

The possible sources of error mentioned previously are listed here with estimates of their magnitude (standard errors):

(1)	neutron source calibration	± 3%
(2)	background	- 2%
(3)	beam monitoring	± 3%
(4)	solution sampling	± 2%
(5)	counting statistics	~ 1%
(6)	energy difference between target and source neutrons	± 3%
(7)	variation in height of solution in tank	± 2%
(8)	neutron capture by targets	< 1%

Thus an estimate of the possible systematic error to be compounded with the relative errors given in Table I is ± 6% (standard error).

Table I

Neutron Yields from Thick Targets
(in units of 10^{10} neutrons per μcoulomb)

A. Deuterons

	24 Mev	15 Mev[a]	10 Mev[b]
Be	18.5 ± 1.0	> 1.90	3.23 ± 0.24
Cu	5.5 ± 0.3	> 0.29	0.55 ± 0.05
Ta	5.2 ± 0.3	> 0.33	0.074 ± 0.014
U	7.3 ± 0.6		

B. Protons

	12 Mev	32 Mev[c]
Be	4.13 ± 0.21	17.7 ± 0.9
Cu	0.61 ± 0.06	8.30 ± 0.42
Ta	0.15 ± 0.04	12.6 ± 0.6

[a] see Ref. 2

[b] see Ref. 1

[c] see Ref. 4

IV. CONCLUSIONS

The results given in Table I establish reference points that permit the design of shielding for medium-energy accelerators. In every case it is seen that Be produces more neutrons than any other element studied.

The effect of the Coulomb barrier in suppressing the yield from the heavier elements is apparent from a comparison of the yields as a function of energy. Thus in going from 10- to 24-Mev deuterons, the yield from U increases by a factor of 100; from Cu, by a factor of 10; and from Be, only by a factor of 6. Similar behavior is shown in the proton data.

To calculate shielding requirements, the safest procedure would be to use the yield from Be to determine the maximum requirements.

V. ACKNOWLEDGMENTS

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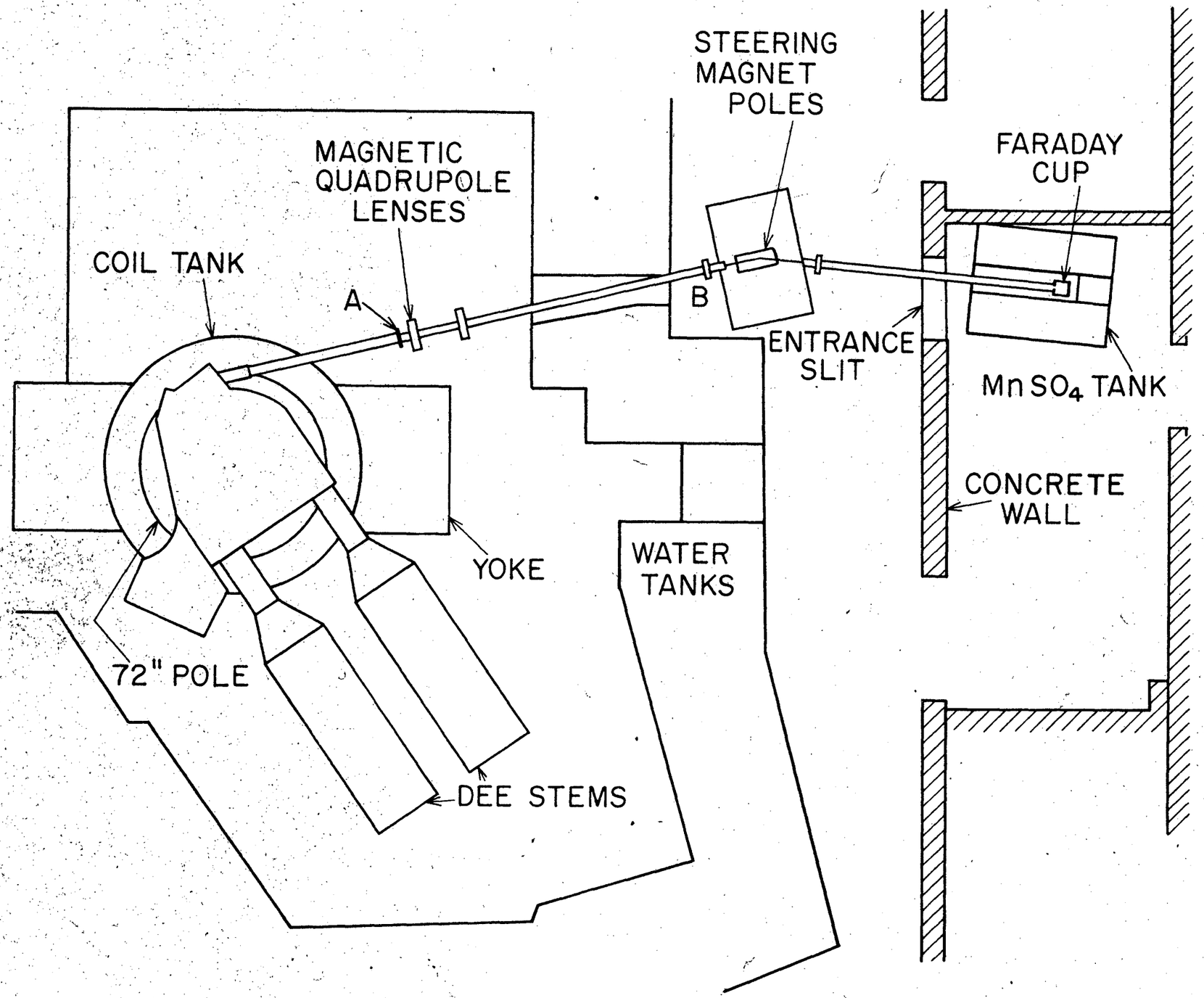
Figure Captions

Fig. 1. Schematic diagram of experimental arrangement.

Fig. 2. Schematic diagram of faraday cup.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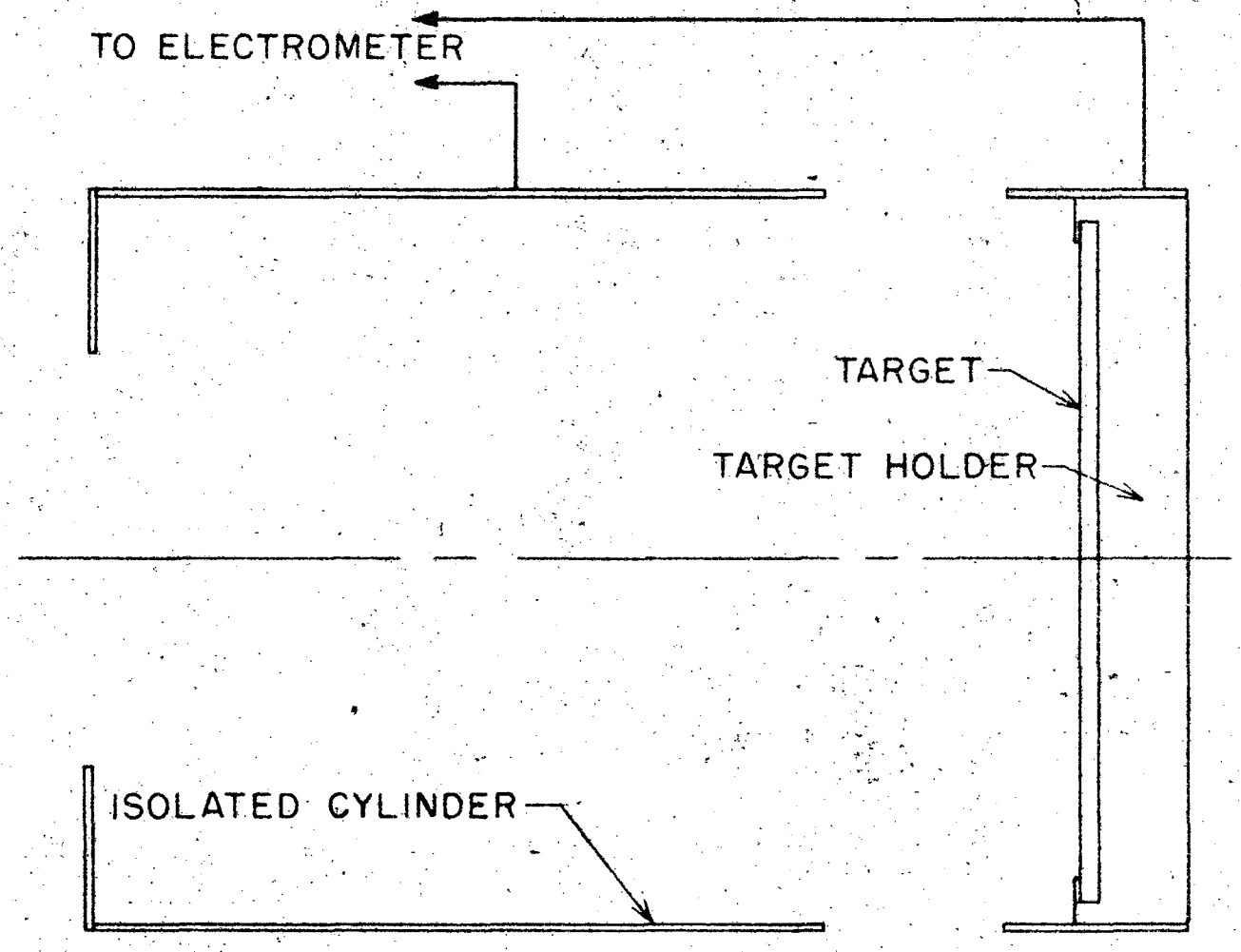

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