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PROTON-PROTON SCATTERING AT 340 MEV

Owen Chamberlain and Clyde Wiegand

February 1, 1950

Berkeley, California

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Proton-Proton Scattering at 340 Mev

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February 1, 1950

ABSTRACT

Measurements of the proton-proton differential scattering cross section using 340 Mev protons show a cross section approximately constant between 41° and 90° in the center of mass system. Two methods of counting the scattered protons have been used. The first method uses a counter telescope to count the scattered protons. The second method utilizes coincidences between counters which record the two protons involved in a single scattering process. The first method gives slightly higher cross sections; the average value of the differential cross section is $(5.5 \pm 1.0) \times 10^{-27}$ cm^2 $steradian^{-1}$ in the center of mass system. Although the scattering appears isotropic it is larger than can be accounted for with pure S-scattering. There is a strong suggestion, but no positive proof, that n-p and p-p forces are different.

Proton-Proton Scattering at 340 Mev

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INTRODUCTION

In spite of the incompleteness of the results it seems proper to report at this time on the proton-proton differential scattering cross section measurements made with the 340 Mev external proton beam from the 184-inch Berkeley cyclotron. The importance of the work stems from the short de Broglie wave-length of the protons in the beam. As is well known, only with short wave-lengths (high energies) can the details of the nucleon-nucleon forces be seen.

While meson theories are at present inadequate to give quantitative predictions, they do predict the range of the nuclear forces to be approximately $\frac{\hbar}{mc}$ (the Compton wavelength of the meson divided by 2π) where m is the mass of the meson. This range is in qualitative agreement with the observed range of nuclear forces if the π-meson is accepted as the particle giving rise to the forces and is then 1.4×10^{-13} cm.

If we cannot look to meson theories for a more detailed description of nuclear forces, then we must fall back on the concept of a potential giving rise to the nuclear forces; moreover since no reliable relativistic theory exists we may ask under what circumstances the available non-relativistic scattering theory is applicable. A restriction, presumably not any too stringent, is that the kinetic energy of the nucleons involved be less than their rest energy. For comparison with the range of nuclear forces given above we may state this restriction in terms of the de Broglie wave-length; the de Broglie wave-length of the proton divided by 2π should be greater than 0.12×10^{-13} cm.

The energy of the protons used in this experiment is of course determined by the cyclotron which is available to us. It so happens that this energy is such that the wave-length divided by 2π (in the center of mass system of two protons) is 0.50×10^{-13} cm, and thus falls within the limiting values mentioned above. It is still not possible to show that relativistic corrections are small.

One very interesting result of the present experiment is that the p-p scattering is even qualitatively very different from the n-p scattering. Because the Pauli principle excludes triplet states of even orbital angular momentum and singlet states of odd angular momentum from the p-p scattering it is not possible to conclude directly that the n-p and p-p interactions are different. However, we will review some arguments which make it seem fairly plausible that these interactions are indeed different.

EXPERIMENTAL ARRANGEMENT

The beam is deflected within the cyclotron tank by a pulsed electric deflector, passes away from the main magnetic field in an iron channel, is deflected about 20 degrees by an auxiliary magnetic field (often called the steering magnet) and then travels 20 feet to the scattering apparatus which is outside of the ten foot thick concrete shield. A collimator can be placed in the beam path before the steering magnet, and a four foot long collimating hole may be arranged where the beam passes through the concrete shield. The paths of the protons in the beam at the shielding are parallel to within 0.002 radians, so good collimation can be employed at the shielding, giving beams down to 1.3 cm diameter.

The beam passes through a 0.010 in. thick aluminum window into the atmosphere, traverses a thin walled air-filled ionization chamber, passes through the target and is stopped in a thick concrete wall ten feet from the apparatus. The target is of polyethylene or graphite (surface density 0.1 to 3.0 g/cm^2). The ionization chamber is used to determine the beam intensity as will be described below.

PROTON COUNTING--METHOD I

The scattered protons have been counted in each of two ways, both employing three proportional counters in coincidence. Method I uses a counter telescope of three counters (3.8 cm diameter, ten cm active length) with a variable tungsten absorber before the last counter[1]. Counting rates are measured as a function of the amount of tungsten absorber to identify the proton component of the scattered radiation by its range.

The counting rate with equivalent carbon target must be subtracted from the counting rate with polyethylene target to obtain the effect due to hydrogen alone. The thickness of a carbon target is adjusted to the same stopping power as the polyethylene target used in conjunction with it. The carbon targets thus have 1.4 times the surface density of the carbon surface density in the polyethylene targets. The counting rates with carbon target are multiplied by $\frac{1}{1.4} = 0.7$ to obtain the counting rates due to carbon in the polyethylene target. Figure 1 shows typical absorption curves for both target materials and the difference attributable to hydrogen.

The sensitivity of the proportional counters is adjusted approximately by insertion within the counter gas of a small polonium source, highly collimated. Precise adjustment of the sensitivity is accomplished by the study of the plateau curve (coincidence counting rate vs. voltage) which is measured at the time of the experiment using the protons scattered from either carbon or polyethylene.

In all cases the counting rates are very low. The proton beam from the cyclotron comes in pulses less than one microsecond long, 60 pulses per second. Since the pulse time is shorter than the resolving time of the proportional counters, each counter must on the average count much less than once each beam pulse. In typical operation the single counters count from 1 to 10 counts per second and the coincidence rate is about 0.5 per second. The cyclotron beam intensity has been varied over a large factor and it has been demonstrated that the operating

intensity is so low that the coincidence rate is a linear function of intensity, as it should be.

The absorber curves (hydrogen counting rate vs. absorber thickness) have all shown the expected behavior near the end of the range of the scattered proton (25 to 35 g/cm^{-2} tungsten, Fig. 1). At most angles the cutoff at the end of the range is not sharp, since the finite range of scattering angles accepted by the counters allows a significant spread in energy and range in the scattered protons. Likewise the thickness of the target is reflected in a gradual rather than sharp cutoff in the absorption curves. For absorber thickness less than the range of the scattered protons (0 to 25 g cm^{-2} tungsten, Fig. 1) the absorption curves show a smooth slope attributable to multiple Rutherford scattering and to nuclear collisions in the tungsten absorber. That the multiple scattering is by far more important is seen from the fact that the effective cross section of tungsten as read from the slope of the absorption curves is several times the geometrical cross section of the tungsten nucleus. Near zero absorber the absorption curves have large statistical errors due to the large amount of scattering by carbon. (The counting rate due to carbon may be regarded as a background to which the counting rate of hydrogen is added.) Down to as little absorber as 2 g/cm^2 of tungsten there is no indication that any of the counting rate is due to other than the high energy proton-proton scattering. At zero absorber the hydrogen counting rate has seemed slightly higher than at 2 g/cm^2 tungsten though the counting statistics do not allow proof.

PROTON COUNTING--METHOD II

Method II has also been used, in which both the scattered and scattering protons are observed.

Two counters of the type described above form a counter telescope to detect one proton; the other proton involved in the scattering process is detected

by a third larger counter (7.6 cm diameter, 30 cm long). As viewed from the scattering target the small counter telescope and the large counter are slightly less than 90° apart; the deviation from 90° is a relativistic effect. No absorbers are involved in method II.

Although it has been necessary to count exceedingly slowly with this method, the background from carbon in the polyethylene is very much reduced. Fig. 2 shows typical data for the triple coincidence counting rate as a function of the angle between the two counter arms. It is of considerable importance that the counting rate due to hydrogen is zero when the angle between the counters is 90°, for it indicates that the protons counted include a negligible number of very low energy. All of the pairs of protons observed from hydrogen are at less than 90 degrees in the laboratory coordinate system and hence must be due to incoming protons with relativistic energies. The calculated angle between protons from hydrogen is 85.5 degrees for the case shown in the figure.

The coincidence counting rate has been measured as a function of the height of the counters, and the height adjusted to maximum counting rate. This guarantees that the plane of the counters contains the beam. Plateau curves--coincidence counting rates versus the voltage on all counters--have been run in all cases and are quite satisfactory. It is essential that the large counter be large enough and close enough to count every proton whose counterpart traverses the small counters. To obtain assurance of this condition we have measured the counting rate as a function of the distance of the large counter from the target, and have found that the counting rate due to hydrogen remains constant over a wide range of this distance.

The background counting rate due to carbon is due principally to accidental coincidences. This is known from the fact that the counting rate due to carbon varies as the square of the beam intensity.

MEASUREMENT OF BEAM INTENSITY

In all cases the beam is monitored with a thin-walled ionization chamber. The ionization chamber has parallel plate electrodes and contains air at atmospheric pressure. The plates of the chamber are circular with useful diameter five inches. The essential elements are two 0.003 in. aluminum foils, spaced one inch apart; one is the sensitive electrode and is connected by a 50 foot cable to a vacuum tube voltmeter, the other is the high voltage electrode and is maintained at -600 volts. On each side of these essential elements are 0.001 in. aluminum shielding foils at ground potential. The proton beam passes through the chamber normal to the foils.

The vacuum-tube voltmeter acts as a beam integrator, for the charge collected in the ionization chamber serves to charge the cable and input capacity of the voltmeter circuit. Fairly exhaustive tests have shown that the voltmeter is correctly calibrated throughout its range 0-1 volts, that its input impedance is adequately high, that its zero drift is negligible, that the total input circuit capacitance including cable behaves like a perfect condenser without dielectric absorption of charge, that only one percent of the charge collected is due to long-life ($>$ 100 sec) radioactivity, and that the electric field is more than adequate to collect all the ions formed in the air of the chamber at the beam intensities used.

The method of calibrating the ionization chamber is by direct comparison with a Faraday cup apparatus made by V. Z. Peterson of the Radiation Laboratory. The proton beam passed through the thin-walled ionization chamber and then impinged on the Faraday cup. The Faraday cup is inside an evacuated enclosure; the beam enters this enclosure through a thin window. In this case of a very penetrating beam the cup consists of a piece of brass six inches thick and six inches in diameter. The Faraday cup apparatus has been carefully calibrated and its performance

studied as a function of the electric field around the cup to make certain secondary electron emission was not a source of error.

RESULTS

The differential scattering cross section in the laboratory coordinate system is defined by the equation:

$$C = n\, N_T\, \Omega\, \sigma(\Phi)$$

where

- C is the number of counts in a counter subtending the solid angle Ω at angle Φ from the beam direction (laboratory coordinate system).
- N_T is the number of hydrogen atoms per square centimeter of target, measured in the direction of the beam.
- n is the number of incident protons in the beam.
- $\sigma(\Phi)$ is the differential scattering cross section, laboratory system.

The differential scattering cross section in the center of mass (zero momentum) coordinate system is then

$$\sigma(\phi) = \frac{\left(1 + \frac{E}{2Mc^2}\sin^2\Phi\right)^2}{1 + \frac{E}{2Mc^2}} \left(\frac{1}{4\cos\Phi}\right)\sigma(\Phi)$$

where

- ϕ is the angle between the direction of the scattered particle and the beam direction in the center of mass coordinate system, corresponding to Φ in the laboratory system.
- E is the energy of the incident protons in the laboratory coordinate system, and M is the proton mass.

The results, with their relative probable errors are shown in Table I.

Table I

Method	ϕ (center of mass system)	$\sigma(\phi)$ (center of mass system) in units of 10^{-27} cm^2 sterad^{-1}.
I	60°	6.0 ± 0.5
I	64°	5.6 ± 0.7
I	85°	6.5 ± 0.7
I	90°	5.8 ± 0.6
II	41°	5.5 ± 0.7
II	43°	5.3 ± 1.0
II	49°	5.1 ± 1.0
II	62°	5.0 ± 0.5
II	90°	4.8 ± 0.4

To obtain the absolute error an estimated 10 percent error due to uncertainty in determination of the beam intensity should be superimposed on the errors given in the table. $\sigma(\phi)$ is the differential scattering cross section (center of mass system) at angle ϕ (center of mass system).

The correct $\sigma(\phi)$ is guaranteed to be the same as $\sigma(\pi-\phi)$. Method I has shown this property in the case of 60° and 120°, and the results are lumped together in the $\sigma(\phi=60^\circ)$ in the table. Method II utilizes both outgoing particles, so the symmetry of $\sigma(\phi)$ around 90° is guaranteed beforehand.

INTERPRETATION

The most striking characteristic of the results is that they are consistent with isotropic scattering and yet the differential cross section is about twice the theoretical maximum for S-scattering alone. (The theoretical maximum for $\sigma(\phi)$ is $\frac{\lambda^2}{4\pi^2} = 2.5 \times 10^{-27}$ cm^2 sterad^{-1}.) This is evidence that the cross section is inconsistent with any of the usually considered short range central force potentials, which at $\phi = 90^\circ$ predict zero P-wave and destructive interference between S- and D-waves.

A similar phenomenon has occurred in the case of the 30 Mev p-p scattering experiments of Panofsky and Fillmore[2] and Cork, Johnston and Richman[3]. At that

energy the cross section appears (if analyzed into the partial waves of a central force interaction) as S-scattering, showing interference with Coulomb scattering; there is no P-wave or D-wave in evidence. The absence of P-wave could be explained (as in the neutron-proton scattering mentioned below) with the use of a potential which gives no scattering in odd angular momentum states. However, any likely central force potential which gives the proper scattering in the S-state and has the effective range required by experiments below 10 Mev, should at 30 Mev show D-scattering in amount not consistent with the experimental results.

This is to be contrasted with the results of n-p scattering experiments[4] at 40, 90 and 270 Mev. These experiments are in at least qualitative accord with a central force interaction which is about half ordinary, half exchange force. They show, in the center of mass system, a large cross section for scattering in both the forward and backward directions. A detailed calculation of the n-p scattering has been given by Christian and Hart[5]. They find that the radial dependence of the potential is not well determined by the experiments to date, but the Yukawa well shape gives a reasonably good fit to the experiment. The use of a potential giving little scattering in P-states is necessary to obtain a total cross section as small as that obtained experimentally.

The p-p scattering at 340 Mev presents somewhat the opposite difficulty, for the differential scattering cross section is larger than can readily be explained by S- and D-scattering alone, especially at 90°. Christian and Noyes[6], working with Professor Serber in the theoretical group of the Radiation Laboratory, have shown that the p-p scattering can likewise be explained by a potential interaction but with a very different potential. The outstanding characteristic of this potential is that it is a pure tensor interaction in the triplet state. The tensor interaction gives rise to scattered waves not present with central interaction. In particular there appear three P-waves in place of the one P-wave for central force, because with the tensor force the orbital angular momentum

is not conserved--only the total angular momentum is conserved.

The 30 Mev p-p scattering cross section can also be explained with the tensor interaction and a radial dependence which is quite normal--such as the Yukawa potential. To give the observed scattering at 340 Mev, the potential must be given a strong singularity at the origin--such as $1/r^2$. In all cases the singlet potential has been adjusted to fit the data below 10 Mev, and the triplet potential adjusted to the 30 Mev data.

It is interesting to note that the singularity at the origin necessary to explain the 340 Mev p-p scattering has practically no effect on the calculations at 30 Mev. This implies that to some extent it may be possible to adjust a different part of the radial dependence function for the explanations of scattering at different energies. If so, it may be impossible to challenge the potential concept on the basis of scattering experiments alone.

PROPOSED CHANGES OF METHOD

After the bulk of the present data were taken, a new method of obtaining the external charged-particle beams from the cyclotron was developed by Leith[7]. A thin thorium foil can be placed in the internal beam of the cyclotron. The multiple Rutherford scattering in this foil is sufficient to give a r.m.s. deflection of 1.5° and causes some of the internal beam to enter the magnetic channel which can lead this part of the beam away from the cyclotron magnetic field in the usual way. In this process there is no pulsed electrostatic deflector used. This "scattered beam" comes in 60 pulses per second as does the electrostatically deflected beam, but has the advantage of being spread (each pulse) over a period of about 25 microseconds (whereas the electrostatically deflected pulses last less than 1 μ sec. each).

As long as the beam pulses were of less than 1 μ sec. duration there seemed little hope of developing a coincidence counting system with resolving time much shorter than the beam pulse time. With the advent of the scattered

beam comes the expectation that many resolving times may be contained in the beam pulse time, and far more effective coincidence techniques used.

Now under construction are very fast amplifiers and coincidence circuits for use with stilbene scintillation counters. It is hoped that fast circuits will lessen the background due to particles penetrating the cyclotron shielding and due to the strong diffraction scattering in the forward direction by carbon in the polyethylene targets. If so, the measurements can be extended to a wider range of angles and improved in accuracy.

Also under consideration is a liquid hydrogen target to reduce the scattering by heavier nuclei in the target.

CONCLUSION

The p-p scattering at high energy is even qualitatively different from n-p scattering at comparable energy. In the p-p scattering the presence of other than S-wave scattering is evidenced in the magnitude of the cross section but not in the angular dependence in the range 41° to 90° center of mass system.

Christian and Noyes have shown remarkable agreement between the observed p-p scattering and that calculated using a strongly singular tensor interaction of protons in the triplet state. The great difference between the n-p potential of Christian and Hart and the p-p potential of Christian and Noyes suggests strongly that the interactions are different; unfortunately there is no rigorous proof of this difference.

The present experiments extend only to angles where the S- and D-scattering are expected (by comparison with the n-p scattering experiment) to be small compared to the observed cross section. The S- and D-scattering should become more important as the range of angles is extended toward the beam direction.

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REFERENCES

1. J. Hadley, E. Kelly, C. Leith, E. Segrè, C. Wiegand and H. York, Phys. Rev. 75, 351 (1949), (Fig. 2).

2. W.K.H. Panofsky and F. L. Fillmore, UCRL-481.

3. B. Cork, L. Johnston and C. Richman, UCRL-482.

4. cf. E. Segrè, International Conference on Nuclear Physics, Basil, High Energy Neutron-proton and Proton-proton Scattering, Helv. Phys. Acta (in press), a review article.

5. R. S. Christian and E. W. Hart, UCRL-384.

6. R. S. Christian and H. P. Noyes, UCRL-554.

7. C. E. Leith, Bull. Amer. Phys. Soc. 24, No. 8, 13 (1949).

FIGURE CAPTIONS

Fig. 1. Coincidence counting rate at average beam level vs. thickness of absorber placed before last counter of counter telescope. (Method I.) The counting rate for carbon has been scaled (multiplied by 0.70) to be equivalent to the carbon in the polyethylene target. The hydrogen curve is obtained from the other two curves by subtraction.

Fig. 2. Coincidence counting rate at average beam level vs. the angle between small counter telescope and large counter as seen from the scattering target. (Method II.)

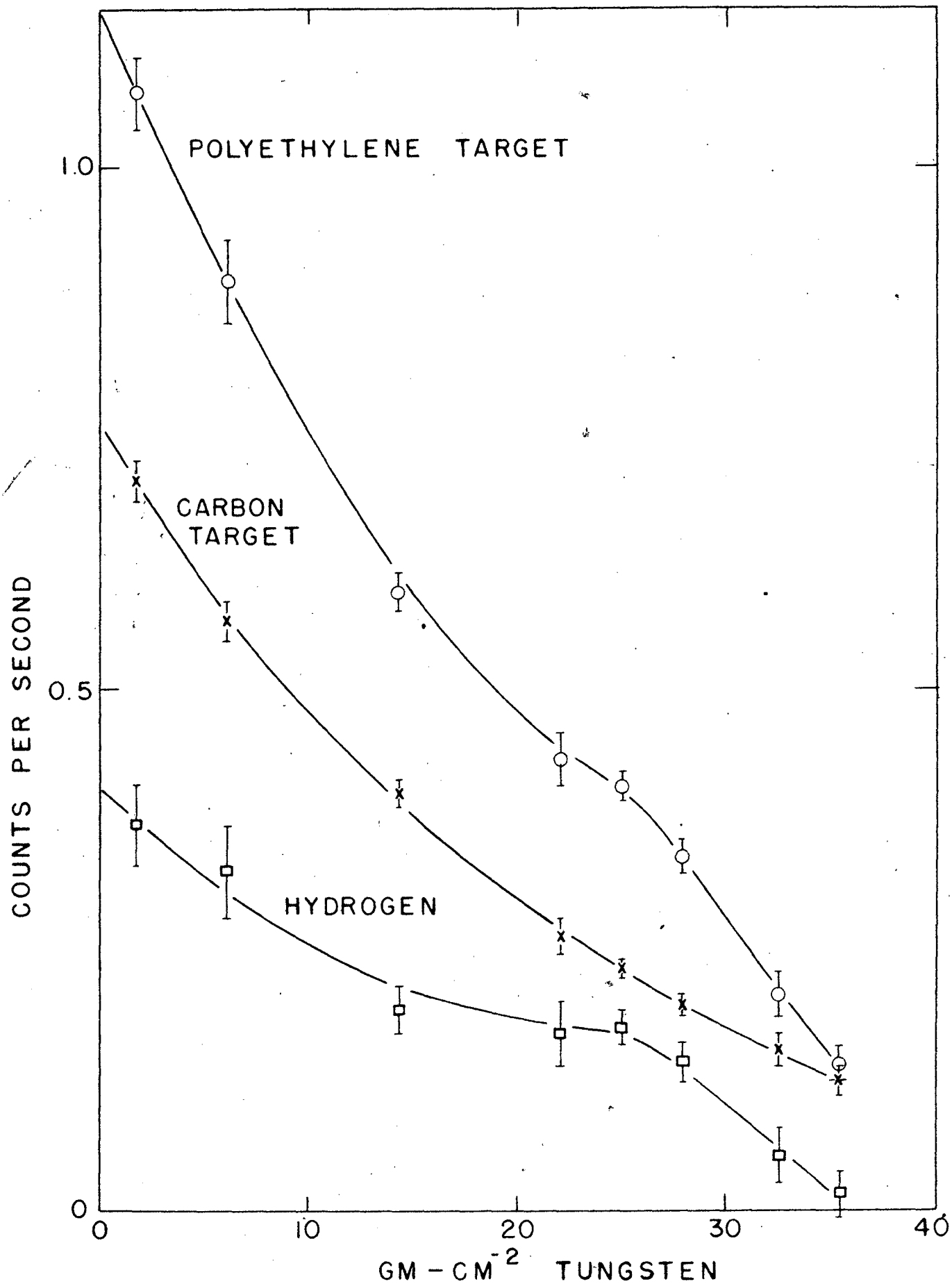
POLYETHYLENE TARGET
CARBON TARGET
HYDROGEN
COUNTS PER SECOND
1.0
0.5
0
0
10
20
30
40
GM - CM^{-2} TUNGSTEN

Fig. 1