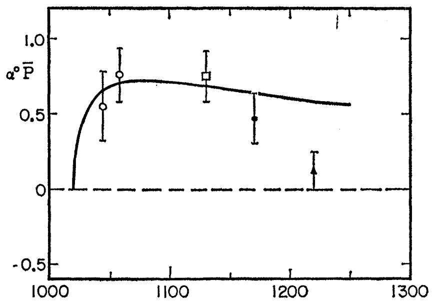

FIG. 7. The up-down asymmetries for the $\Sigma^+ \rightarrow p+\pi^0$ decay mode compared with other experimental results. The solid curve was determined from fitted s and p amplitudes. The result of Cool *et al.* has been determined by a counter experiment, looking at an angle (c.m.) of 87 ± 15 deg. The corresponding value taken from s and p amplitudes is 0.92. Symbols are as follows: (●) from reference 23; (▲) from reference 5; (○) this experiment; (□) from reference 16.

is presented in Figs. 6 and 7, along with the prediction of the maximum-likelihood solution to s- and p-wave amplitudes. Deviation of the curves from the data beyond approximately 1150 MeV/c indicates that the energy dependence of the coefficients, represented by Eq. (3), is no longer valid at these energies. Nevertheless, in order to make a check of the charge-independence hypothesis,[22,23] the results of this analysis were extrapolated to 1090 MeV/c, where data of Σ^- and Σ^0 production by π^-p interactions exists.[6,7] Based on this extrapolation, there is no evidence of a violation in either the total or differential cross sections.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge Professor Frank S. Crawford, Jr., who generously placed films at the authors' disposal, and with whom many useful discussions were carried on in the course of the analysis. The authors also acknowledge the encouragement of Professor Luis W. Alvarez. Thanks go to J. Anderson and L. J. Lloyd for their aid in this experiment. One of us (F. G.) is grateful to the Institut Interuniversitaire des Sciences Nucléaires, Belgium, and to the U. S. Atomic Energy Commission for having made possible his stay at the Lawrence Radiation Laboratory, Berkeley.

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PHYSICAL REVIEW VOLUME 127, NUMBER 2 JULY 15, 1962

Electron-Proton Coincidences in Inelastic Electron-Deuteron Scattering*

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(Received March 12, 1962)

Electron-proton coincidences in inelastic electron-deuteron scattering were detected under the following conditions: incident beam energy 500 MeV; electron scattered at 75° and 359 MeV; proton detected at 40° 23′ (the $\mathbf{q}$ direction for the e-p elastic scattering). The coincidence cross-section with a D_2 target was found to be $(4.2\pm0.8)\times10^{-32}$ cm^2/sr^2 MeV. The experimental result agreed, within the statistical errors, with the value calculated from a theory of Durand. One may conclude that proton form factors in a bound state and the free state do not differ significantly.

I. INTRODUCTION

THE structure of nucleons and the nucleon-nucleon interaction are very important in modern physics. Durand[1] showed that the angular distribution of outgoing nucleons in inelastic electron-deuteron scattering can give much information on the nucleon form factors and the interaction between the nucleons in the final state of the neutron-proton system. To get such a distribution it is necessary to detect the scattered electron and the outgoing nucleon in coincidence. The presence of two magnetic spectrometers in the target room of the Stanford Mark III linear accelerator made possible such an experiment (or at least made it easier) by allowing the analysis in a precise way, of the momenta of two particles emitted simultaneously during a scattering experiment.

This article explains what kind of problems are encountered in the measurement of electron-proton coincidences from electron-deuteron collisions.[2] One of the objects of this experiment was to detect the coincidences; therefore, we chose the conditions such as to produce the largest number of coincidences. This means we placed the spectrometer for proton detection in the $\mathbf{q}$ direction, where $\mathbf{q}$ is the three-momentum transfer

* This work was supported in part by the Office of Naval Research and the U. S. Atomic Energy Commission and by the U. S. Air Force, through the Office of Scientific Research of the Air Research and Development Command.
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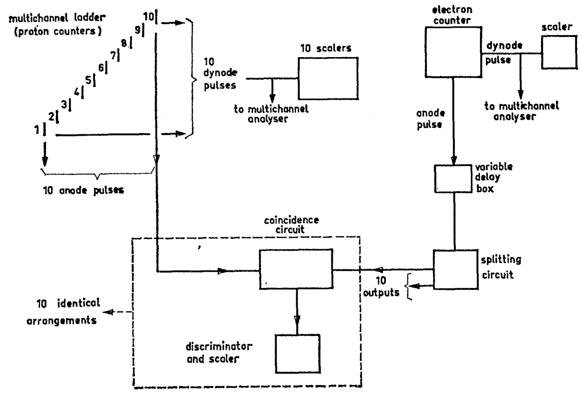

FIG. 1. Block diagram of electronics used for detection of electron-proton coincidences.

in the electron-proton collision. The measurement of the absolute coincidence cross section permitted us to compare the proton form factors in a bound state and in the free state. To have absolute cross sections, measurements relative to elastic scattering from hydrogen were made.

For simplicity, these first measurements were made under the conditions of the Durand's calculations: incident beam energy $E_e=500$ MeV, scattered electron angle $\theta=75°$, scattered electron energy $E_e'=359$ MeV, proton detection angle$=40°\ 23'$ in the laboratory system.

II. APPARATUS

The targets were liquid hydrogen and deuterium, 1-in. thick. The walls of the containers were of 0.001-in. thick stainless steel.

The scattered electrons passed through an entrance slit which defined the solid angle, and entered the 36-in. mean radius spectrometer, used in previous electron scattering experiments.[3] A liquid Čerenkov counter 8-in. long was placed behind the exit slits of the spectrometer. Likewise, protons entered the 72-in. spectrometer[4] and were detected in a 10-channel counter.[4] The multichannel counter is an array of 10 photomultiplier tubes, each observing a $2\times1\times\frac{1}{4}$ in. plastic scintillator mounted on its face. The multichannel counter is placed in the focal plane of the 72-in. double-focusing spectrometer.

The electron counter anode output is sent to a splitting circuit and each of the 10 outputs goes to a coincidence circuit.[5] The other input of each coincidence circuit is connected with the anode output of one channel of the multichannel counter (Fig. 1).

On separate scalers, we also counted single pulses from each photomultiplier, so that cross sections for detection of only one kind of particle (and not electron-proton coincidences) could be measured at the same time.

III. EXPERIMENTAL PROCEDURE

The differential electron-proton coincidence cross-section for scattering from a deuterium target $d^3\sigma/d\Omega_e d\Omega_p dE_e'$ was measured in comparison with the corresponding cross section for a hydrogen target $d\sigma/d\Omega$. This was done in order to reduce systematic errors. In scattering from the hydrogen target, the kinematics of the collision (in this case a two-body collision) fix the relationship between the emission angles of the electron and the proton.

If the electrons are detected in solid angle $d\Omega_e$, there will exist a solid angle for proton detection $d\Omega_p$ such that every time an electron is scattered into $d\Omega_e$ the recoil proton will enter $d\Omega_p$ and vice versa. Therefore, if the accepted solid angles are properly chosen, the electron, proton, and coincidence counting rates should be equal. This relationship is exact only for a point target, and the use of a finite target will cause some true coincidences to be lost.

In this first attempt to get coincidences, it was found that a 1-in.-thick target was too large. A thinner target is under construction to improve this situation. However it was still possible to measure correctly by using the counting rate of the electron counter alone.

The coincidences were first sought with a hydrogen target, because of the strong correlation in angle and energy between the electron and the proton with such a target, making it easier to find the coincidences.

The right delay between the proton and electron counters was then found by making a delay curve. At first, to set the delay approximately, one has to take into account the different times of flight of the electrons and protons in the spectrometers due to the different sizes of the magnets and the different speeds of both particles.

We evaluated the relative efficiency in coincidences of the 10-channel counter by the following method: We have the H_2 coincidence peak on the multichannel counter for one setting of the current of the spectrometer. We checked the efficiency differences between the different channels by changing the current step by step so that each crystal of the ladder counted the whole peak. By comparing the area under the ten peaks, we could give a efficiency factor to each channel. In fact, all efficiencies were found nearly equal and the cross sections were never affected by this correction factor.

To get all real coincidences we had to choose the resolving time of the circuits as small as possible to avoid accidental coincidences, but large enough to count as coincidence all pulses due to the protons going through different paths in the 72-in. radius spectrometer. Because of the large size of the vacuum chamber of this spectrometer, the times of flight of two protons could differ by as much as 8.4×10^{-9} sec for the mo-

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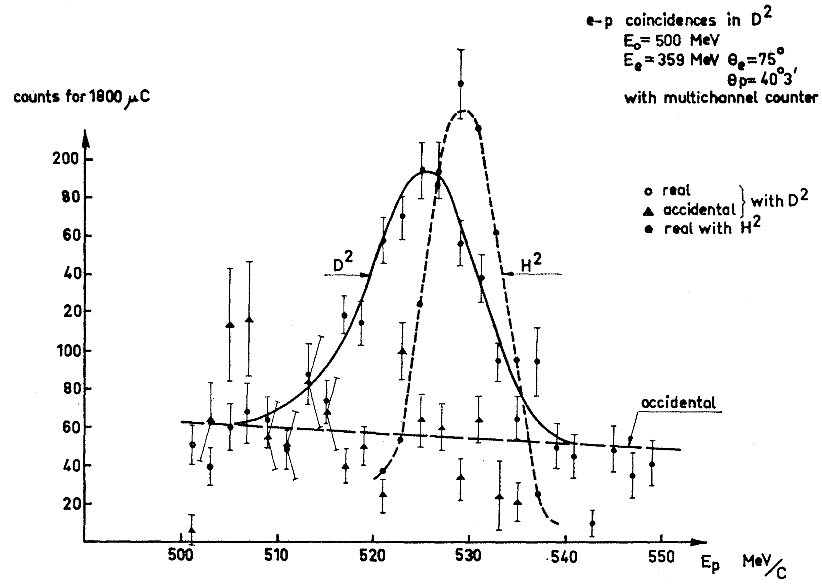

FIG. 2. Coincidence spectrum with D_2 target. The H_2 peak is indicated for comparison of the position of the peak. The shift between the two maxima is due to the binding energy of the deuteron. The large accidental coincidence counting rate is due to the large τ necessary to get all coincidences, because of the large time-of-flight difference of protons in the 72-in. magnet.

mentum of the protons in this reaction. We finally chose $\tau=12\times10^{-9}$ sec. With such a resolution time, the accidental coincidences counting rate is not negligible. Therefore, during a run, accidental coincidences were frequently counted. We did this by inserting a cable much longer than the resolution time of the circuit in the electron cable before the splitting circuit. In this way, one cable was enough to give the accidental coincidences in the 10 coincidence circuits.

After all adjustments were made with the hydrogen target, measurements were done with H_2 and D_2 targets by counting coincidences for a known integrated beam. Current setting of the 72-in. spectrometer was changed sometimes in such a way that the protons detected in a certain channel were counted in another channel during another measurement. In this way we averaged the possible different efficiencies of counters and electronic circuits, and rapidly saw possible systematic errors.

An example of a coincidence spectrum with D_2 and H_2 targets is shown in Fig. 2.

IV. REDUCTION OF THE DATA

One uses the area under the coincidences peaks to obtain the cross sections. Because we did measurements relative to a H_2 target, we had to compare the area under the peaks for H_2 and D_2 targets.

Furthermore, we had to take into account the radiative corrections in the case of the detection of electron-proton coincidences. There is for the moment no exact theory which gives the radiative correction to be applied. We assumed that the Schwinger and bremsstranlung corrections are negligible when the protons only are detected.[6] Therefore, by estimating qualitatively how coincidences could be lost by the radiative effects, we came to the conclusion that the correction to be applied is the radiative correction for the case of detecting electrons only. Sobottka[7,8] and Tsai[9] made calculations for such radiative corrections. Since the two calculations agree quite closely, we have chosen the simpler Sobottka correction.

For the absolute scattering cross section by the proton we used the proton form factors F_{1p} and F_{2p} taken from the latest work of Bumiller *et al.*[10] At $q^2=6.82$ f^{-2} we find $F_{1p}=0.56$ and $F_{2p}=0.45$, which gives $(d\sigma/d\Omega)_{\text{protons}}=3.6\times10^{-32}$ cm^2/sr.

With these assumptions we found

$$[d^3\sigma/d\Omega_e d\Omega_p dE_e']_{\theta=0}=(4.2\pm0.8)\times10^{-32}\ \text{cm}^2/\text{sr}^2\text{MeV}.$$

V. COMPARISON WITH THEORY

Durand[1] and Scofield[11] studied the angular distribution of the outgoing nucleons from an inelastic electron-deuteron scattering.

Durand gives the differential cross section in the center-of-mass system of the outgoing nucleons. Scofield gives the result directly in the laboratory system. To compare the experimental result to theory, we used Durand's formula plus a center of mass to laboratory system transformation formula due to Scofield.[11]

At this early stage of the experiment it was not thought to be useful to include in the theory the calculations of the final-state interaction and of the D-state contribution, because the correction would be at most about 10% and the experimental value is not

[6] Y. S. Tsai is calculating these effects at Stanford. The effect is probably of the order of few percent and can be neglected in first approximation.

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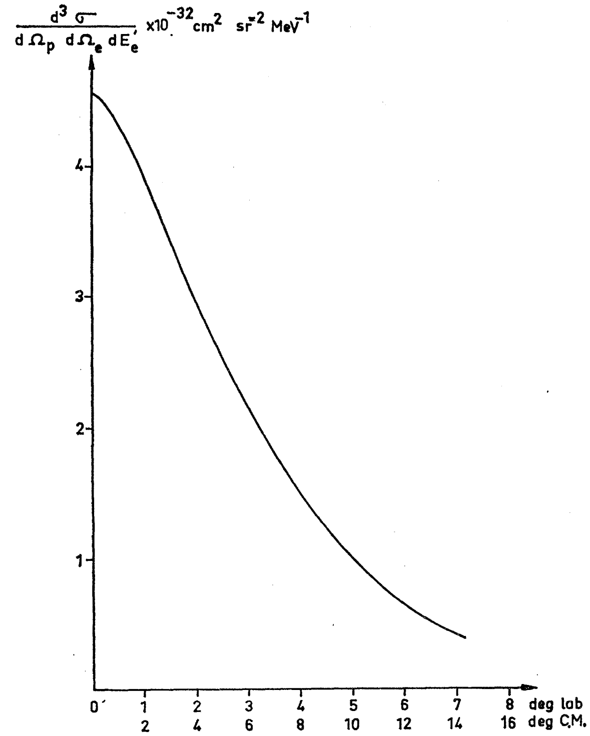

FIG. 3. Calculated theoretical cross section from Durand's formula in the lab system.

known with this accuracy. Accordingly we used the formulas 11.1 and 11.2 of Durand's article.

By restricting ourselves to forward angles ($\theta_{\text{lab}} < 4°$), we can neglect, in first approximation the contribution of the interference and neutron terms in 11.2. Therefore, Durand's formula becomes

$$\frac{d^3\sigma}{d\Omega_e d\Omega_p dE_e'} = \sigma_{\text{Mott}} \frac{Mp}{4\pi^2\hbar^2} F^2(\theta) \left\{ F_1^2 + \left(\frac{\hbar q}{2Mc}\right)^2 \left[2(F_1+K_pF_2)^2 \tan^2(\theta/2) + F_2^2K_p^2\right]\right\}.$$

We have included a factor 2π to put the expression in terms of $d\Omega_p$ as well as the protons form factors F_1 and F_2.

To compare with experiment, three important matters are still to be considered:

(i) the transformation from the center of mass to the laboratory system,

(ii) the calculation of $F(\theta)$ according to the neutron-proton potential in the deuteron,

(iii) the finite experimental entrance solid angle for proton detection.

By taking into account point (i) with a Scofield calculation[11] and (ii) with a Hulthén model for the deuteron the angular distribution in the laboratory system is as shown in Fig. 3. The theoretical cross section is sharply peaked at small angles and varies very rapidly near 0°. Therefore for point (iii) we decomposed the solid angle $d\Omega_p$ in small areas where we could assume that the cross section does not vary too much; for each area we used the cross section for the mean angle and calculated an average over the experimental solid angle.

In these conditions, the theoretical average becomes

$$[d^3\sigma/d\Omega_e d\Omega_p dE_e']_{\theta=0,\text{av}} = 3.37\times 10^{-32} \text{ cm}^2/\text{sr}^2\text{MeV}.$$

The experimental value $(4.2\pm 0.8)\times 10^{-32}$ cm^2/sr^{2}MeV differs from the theoretical one by 20%. This is not surprising because the experimental result is not known to within 20%. Therefore we can conclude that in first approximation the experiment agrees with the theory and proton form factors in a bound state do not differ by more then 10 or 20% from the values for the free state. More precise data and refinements in theory are necessary to give a better comparison.

VI. ACKNOWLEDGMENTS

I wish to thank Professor R. Hofstadter for suggesting this experiment and for many helpful discussions. I am also indebted to many people in the laboratory who assisted me during the different stages of this work.

I wish to acknowledge the kind support of Professor S. Gorodetzky and the Centre National de la Recherche Scientifique (France) in permitting me to work at Stanford University.