CEAL- 1012

CONF-724-2

MASTER

RESEARCH WITH 6-GEV CAMBRIDGE
ELECTRON ACCELERATOR

by

M. Stanley Livingston

October 6, 1964

PATENT CLEARANCE OBTAINED. RELEASE TO
THE PUBLIC IS APPROVED. PROCEDURES
ARE ON FILE IN THE RECEIVING SECTION.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
and HARVARD UNIVERSITY

CAMBRIDGE ELECTRON ACCELERATOR

CAMBRIDGE 38, MASSACHUSETTS

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

LEGAL NOTICE _____

[illegible]

CAMBRIDGE ELECTRON ACCELERATOR

HARVARD UNIVERSITY
42 OXFORD STREET
CAMBRIDGE, MASS. 02138
♦

CEAL-1012
October 6, 1964

RESEARCH WITH 6-GEV CAMBRIDGE ELECTRON ACCELERATOR

by

Prof. M. Stanley Livingston, Director

Cambridge Electron Accelerator, Harvard University

(Paper delivered at the Plenary Session
of the German Physical Society
at Dusseldorf, on October 6, 1964) ✓

The Cambridge Electron Accelerator produces electrons and photons at energies up to 6-Gev for research in high-energy physics. The laboratory is sponsored by Massachusetts Institute of Technology and Harvard University, and is supported by funds from the U.S. Atomic Energy Commission. The accelerator was brought into full operation for research in early 1963. The research work reported here has been performed by many scientists and students from the two sponsoring institutions and from several other New England Universities. Most of the results have been reported in papers at scientific meetings and in publications. My purpose here is to summarize this work and to describe some of the more interesting and significant conclusions.

THE ACCELERATOR

The accelerator is an electron synchrotron consisting of a ring of alternating gradient magnets of 72-meters diameter. Electrons are pre-accelerated to 30 Mev in a linac and are inflected into the orbit when the magnetic field is about 40 gauss. The magnet is excited at 60 cycles per second in a fully biased wave form in which the maximum field is 7600 gauss. A set of 32 radiofrequency cavities spaced around the orbit provide synchronous acceleration and compensate for energy lost by radiation, which amounts to 4.5 Mev per turn at peak energy.

At high energy the electrons are diverted against targets located at the edge of the orbit aperture by pulsed excitation of selected pairs of magnets in the ring. X-rays from these targets will emerge tangentially from any one of six target locations. Control of the pulsed excitation of these magnets allows long pulse lengths and large duty cycles. Beam intensities of up to 2×10^{10} e/pulse or 1.2×10^{12} e/second have been achieved, with spill times of 0.5 to 3.0 milliseconds (3% to 18% duty cycle). With the shorter beam pulses the energy spread is less than 0.5%; with the longer beam pulses it is about 10%.

A recent development has been the extraction of an emergent beam of mono-energetic electrons by using a pulsed current-strip deflector at the edge of the aperture which excites resonant radial betatron oscillations. An extraction

efficiency up to 70% has been obtained. The emergent beam has an energy spread less than 0.2% and can be focused to a spot of 0.5 mm by 2.0 mm on a target far removed from the accelerator. This beam is now being adapted to experimental uses.

The unique feature of the Cambridge Accelerator is that it produces electrons (and photons) at an energy some 5 times higher than from earlier electron accelerators. This energy is sufficient to produce and study all of the known mesons, hyperons and their antiparticles and to excite most of the known nuclear resonances. The production of nuclear particles or excitation of resonances through the electromagnetic photoproduction process provides new information on the nature of these interactions. The X-rays produced from targets in the machine emerge in a narrow cone, resulting in high flux densities and allowing the use of small experimental targets. The very short wavelength associated with electrons at this energy provides a sharper probe for scattering experiments than has hitherto been available, capable of penetrating nucleons and resolving details of their structure. Emergent electron beams can be focused to small dimensions, providing excellent geometrical conditions for precise experiments.

EXPERIMENTAL RESULTS

The experiments which have been performed can be grouped into several categories:

- a) Elastic scattering of electrons by nucleons to determine the internal structure of nucleons.
- b) Tests of the validity of quantum electrodynamics at small interaction distances, through studies of e^- , μ^- and π -pairs.
- c) Photoproduction cross-sections for production of mesons, hyperons and nucleon resonances.
- d) Hydrogen bubble chamber studies of nuclear events through the photoproduction process.
- e) Confirmation of the peripheral (small angle) production of pions in the photoproduction process.

Over 12 experimental groups have been scheduled for research operations during the past year. I will not attempt to discuss all of the experimental results, but will select a few experiments to describe in detail, which are typical and in which the results are of considerable scientific interest.

1. Electron Scattering

R. Wilson, N.F. Ramsey, et al (Harvard)* +

The purpose of this experiment is to observe the intensity of elastically scattered electrons from protons and

neutrons as a function of incident energy and scattering angle, in order to calculate the form factors for the electric (G_E) and magnetic (G_M) structure of the nucleons.

The circulating beam of electrons in the synchrotron is deflected against a small "thimble" target of liquid hydrogen located close inside the orbit in a straight section. Scattered electrons emerge through a thin foil window into a detection system mounted on a movable platform which is pivoted under the target. A 12-inch quadrupole magnet with a central obstacle acts as a momentum analyzer and gives a line focus in the vertical plane. A Cerenkov counter and a scintillation shower counter system identify the electrons and discriminate against the considerable background of unwanted particles.

The elastic scattering cross-section for H_2 is measured at several angles from 31° to 90° , at several energies representing momentum transfers from $q^2 = 10$ to 175 f^{-2} . The form factors computed from these data, when plotted against q^2 , decrease smoothly to a value of about 0.04 at the largest value of q^2 . The G_E factor remains less than the G_M factor. The most reasonable interpretation of these curves is that they are asymptotic to zero at infinite q^2 . If so, there is no evidence for a central charge or magnetic core for the proton. The charge and magnetic distributions are roughly uniform and continuous through the center of the proton.

Similar measurements with liquid deuterium in the target cup can be analyzed by a subtraction technique to give form factors for the neutron. The same conclusion holds for the magnetic distribution near the core of the neutron, with somewhat less statistical accuracy. The electric form factor for the neutron is found to be consistent with zero at all momentum transfers studied.

Preliminary measurements of inelastic scattering from protons have been made, and show that nucleon excitation states and resonances can be identified and measured using this technique. Equipment is now being assembled for studies using the emergent beam of electrons, which should improve the precision of measurements and extend the results to even larger momentum transfers.

-
- * Chen, K.W., Cone, A.A., Dunning, J.R.Jr., Frank, S.G.F., Ramsey, N.F., Walker, J.K. and Wilson, R.
Phys. Rev. Letters, 11, 523 (1963)
- + Chen, K.W., Cone, A.A., Dunning, J.R.Jr., Hartwig, G., Ramsey, N.F., Walker, J.K., and Wilson, R.
Contributed Paper -- Internat. Confer. on High Energy Phys., Dubna, U.S.S.R., August, 1964.

2. Wide Angle Photoproduction of Electron Pairs

F.M.Pipkin, D.G.Stairs, et al, (Harvard) *

This experiment is designed to test the validity of quantum electrodynamics at very short interaction distances, by observing wide angle, symmetrical electron pairs produced by photons in a carbon target. Wide angles (5° to 8° in the laboratory) involve large momentum transfers, but intensities are small and the detection equipment must have large solid angle and must be highly selective. The observation of symmetrical pairs eliminates interference terms in the theoretical analysis and reduces the uncertainty in interpretation caused by our imperfect knowledge of nuclear form factors. Only the elastic electric form factor appears in the theory for pair production in a spin-zero target such as carbon. The electrodynamic effects can be isolated from nuclear structure complications by selecting angles and energies which maintain constant momentum transfer to the nucleon while the momentum of the virtual lepton is varied.

In the experimental system a collimated photon beam from the accelerator strikes a thin carbon target located over the pivot of a two-armed spectrometer, with identical detection equipment on the two arms. Charged pairs are first separated by a magnetic field, so observations can be made down to small angles, and then enter the apertures of two focusing half-

quadrupole magnets. Each half-quadrupole focuses in the vertical plane and its center is filled with a lead obstacle to pass a momentum analyzed beam with a resolution of $\pm 4\%$. Particle trajectories are defined by scintillation counters in coincidence. A gas Cerenkov counter discriminates between electrons, pions and muons.

Measurements were taken for photon energies of 2.5, 5.0, 5.5 and 6.0 Gev and at angles of 4.75° , 6.26° and 7.5° . Coincidences between the two channels which could be identified as electron pairs were plotted and compared with theoretical estimates of electron pair yields obtained from Monte Carlo integrations for the appropriate energies. The experimental results agree with the theoretical estimates to within the variation expected from counting statistics alone. This result indicates no deviation from the predictions of quantum electrodynamics up to a momentum transfer Q of 400 Mev/c.

Further measurements are planned with the emergent electron beam, to reduce errors and to extend the results to the maximum momentum transfer possible with the 6-GeV energies available at the CEA.

* Blumenthal, R.B., Ehn, D.C., Faissler, W.L., Joseph, P.M., Lanzerotti, L.J., Pipkin, F.M. and Stairs, D.G. (Harvard) Contributed paper: Internat. Conf. on High Energy Phys. Dubna, U.S.S.R., August 1964.

3. Photoproduction of Mesons

L.S.Osborne, D.Luckey, et al (M.I.T.) *

Cross-sections for the photoproduction of pions and other mesons from a liquid hydrogen target have been measured over a wide range of photon energy and angular distribution. The apparatus has two rotating platforms pivoted under the target. The larger platform carries magnets and counter systems for detection and momentum analysis of the recoil protons; the second platform carries a total absorption gamma ray counter which detects the secondary photons from π^0 decays, in coincidence.

The primary reaction of interest is: $\gamma + p \rightarrow p + \pi^0$, followed promptly by: $\pi^0 \rightarrow \gamma + \gamma$. The photon spectrum from π^0 decay is sharply peaked in the gamma ray counter; coincidences between this photon energy peak and protons in the other arm identify this reaction. This is the dominant process for incident photon energies from 1 to 2 Gev. With increasing energy multiple-pion or η -meson channels compete with single pion production; the intensity of photons of lower energy increases.

The overall behavior of the photoproduction cross-sections is a rapid decrease with increasing energy and with increasing angle, complicated by peaks and shoulders due to resonances and multi-particle channels. The "1.69-GeV" ($T = \frac{1}{2}$) resonance

and the "1.92-Gev" ($T = 3/2$) resonance can be identified, and shoulders on the curve are compatible with the "2.19-Gev" ($T = \frac{1}{2}$) and the "2.36-Gev" ($T = 3/2$) resonances.

An alternate channel is π^+ production: $\gamma + p \rightarrow n + \pi^+$. The π^+ mesons can be measured concurrently in the proton arm of the spectrometer, and are distinguished by their velocity. Cross-sections are much smaller than for π^0 production at the same angles and energies, which can be understood if the basic interaction involves the exchange of a virtual $T = 0$ particle such as the ω^0 .

An interesting feature of the results is the structure observed at energies beyond the known resonances. At an incident energy of 3.5 Gev the π^0 data at 90° showed a small shoulder which justified further study. When coincidences between protons and low energy photons (0.35 to 1.0 Gev) were studied, a sharp peak was found having 10 times the cross-section of the π^0 production identified by the high energy (2.0 Gev) photon peak. A "missing mass" analysis of the low energy photons suggests the emission of an η^0 meson with a mass of about 500 Mev. This η^0 meson would decay into three π^0 mesons, each of which would produce two low energy photons. The number of low energy photons observed agrees with calculated intensities based on this analysis. It is interesting to note that this η^0 -nucleon state occurs at an

energy of 2.75 Gev, considerably higher than any previously observed nucleon state. The cross-section for η^0 production is 80 ± 10 nanobarns, compared with 2 ± 1.5 nanobarns for π^0 production at this energy. The interpretation of this large production ratio leads to interesting speculations in terms of possible groups of the SU-3 type.

* Alvarez, R.A.Jr., Bar-Yam, Z., Kern, W., Luckey, P.D., Osborne, L.S., Tazzari, S. (M.I.T.), and Fessel, R., (CEA) Phys. Rev. Letters, 12, 707 (1964)
Phys. Rev. Letters, 12, 710 (1964)

4. Hydrogen Bubble Chamber Studies

(Cambridge Bubble Chamber Group)

A group of 24 scientists from M.I.T., Harvard and other universities has collaborated in the procurement and analysis of pictures from a 12-inch liquid hydrogen bubble chamber exposed to a photon beam from the CEA at energies up to 4.8 Gev. The bubble chamber operates at 2 or 3 pictures per second. Over 1,200,000 pictures have been taken, of which about 10% have been analyzed. The results were reported at the Dubna Conference in August 1964. *

Beam intensity is reduced to acceptable levels, and background radiation is minimized, by double conversion of the photon beam from the CEA into positrons and back to photons. Momentum analysis of the positrons determines the peak energy of the photon beam entering the bubble chamber. Intensities of about 40 equivalent quanta per picture give an average of 4 electron pairs (2-prong tracks) per picture, and one nuclear event per 100 pictures.

A nuclear event is defined as one having 3 or more prongs. The several classes of events are separated using the CERN kinematical fitting program "GRIND". In the sample of 120,000 pictures analyzed the observed types of events are:

- 588 - 3-prong events ($\gamma + p \rightarrow p + \pi^+ + \pi^-$)
- 311 - 4-prong events
- 43 - 5-prong events
- 52 - strange particle events

The total cross-section for nuclear events, for photon energies above 1 Gev, is about 100 microbarns. The two-pion events (3-prong) reach a maximum at 1 Gev and fall off at higher energy due to competition with the more complex events. Above 2 Gev the cross-sections for the 2-, 3-, 4- and 5-pion events and strange particle events are all of comparable magnitude, of the order of 10 microbarns each.

The results can be summarized as follows:

- a) In two-pion production the main feature, for energies below 2 Gev, is the copious production of the "1238-Mev" ($p\pi^+$) isobar. The observed cross-sections are in good agreement with theoretical estimates assuming a dominant one-pion exchange.
- b) For energies above 1.1 Gev the photoproduction of ρ^0 -mesons dominates the direct charged pion production. This process is presumed to go in two steps: $\gamma + p \rightarrow p + \rho^0$; $\rho^0 \rightarrow \pi^+ + \pi^-$. The protons from ρ^0 production are peaked strongly backward, and the charged pion distributions are peaked forward. This momentum transfer distribution to the protons is also in agreement with predictions from the one-pion exchange theory.
- c) Three or more pions are produced in a smaller number of events. There is some indication of ω production, but with a cross-section of less than 10% of the ρ -meson production.
- d) Strange particle production shows four classes of events:

$$\begin{array}{lcl}
 11 - K^- K^+ p (n\pi) & & \\
 30 - K \Lambda^0 (n\pi) & \left. \begin{array}{l} \text{through} \\ \text{either} \end{array} \right\} & \begin{array}{l} Y_1^* (1385 \text{ Mev}) \text{ resonance} \\ Y_0^* (1520 \text{ Mev}) \text{ resonance} \end{array} \\
 10 - K \Sigma (n\pi) & & \\
 1 - \Xi^- K + K^+ & &
 \end{array}$$

In all events, one combination of secondary particles agrees in mass with either the Y_1^* or the Y_0^* resonance. Observed cross-sections for these two alternate production channels

are 4 and 6 microbarns in the energy range between 2.0 and 4.8 Gev.

* Eisenberg, Y., Bastien, P., Feld, B.T., Fischer, V.K., Pless, I.A., Rogers, A., Rogers, C., Rosenson, L., Watts, T.L., Yamamoto, R.K., (M.I.T.); Widgoff, M., Shapiro, A.M., Lanou, R.E., Bulos, F., (Brown Univ.); Brenner, A.E., Law, M.E., Ronat, E.E., Strauch, K., Street, J.C., Szymanski, J.J., Teal, J.D. (Harvard); Guerriero, L., Salandin, G.A., (Padua); Fischer, G.E., (C.E.A.)
Contributed Paper -- Internat. Conf. on High Energy Phys., Dubna, U.S.S.R., August 1964.

Other experiments which cannot be described in detail deserve mention, in order to show the variety and scope of the program. A group headed by D.O.Caldwell (M.I.T.) has studied the peripheral production of charged pions from a liquid hydrogen target; the results confirm the theoretical predictions of Drell and show large cross-sections at small forward angles of 2° to 3° , in excess of those at 0° . A group led by R. Weinstein (Northeastern Univ.) and J.I.Friedman and H.W.Kendall (M.I.T.) have studied the wide angle production of muon pairs, in a two-arm array using thick absorbers of iron plates to absorb the more interactive particles such as pions; again the results show no deviations from the predictions of quantum electrodynamics. M. Deutch and others (M.I.T.) have observed and studied the

"proton Compton effect", which becomes technically feasible at these energies. R.H.Milburn (Tufts Univ.) has demonstrated the feasibility of the nuclear emulsion technique in a study of the production of charged Σ hyperons.

CONCLUSION

It is clear that the Cambridge Electron Accelerator has enjoyed a very productive first year of operation. The large duty cycle of the synchrotron, and the flexible arrangements for utilizing the emergent radiations, have provided scientists with a new and useful tool in this higher energy range. The electron-nucleon scattering studies have greatly clarified our understanding of the structure of protons and neutrons. The range of validity of quantum electrodynamics has been extended by an order of magnitude to much shorter interaction distances and larger momentum transfers. The photoproduction process has been shown to be capable of exciting most of the known nucleon resonances and even of extending the energy range. The gap between the phenomena dominated by the electromagnetic force and by the nuclear force has been narrowed.

It is my great pleasure to welcome the newly completed DESY synchrotron at the University of Hamburg to the new field of high-energy electron physics. Physicists from your country will soon be joining those at the Cambridge Accelerator in

CEAL-1012

exploring this exciting field of science. We can all hope
for more significant scientific results in the years ahead.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

- A. Makes any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights or
- B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission to the extent that such employee or contractor prepares, handles or distributes, or provides access to any information pursuant to this employment or contract with the Commission.