Laboratori Nazionali di Frascati

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Wide-Angle Electron-Proton Bremsstrahlung.

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1. – The differential cross-section for wide-angle electron-proton bremsstrahlung (WAB)

$$e + p \rightarrow e + p + \gamma$$

has been measured using the external electron beam of the Frascati 1 GeV Electron Synchrotron. The relevant features of this process are characterized by the two invariants

$$q_s^2 = (p - k)^2 \qquad \text{(spacelike)}\,,$$

$$q_t^2 = (p' + k)^2 \qquad \text{(timelike)}\,,$$

where p, p' and k are the 4-momenta of the ingoing, outgoing electrons and photon respectively; in the two lowest-order Feynman diagrams, q_s and q_t correspond to the 4-momenta of the virtual lepton.

The experimental results have been compared with the theoretical WAB cross-section, calculated by QED (quantum electrodynamics) to lowest order in e^2, including proton form factors (¹); corrections due to the virtual Compton contribution are also included. No significant deviation between the measured and the expected cross-section

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(¹) P. S. ISAEV and I. S. ZLATEV: *Nuovo Cimento*, **13**, 1 (1959); R. A. BERG and C. N. LINDNER: *Phys. Rev.*, **112**, 2072 (1958); A. COSTESCU and T. VESCAN: *Nuovo Cimento*, **48** A, 1041 (1967).

has been found, to within ~5% accuracy, at the measured points: $q_s^2 = -(260\,\text{MeV})^2$, $q_t^2 = (70\,\text{MeV})^2$ and $q_s^2 = -(265\,\text{MeV})^2$, $q_t^2 = (100\,\text{MeV})^2$.

The principal virtue of this experiment is that is tests the validity of QED in the timelike lepton propagator region where data are still lacking (²); while it is already known from lepton pair photoproduction experiments that QED holds in the spacelike region up to the explored values of $q_s^2 \simeq -(500\,\text{MeV})^2$ (³).

2. – A sketch of the experimental apparatus is given in Fig. 1. The electron beam (0.9 GeV) hits a 20 cm long liquid-hydrogen target. The three outgoing particles are detected in coincidence. Two total-absorption Čerenkov counters (lead glass cylinders, 20 cm in diameter, 12 radiation lengths thick, 2 m from the target) detect the outgoing

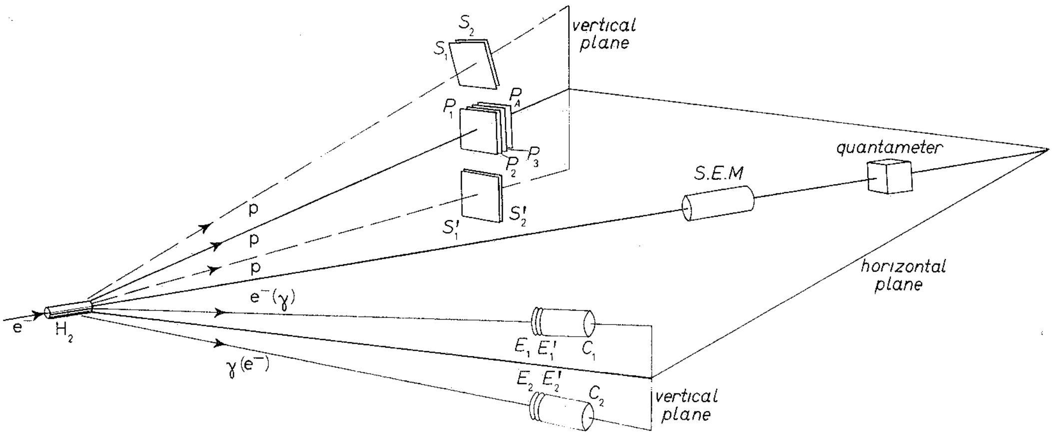

Fig. 1. – Experimental apparatus. $P_1P_2P_3P_A$ is the proton range telescope; $E_1E'_1C_1$, $E_2E'_2C_2$ (symmetrical with respect to the horizontal plane) are the electron and photon detectors; S_1S_2, $S'_1S'_2$ are the proton scattering telescopes; an e-p scattering event is defined by $(S_1S_2)(E_2E'_2C_2)$ or $(S'_1S'_2)(E_1E'_1C_1)$. The angles of the proton, electron and photon telescope in the two kinematical regions explored were respectively: $\theta_p = (66 \pm 1.5)°$, $\varphi_p = (0 \pm 3)°$, $\theta_e = \theta_\gamma = (25.7 \pm 3.5)°$, $\varphi_e = (166 \pm 8)°$, $\varphi_\gamma = (194 \pm 8)°$ for the point at $q_t^2 = (70\,\text{MeV})^2$ and $\theta_p = (65.8 \pm 1.5)°$, $\varphi_p = (0 \pm 3)°$, $\theta_e = \theta_\gamma = (26.5 \pm 3.5)°$, $\varphi_e = (162 \pm 8)°$, $\varphi_\gamma = (198 \pm 8)°$ for the point at $q_t^2 = (100\,\text{MeV})^2$. The secondary emission monitor (S.E.M.) was used to check against a possible saturation of the quantameter.

(²) See however systematic searches for heavy electrons following F. Low's suggestion: *Phys. Rev. Lett.*, **14**, 238 (1965); C. Betourne, H. Nguyen Ngoc, J. Perez y Jorba, J. Tran Thanh Van: *Phys. Lett.*, **17**, 70 (1965); H.J. Behrend, F. W. Brasse, J. Engler, E. Ganssauge, H. Hultschig, S. Galster, G. Hartwig and H. Shopper: *Phys. Lett.*, **15**, 900 (1965); R. Budnitz, J. R. Dumming, Jr. M. Goitein, N. F. Ramsey, J. K. Walker and R. Wilson: *Phys. Rev.*, **141**, 1313 (1966); C. D. Boley, J. E. Elias, J. I. Friedmann, H. W. Kendall, P. N. Kirk, M. R. Sogard, L. P. Van Speybroeck and J. K. De Pagter: *Phys. Rev.*, **167**, 1275 (1968). Preliminary results of a WAB experiment on carbon by a Cornell Group have been presented by K. Berkelman at the recent Vienna Conference.

(³) A. Alberigi-Quaranta, M. de Pretis, G. Marini, A. Odian, G. Stoppini and L. Tau: *Phys. Rev. Lett.*, **9**, 226 (1962); J. G. Asbury, W. K. Bertram, U. Becker, P. Joos, M. Rohde, A. J. S. Smith, S. Friedlander, C. Jordan and C. C. Ting: *Phys. Rev. Lett.*, **18**, 65 (1967); J. K. de Pagter, J. I. Friedman, G. Glass, R. C. Chase, M. Gettner, E. Von Goeler, R. Weinstein and A. M. Boyarski: *Phys. Rev. Lett.*, **17**, 767 (1966); D. J. Quinn and D. M. Ritson: *Phys. Rev. Lett.*, **20**, 890 (1968). In the pair production process QED is contaminated, when the invariant mass of the pair is around 750 MeV/c², by strong production of ρ⁰-mesons decaying into lepton pairs.

photon and electron emitted at the same angle with respect to the incident beam, but symmetrically (up and down) with respect to the horizontal plane. A range telescope of scintillation counters ($P_1P_2P_3P_A$, see Fig. 1) detects protons emitted on the horizontal plane, if their kinetic energy is between ~ 50 and ~ 100 MeV.

When a master coincidence of the three outgoing particles occurs, we print:

1) The pulse height in the two Čerenkov counters, providing the energy ot the detected particles with $\sim 30\%$ resolution (full width at half height).

2) The nature (electron or photon) of the particles detected in the Čerenkov counters. This information is provided by two scintillation counters in front of each Čerenkov.

3) The time of flight of the proton: the proton telescope is 4 m from the target.

4) The kinetic energy of the proton through the pulse height in the stopper counter P_3 (see Fig. 1).

The angles and apertures of the counters, and the ranges of energy, are chosen so that the accepted phase-space region is determined only by the dimensions of the counters, the energy spreads being small and centered with respect to the energy intervals explored by the three telescopes.

In the symmetrical situation chosen by us, in which the energies of the electron and photon are equal, q_t^2 is sharply defined by the angle between the emitted electron and photon, and q_s^2 by the azimuthal angle of the electron and photon plane around their total 3-momentum.

This allows us:

a) To fix q_t^2 independently of q_s^2.

b) To change from one kinematical situation to the other (from $q_t^2 = (70\text{ MeV})^2$ to $q_t^2 = (100\text{ MeV})^2$) moving only the angles of the Čerenkov counters.

c) To use the energy spectra of the observed particles as a check that we are really observing WAB, with no apreciable contamination from other processes.

A comparison between the observed energy spectra and those expected on the basis of the requirements on the angles (Monte Carlo calculation) is shown in Fig. 2*c*), 2*d*), 2*e*), 2*h*), 2*i*), 2*j*); in Fig. 2*a*), 2*b*), 2*f*), 2*g*) we show the regions of q_t^2 and q_s^2 explored in the two kinematical situations chosen for the experiment.

Note that $q_t^2 \ll -q_s^2$, and that the change from one situation to the other did not modify appreciably the energy spectra of the detected particles. This tends to reduce the importance of possible systematic errors (nuclear interaction of the protons, counters efficiencies, etc.).

The fact that the contamination from other processes appears to be negligible is consistent with the fact that both kinematical situations are below threshold for electroproduction of π^0's.

3. – The results are summarized in Table I. The incoming flux of electrons has been determined by a Wilson quantameter, whose constant is taken to be $Q = 4.62 \cdot 10^{18}$ MeV/coulomb, in agreement with the intercalibrations performed in various laboratories: the measurements of $d\sigma_{\text{exp}}$ are thus absolute determinations. No attempt has been made to attach an error to Q. As a check, however, the cross-

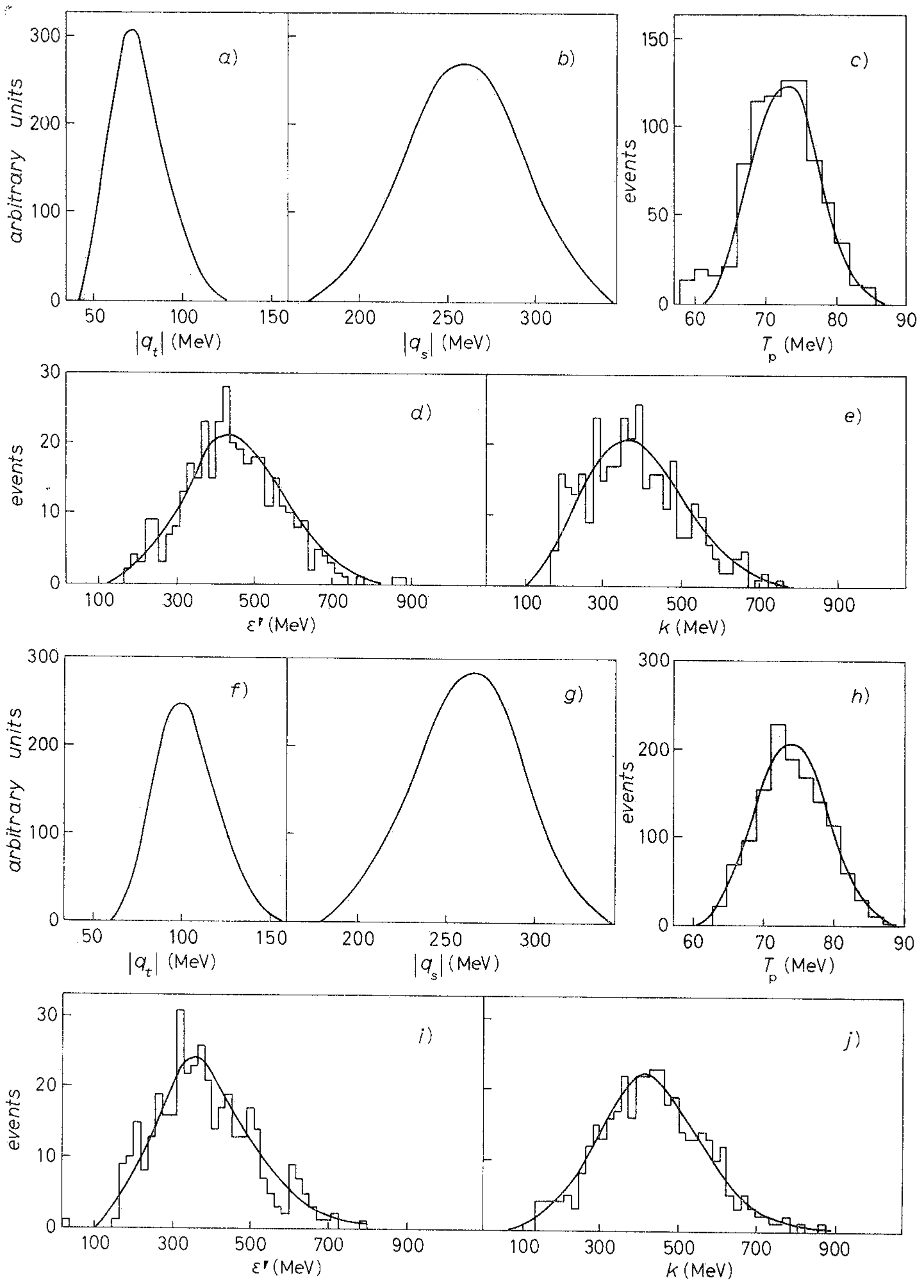

Fig. 2. – Spectra of the relevant kinematical parameters, as obtained by Monte Carlo calculation, including experimental acceptance and resolution (full line). For comparison with the theoretical prediction, we show in *c*), *d*), *e*), *h*), *i*), *j*) the measured spectra relative to a sample of the events. T_p, ε', k are the kinetic energy of the recoil proton, the energy of the scattered electron and photon respectively. In *d*) and *e*) events with the electron in the lower Čerenkov and the photon in the upper Čerenkov; n *i*) and *j*) events with the electron in the upper Čerenkov and the photon in the lower Čerenkov.

section for elastic e-p scattering has been measured in two independent channels in parallel to the WAB measurement, using the same Čerenkov counters for the electron, and in addition two auxiliary telescopes to detect the recoil proton (Fig. 1). The results of this measurements are shown in the last column of Table I (radiative corrections are negligible). The agreement is remarkably good, considering that the counting rate is much more sensitive to geometry (in particular to the primary-beam alignment and angular spread) for scattering than for WAB.

TABLE I. – *Summary of results.*

q_t^2 ((MeV)^2)	$-q_s^2$ ((MeV)^2)	T_p (MeV)	ε (MeV)	Uncorrected events	Corrected events	$\dfrac{d\sigma_{exp}}{d\sigma_{BH}}$	$\dfrac{d\sigma_{exp}}{d\sigma_{BH+C}}$	$\left(\dfrac{d\sigma_{exp}}{d\sigma_{th}}\right)_{scatt}$
1	2	3	4	5	6	7	8	9
$(70)^2$	$(260)^2$	74	900	1872	2083	0.995 ± 0.04	0.955 ± 0.04	0.935 ± 0.04
$(100)^2$	$(265)^2$	74	900	1282	1130	1.065 ± 0.05	0.993 ± 0.05	0.995 ± 0.03

Col. 1, 2: mass squared of electron propagators;
Col. 3: central value of the proton kinetic-energy spectrum (see Fig. 2);
Col. 4: incident electron beam energy;
Col. 5, 6: number of WAB events (see text, Sect. 3);
Col. 7: ratio between experimental WAB cross-section and theoretical Bethe-Heitler cross-section, including proton form factor;
Col. 8: ratio between experimental WAB cross-section and theoretical Bethe-Heitler cross-section, including proton form factor, but with theoretical cross-section including virtual Compton contribution;
Col. 9: ratio between the experimental scattering cross-section and the theoretical one (see text, Sect. 3).

The difference between «uncorrected» and «corrected» number of WAB events (col. 5 and 6 of Table I) occurs mainly because of two types of background: besides the (e, γ, p) events we also recorded events in which the proton is accompanied by two charged particles (called (e, e, p)) or by two neutrals (called (γ, γ, p)). In both cases the nature of the signals from the scintillation counters in front of the Čerenkov counters gave the only difference from the expected (e, γ, p) events, all the other requirements (pulse heights and time of flight) being well met.

Since there are no genuine physical processes giving a significant number of events of the (e, e, p) type, we attribute these events to accidentals of soft electrons from the target and (e, γ, p) events. A weak magnetic field on the H_2 target helps to sweep out most of the soft electrons, providing thus a partial check of this assumption. Direct determination of the accidental rates allows correction for the (e, e, p) effect; the result of the correction checks well with the assumption that no genuine (e, e, p) events are produced. Also, (γ, γ, p) events can occur because of π^0 electroproduction in the target, although events of the (e, γ, p) type are strictly forbidden when $q_t^2 \leqslant m_\pi^2 = (135\text{ MeV})^2$. Conversion of a (γ, γ, p) event into an (e, γ, p) is again due to accidentals with soft electrons so that a subtraction has to be applied.

We are confident that this correction (not exceeding 15%) has been evaluated with an error lower than 20% of the correction itself, also considering the many internal checks available. This error has been propagated to the results.

Other applied corrections (empty target ~ 1%, nuclear interactions ~ 3%, counters efficiencies ~ 3%) do not contribute appreciably to the overall error,

4. – To evaluate the WAB Bethe-Heitler cross-section $d\sigma_{BH}$, including the proton recoil, the scaling law $G_E = G_M/\mu$ was used for the proton form factors. Also, the dipole fit $G_E(q^2) = (1 - q^2/0.71\,(\text{GeV})^2)^{-2}$ has been adopted in the Monte Carlo calculation after checking that the experimental values of G_E and G_M were well reproduced in the range of interest. Note that a possible systematic error in the form factors cancels out in the comparison between our two points: they refer in fact to the same value of q^2.

The virtual proton Compton contribution ($d\sigma_C$) was evaluated using the formulae by GRECO, TENORE and VERGANELAKIS (4); their model includes both the proton and the first-isobar contributions. As one can see from the ratio $d\sigma_{BH+C}/d\sigma_{BH}$ in Table I the correction for the virtual Compton contribution amounts to $\sim 4\%$ at $q_t^2 = (70\,\text{MeV})^2$ and $\sim 7\%$ at $q_t^2 = (100\,\text{MeV})^2$.

Radiative corrections do not probably exceed the experimental errors, considering the low resolution of the apparatus. However a detailed calculation has not yet been performed.

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(4) R. A. BERG and C. N. LINDNER: *Nucl. Phys.*, **26**, 259 (1961): A. COSTESCU and T. VESCAN: *Nuovo Cimento*, **48** A, 1041 (1967); M. GRECO, A. TENORE and A. VERGANELAKIS: *Phys. Lett.*, **27** B, 317 (1968).