SPARK CHAMBER STUDY ON THE ELASTIC PRODUCTION OF MUONS AND ELECTRONS BY HIGH-ENERGY NEUTRINOS

G. Bernardini, H. Bienlein, G. von Dardel, H. Faissner, F. Ferroro, J. M. Gaillard, H. J. Gerver, B. Hahn, V. Kaftanov, F. Krienen, M. Reinharz, R. A. Salmeron, P. G. Seiler, A. Staude, H. J. Steiner

CERN, Switzerland
(Presented by H. FAISSNER)

1. THE EXPERIMENTAL ARRANGEMENT

The set-up used in the 1963 experiment was described at previous conferences [1—3]. In brief, it consisted of a thin-walled spark chamber followed by a magnet and by a thick-walled range chamber (Fig. 1). The chamber comprised thick lead and iron walls with spark chamber modules in between.

In principle the arrangement used in 1964 had the same structure. There was one important change: The magnet coil was replaced by a spark chamber with 5 cm thick magnetized

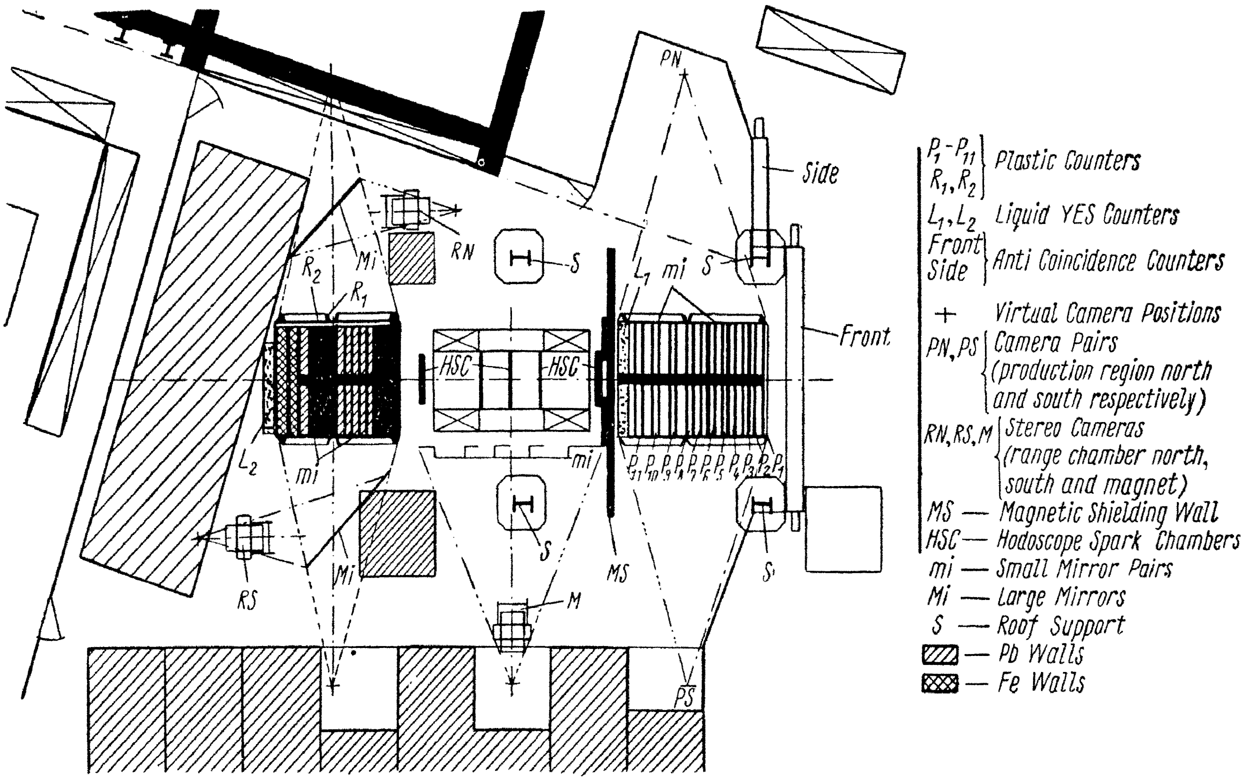

Fig. 1. Top view of the 1963 apparatus. Neutrinos came from the right.

a high-resolution part, which consisted, during the first part of the 1963 experiment, of a mixture of aluminium and brass spark chamber modules in the ratio 2 : 1 (altogether 8.3 tons). It was later replaced by 4.6 tons of pure aluminum. The subsequent low-resolution section consisted of 12 tons of brass spark chambers. The magnet, a pair of Helmholtz-type coils, (4kgauss), permitted the determination of the charge of the particles up to 10 *GeV/c*. The range chamber was made up to 5 to 20 cm iron walls. There were also two slabs of magnetized iron at the end of the extended range chamber, permitting a charge measurement for particles leaving the set-up [4].

Photograph, triggering, time of flight measurement etc. have been amply described elsewhere [1—3]. In 1963 the average triggering rate was 40 per hour, and every third trigger was due to a neutrino event. With the heavier set-up of 1964 the trigger rate increased to 60 per hour, and the corresponding event rate to 35.

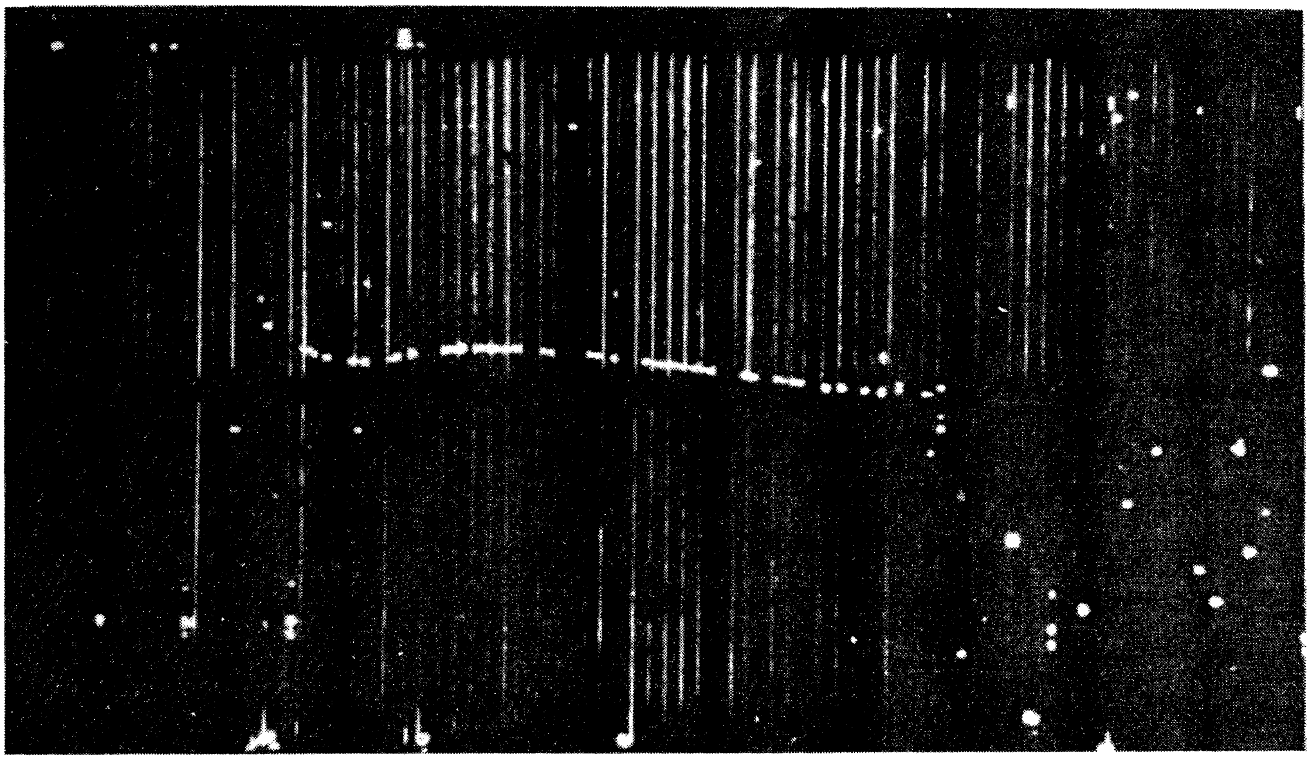

Fig. 2. One of the first examples of elastic muon production photographed in 1963.

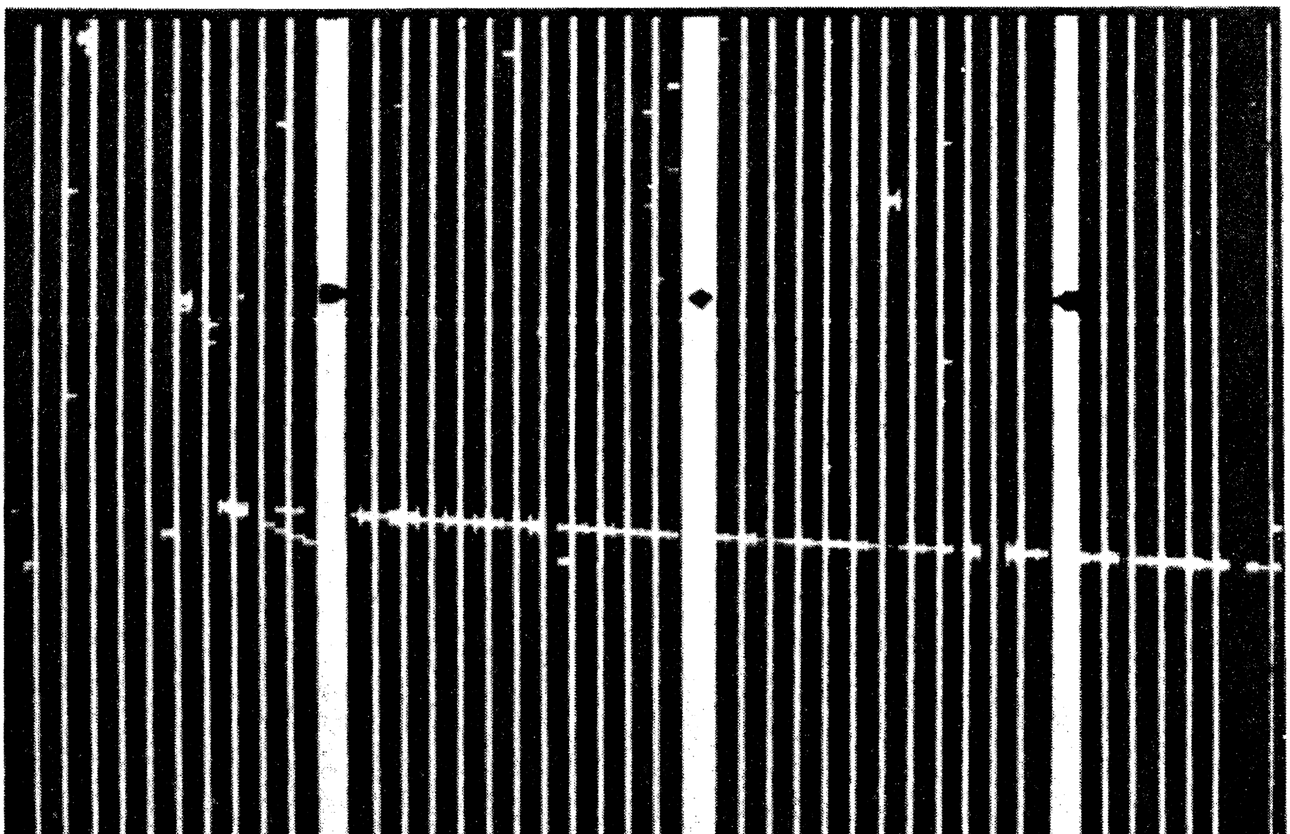

Fig. 3. Elastic ν_μ-reaction photographed with improved optics in 1964.

2. ELASTIC MUON PRODUCTION

2.1. Selection of events. In order to select candidates for the elastic reaction:

$$\nu_\mu + n \rightarrow \mu^- + p \qquad (1)$$

we considered only events initiated in a restricted fiducial volume (50% of the total) of the pure aluminium set-up. Events are called elastic, if they are not accompanied by a visible meson. Correspondingly, the following selection criteria were applied:

1. The event must contain at most 2 tracks and no shower, a track being defined as $\geqslant 4$ sparks in line, a shower as > 4 sparks not in line.

The conditions on the long track were:

2. It must not show an interaction.
3. It must be capable to trigger.
4. Its charge (if measured) must be negative.

The short track (if any) should be compatible with a proton. This is attempted by requiring:

5. The short track must stop.
6. Its range must be shorter or equal to the one inferred from the square of the 4-momentum transfer q^2 of the muon.
7. The multiple scattering must be compatible with the one displayed by a proton.

208 events in 1963, and 143 events in 1964 fulfilled these criteria. One third of them were two-track-events. Examples are given in Figs. 2 and 3.

2.2. Biases and contamination. Biases are imposed by the triggering counters:

(a) The projected range of the muon may be too short to give a coincidence. (b) The angle of the muon is too large to hit the following counter. These losses are not very large. The geometrical detection efficiency, computed on the basis of the Van der Meer spectrum [5] and the Lee — Yang cross section [6, 7] is 88% (for 1963).

There is also a physical effect which could give rise to a loss of elastic events: a recoil proton may produce a pion inside the parent nucleus and thus simulate an inelastic reaction. This effect was estimated to be small ($\leqslant 2.5\%$) and was neglected.

More serious is the contamination by unwanted events. There are three types of them:

(a) Neutron stars. They have been shown to contribute $\leqslant 4\%$ of all our neutrino events [3], and are negligible in our elastic sample.

(b) Elastic antineutrino reactions:

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n. \qquad (2)$$

This contamination is estimated to be 5% in 1963 and 3% in 1964. Lacking information about the charge, in the 1963 experiment elastic antineutrino events could not be removed from the sample. In 1964 it could be done in half of the cases.

(c) Inelastic reactions:

$$\nu_\mu + N \rightarrow \mu^- + N + \text{meson} \qquad (3)$$

where the meson is not seen, for instance because it was re-absorbed inside the parent nucleus. This is the most serious background. Estimates indicated that it may amount to about $(20 \pm \pm 10)\%$ of the selected events.

2.3. Kinematical distributions. One obvious test is to look for coplanarity. Fig. 4 gives the

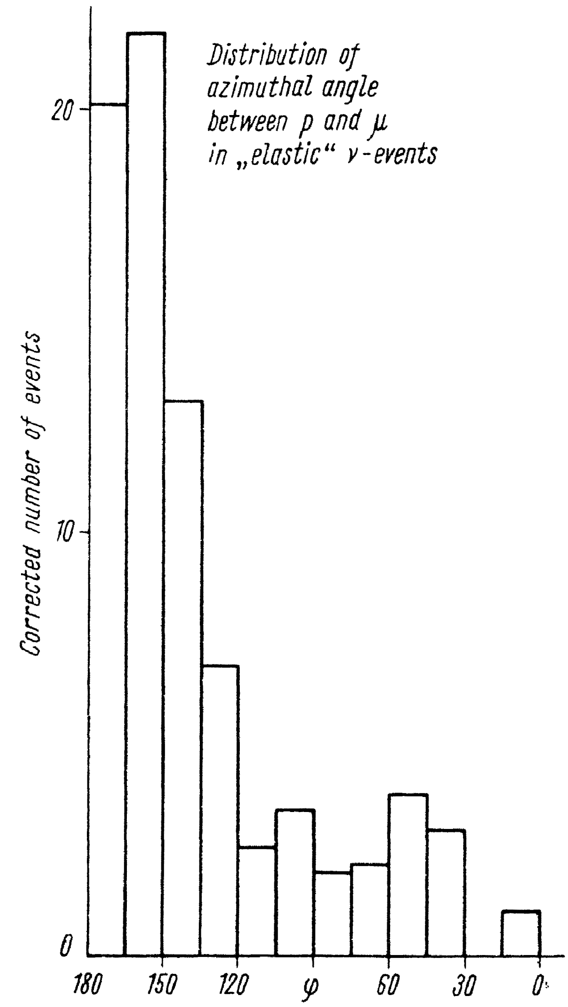

Fig. 4. Distribution of azimuthal angles between long and short tracks (1963 data).

distribution of azimuthal angles between long and short tracks. The peak at 180° indicates that about 50% of the events are coplanar. Besides there is a practically isotropic background. We attribute this mainly to nuclear interaction of the primary proton. The fraction of 50% is in good agreement with theoretical estimates of the escape probability from the parent nucleus [7], and with the observations of the bubble chamber group [9, 10]. Similar conclusions may be drawn from the observed range spectrum of the presumed recoil protons.

2.4. Observed and expected rate. From the 1963 data we obtain, after correction for detection efficiency, a rate for reaction (1) of 0.48 events per ton and CPS — hour (1 CPS — hour = 1200 pulses of 7×10^{11} circulating protons ejected with 90% efficiency). This number has an uncertainty of $\approx$25%, mainly because of the difficulties in monitoring the neutrino beam. The corresponding rate expected from the Lee — Yang cross section [6, 7, 8] and the van der Meer spectrum [5] is 0.34. The factor 1.4 between observed and expected rate agrees with the value of 1.5 found by the bubble chamber group [9]. It indicates that the respective elastic samples have comparable contaminations. The quoted rate corresponds to 50% of all events being elastic.

As it was seen in the preceeding report [9], there is evidence that the excess observed occurs at neutrino energies confined to a narrow band below 0.5 Gev. The reason for this excess is not clear. Perhaps secondary, ternary etc. pions produced not only in target and magnetic horn, but all over the walls of the decay tunnel, give an excess of low energy neutrinos which is not contained in Van der Meer's calculations [5].

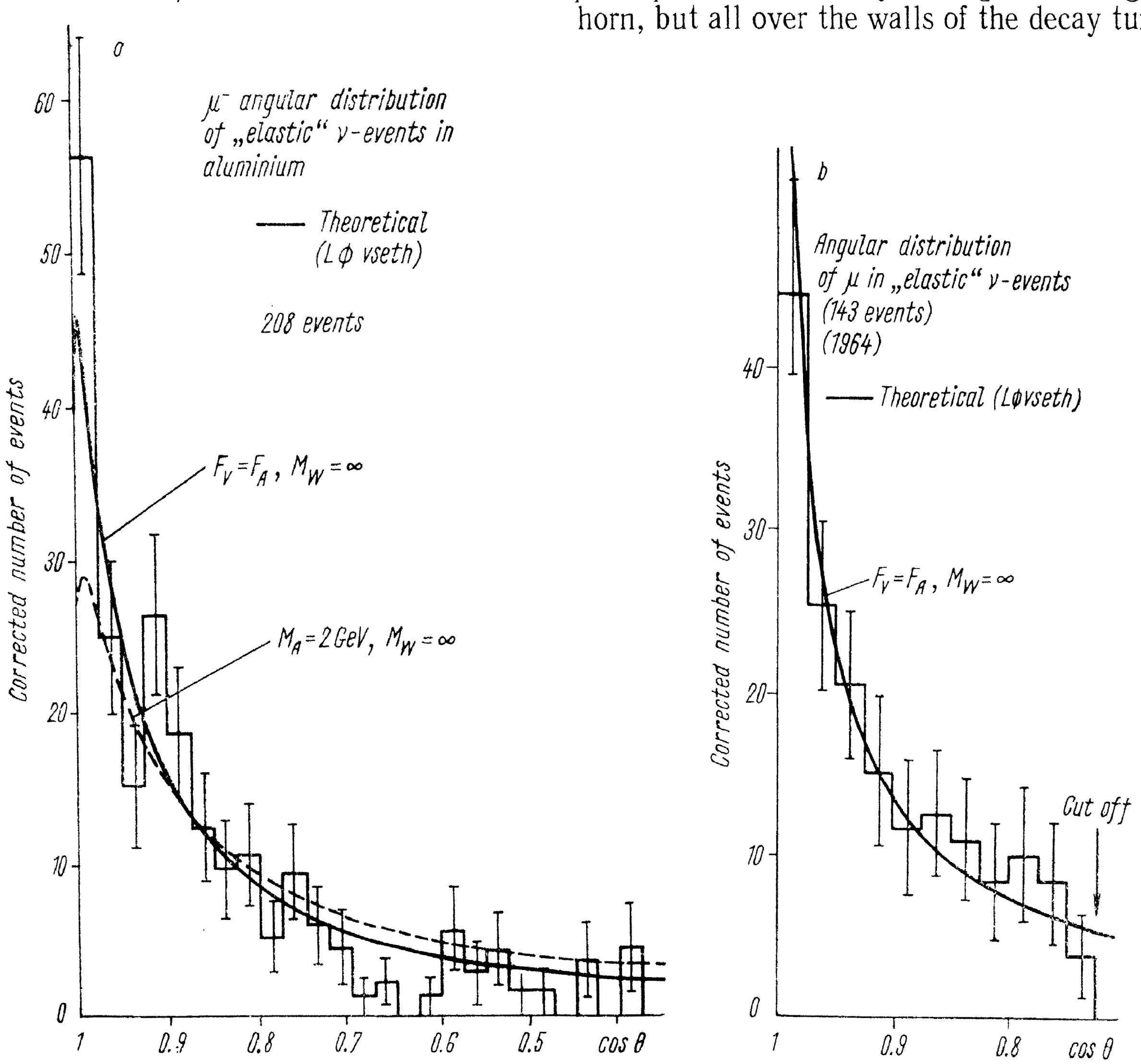

Fig. 5. Angular distribution of elastically produced muons (a : 1963, b : 1964). Theoretical curves from Løvseth [7], under the assumption of infinite W-boson mass, and with two values for the cut-off in the axial vector form factor M_A.

2.5. The muon angular distribution. The cross section [6] used in the rate estimate is characterized by having the axial vector form factor F_A equal to the vector form factors. The fair agreement between expected and observed rate indicates already that this asumption cannot be too wrong. This is confirmed in more detail by the angular distribution of the emitted muon. Because of the different biases involved we give the 1963 and the 1964 data separately (Fig. 5, a and b). The theoretical curves have been computed by Lovseth [7], taking nuclear effects into account. They have been normalized to the number of observed events. The bias due to insufficient projected range is included in the theoretical curves, the correction for angle cut-off was applied to the experimental data. For both samples a point-like current-current interaction with $F_A = F_V$ gives a reasonable fit, $P(\chi^2)$ being $\approx 5\%$.

Writing

$$F_A(q^2) = (1 + q^2/M_A^2)^{-2} \quad (4)$$

$M_A \leqslant 0.5$ or $\geqslant 2$ Gev seems to be incompatible with the data. The conclusion $F_A \approx F_V$, i.e. $M_A \approx M_V = 0.84$ GeV is quite compatible with the bubble chamber results [8, 9].

2.6. Test on «lepton conservation». The magnetic spark chamber used in the 1964 experiment permitted a test on lepton conservation, in sense that $\nu_\mu + n \rightarrow \mu^- + p$ is allowed, but $\nu_\mu + p \rightarrow \mu^+ + n$ is forbidden. A ratio μ^+/μ^- of $6^{+3}_{-4}\%$ was found for elastic muons crossing the magnet. The expected contribution from antineutrinos was $\approx 3\%$. An even better number seems to be obtainable from the charge measurement in 2 thick iron plates at the end of the set-up. A preliminary counting of all transversing particles gave a ratio of positive to negative of $2.5 \pm 1\%$.

3. ELASTIC ELECTRON PRODUCTION

3.1. Selection of events. Candidates for elastic electron production:

$$\nu_e + n \rightarrow e^- + p \quad (5)$$

were selected along the same lines as outlined in the muon case. The conditions imposed there on the long track were replaced by the following conditions on the shower: 1. There must be exactly 1 shower with a minimum energy of 500 MeV. 2. The shower must start right at the apex, i.e. there must be at most 2 empty gaps. The acceptance criteria for accompanying tracks were the same as in the muon case.

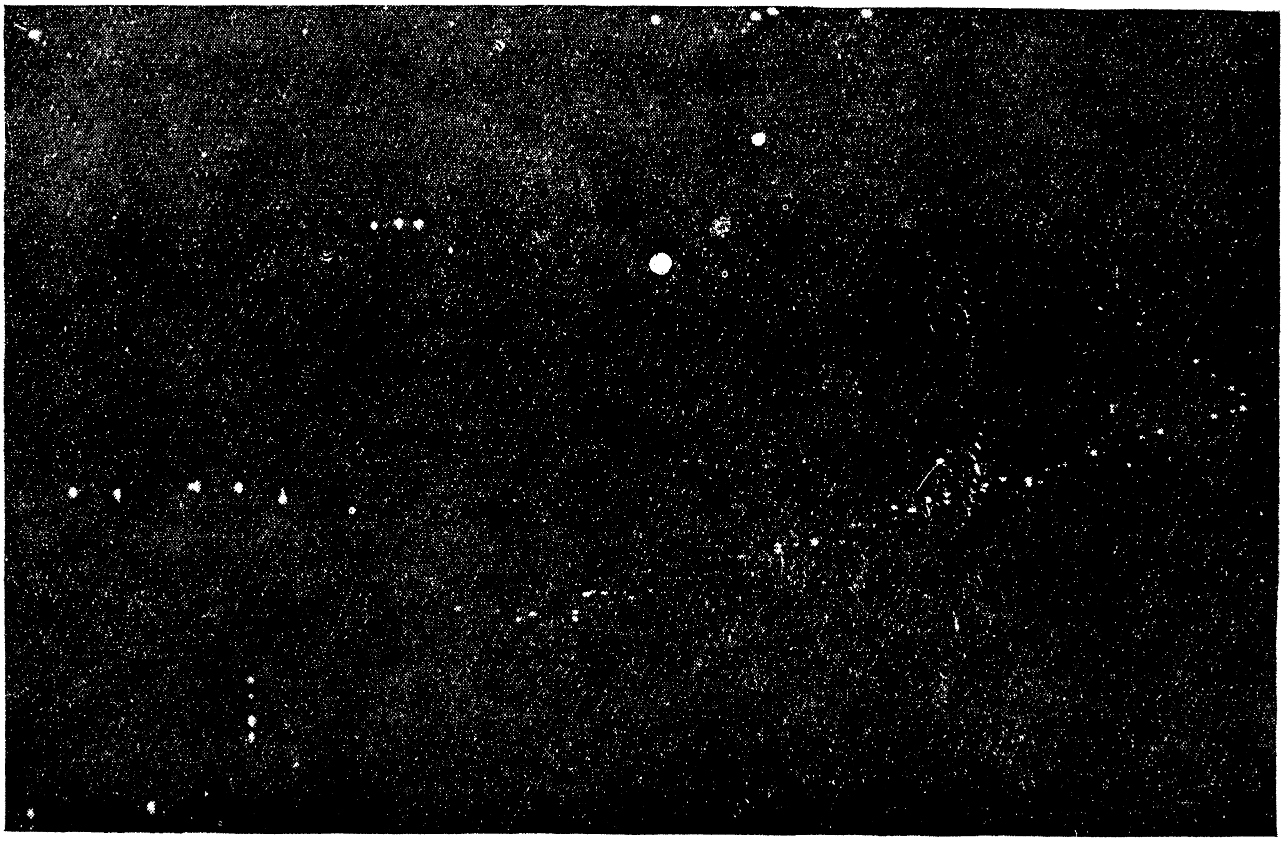

Fig. 6. Example of elastic electron production in the thin-walled aluminium chambers.

Here the whole fiducial volume of the thin-walled chamber was used (=80% of the total volume), including the sections consisting of brass (B) and the aluminium-brass mixture (AB). Out of ≈ 4400 neutrino events seen 39 fulfilled the acceptance criteria. An example of elastic electron production in aluminium (A) is given in Fig. 6.

Despite the lower resolution in the B- and AB-sections of the chamber, we feel that the contamination with inelastic events is not worse than in the muon case. One reason for this is that the electron is now completely measured in almost all cases: The energy can be inferred, with an average accuracy of 30%, from the total number of sparks. The shower axis can be determined in the average to $\pm 2.5°$. Consequently the kinematical test on the range of the accompanying track can be applied to practically all events.

3.2. Observed and expected rates. From the observed 39 events one derives a rate of $(5.7 \pm 1.7) \times 10^{-3}$ per ton and CPS-hour. The stated error was obtained by combining the statistical one with an estimated systematic uncertainty. It is preferable to discuss the rate of elastic electron relative to elastic muon production: since the contamination should be comparable in both cases, the ratio should be a reliable number. The observed value is $\frac{\text{elastic } e}{\text{elastic } \mu} = (1.2 \pm 0.4)\%$.

What one has to expect under the usual assumptions [5, 6] depends upon the relation of the neutrinos from π-decay ($\nu_{\mu\pi}$), $K_{\mu2}$-decay ($\nu_{\mu K}$), K_{e3}-decay (ν_{eK}) to the β-decay-neutrino (ν_e). One calculates taking detection efficiencies into account:

I. $\sim$50% for $\nu_{\mu\pi} = \nu_{\mu K} = \nu_{eK} = \nu_e$ (one-neutrino-hypothesis).

II. 8% for $\nu_{\mu\pi} = \nu_\mu \neq \nu_e$ but $\nu_{\mu K} = \nu_e$ and $\nu_{eK} = \nu_\mu$ (neutrino-flip-hypothesis [10]).

III. 0.7% for $\nu_{\mu\pi} = \nu_{\mu K} = \nu_\mu$ and $\nu_{eK} = \nu_e$ (two neutrinos without ν-flip).

The experimental result confirms the conclusions drawn from the first Brookhaven experiment [11]. It also excludes the extreme neutrino-flip-hypothesis II. Flipping of part of the $K_{\mu2}$-neutrinos (say 10 to 20%) cannot be excluded.

To have observed elastic electron production, at about the rate appropriate for K_{e3}-neutrinos, is significant. Since we have indications that there are somewhat more neutrinos from K-decay than originally thought [4], the agreement of the observed rate with the one predicted by hypothesis III is good.

3.3. Structure effects in the elastic electron reaction. It is interesting to check if what we learn from these few events about the structure of the electron-neutrino-hadron interaction is compatible with what is known about the muon-neutrino interaction. Again, the first indication that this is so, comes from the good agreement of the observed rates with the ones expected under hypothesis III. Furthermore,

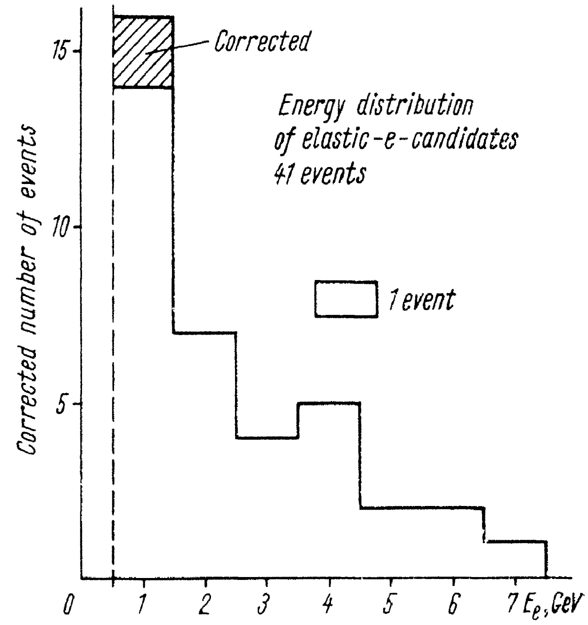

Fig. 7. Energy distribution of elastically produced electrons. (The shaded area gives the correction for detection efficency in brass.)

the energy distribution of elastic electrons (Fig. 7) follows closely the shape of the spectrum computed for neutrinos from K_{e3}-decays.

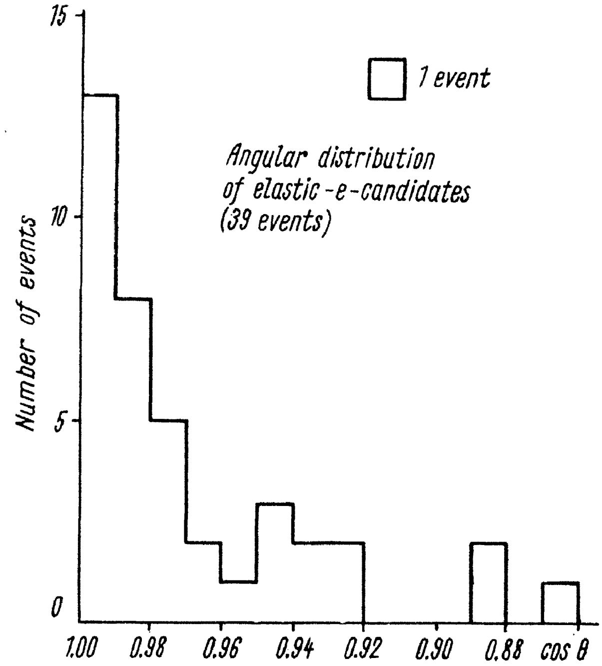

Fig. 8. Angular distribution of elastically produced electrons.

This shows that the cross section in the relevant energy region (1 to 8 GeV) is flat, in agreement with the theoretical prediction [6]. The angular distribution (Fig. 8) is more peaked

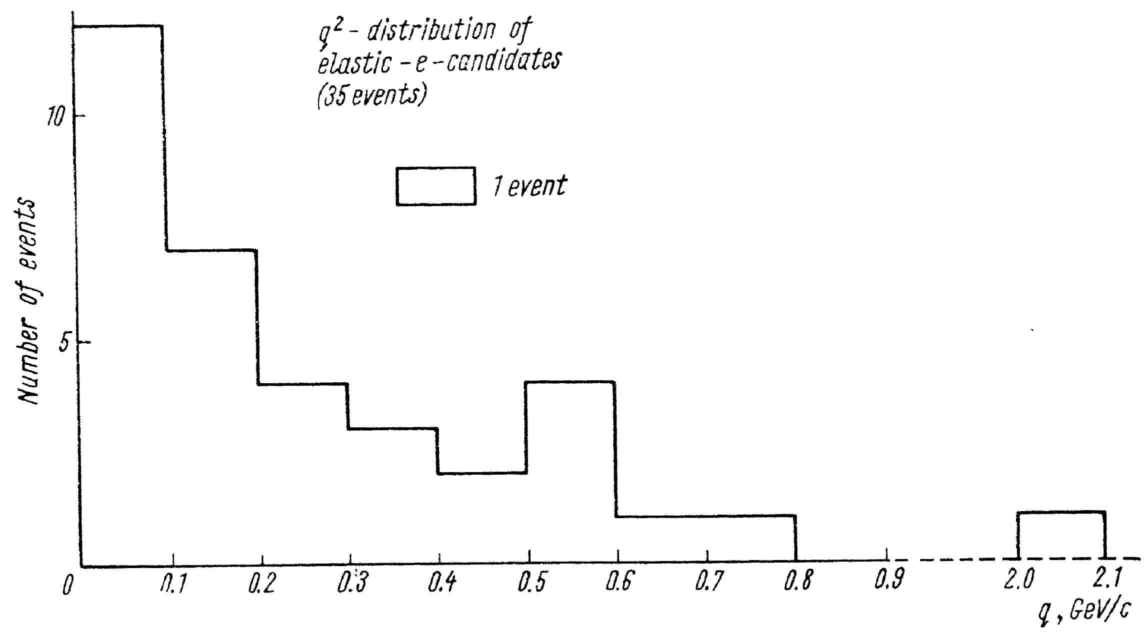

Fig. 9. Tentative q^2-distribution of elastically produced electrons.

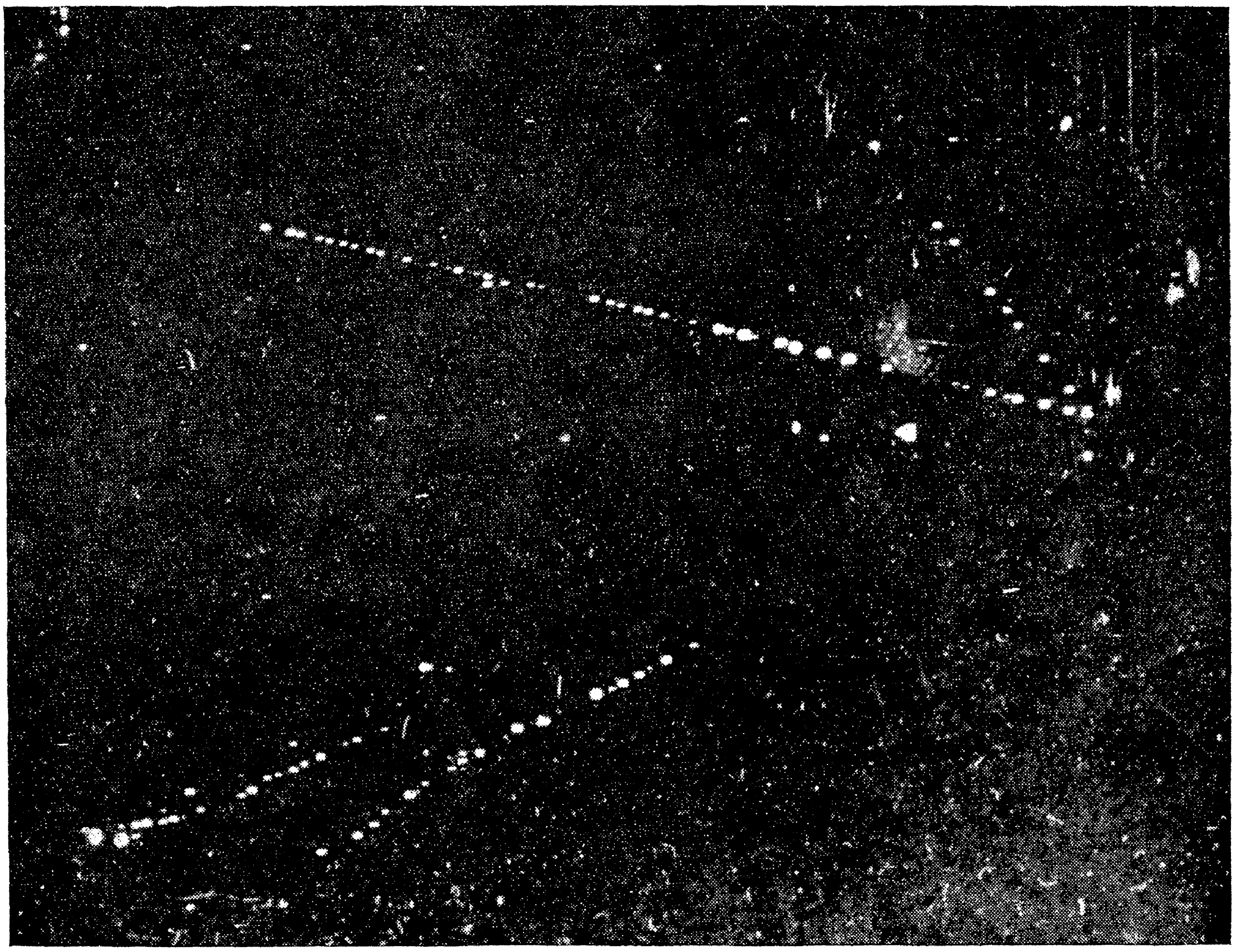

Fig. 10. Single π^0 produced in a ν_μ-reaction.

than the one observed for muons (Fig. 5), as it should be, considering the higher average neutrino energy. Combining energy and angle measurement we arrived at a tentative q^2-distribution (Fig. 9) is similar to the one

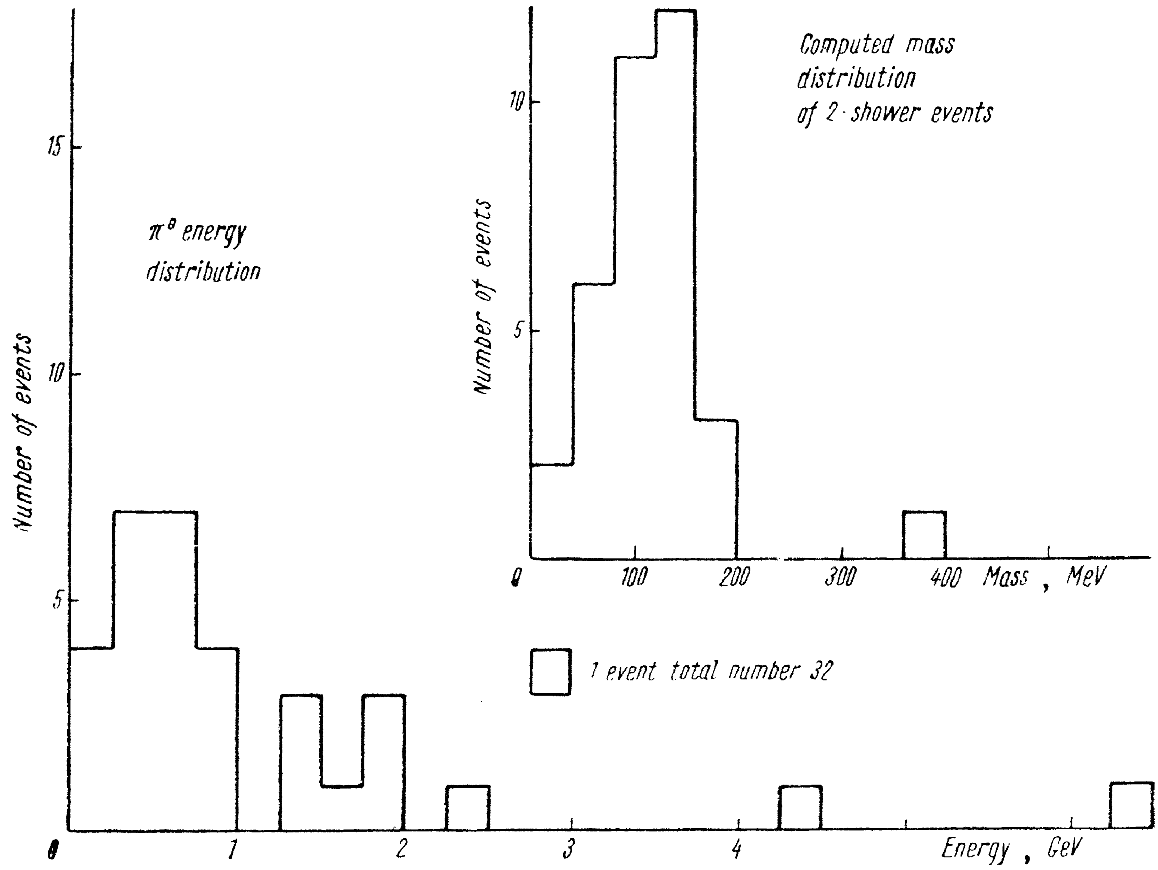

Fig. 11. Distribution of invariant masses of 2γ's and tentative energy distribution of π^0's.

obtained by the bubble chamber group for the muon reaction [8, 9].

A p p e n d i x: A study of single π^0-production in ν-reactions (Work done mainly by A. Böhm)

We also made an attempt to study (in pure aluminium) one particular inelastic reaction, namely

$$\nu_\mu + n \rightarrow \mu^- + p + \pi^0.$$

The practical purpose was to get a better estimate of the background, this reaction gives rise to in the search for (μe)-pairs. One event satisfying the selection criteria is shown in Fig. 10. In the upper part of Fig. 11 we plotted the distribution of invariant masses of the two gammas. We obtain an average value of (130 ± 50) MeV, in agreement with the pion mass and our stated measuring accuraccy. The energy spectrum of π^0's is given in the lower part of the Figure. It shows the pronounced peak at low energies, which may have to do with N^* production. In addition there is a flat tail, extending to quite high energies. The relative frequency of ($\mu\pi^0$)-events with an energy >500 MeV, which could contribute background to our «μe»-sample, is $(3.0 \pm 0.5)\%$ of all neutrino events.

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