ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CALCULATION OF THE NEUTRON-INDUCED BACKGROUND
IN THE GARGAMELLE NEUTRAL CURRENT SEARCH

W.F. Fry and D. Haidt

G E N E V A
1975
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ABSTRACT

A calculation is presented of the neutron-induced background in the Gargamelle heavy-liquid bubble chamber, in connection with the search for neutral currents in neutrino interactions. In particular, the cascade effect of high-energy nucleons has been included. Results of an experiment to verify these cascade calculations are discussed. The conclusion is that the observed neutral current candidates cannot be explained by neutron-induced background.
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1. INTRODUCTION

The search for neutral currents, $\nu N \rightarrow \nu +$ hadrons, in the CERN neutrino experiment with the heavy-liquid bubble chamber Gargamelle led, in early summer 1973, to the result summarized in Table 1:

<table>
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<th>Neutral current candidates</th>
<th>Associated events</th>
<th>Number of pictures</th>
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<tr>
<td>$\nu$</td>
<td>102</td>
<td>15</td>
<td>85,000</td>
</tr>
<tr>
<td>$\bar{\nu}$</td>
<td>64</td>
<td>12</td>
<td>207,000</td>
</tr>
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In order to be sure that a new effect had been observed, all conceivable background sources had to be investigated. This investigation boiled down to the crucial question: Can the observed neutral current candidates be explained by neutron-induced reactions alone? This question has been attacked from two sides by

a) calculating the absolute neutron flux through the chamber;

b) analysing distributions of internal quantities, e.g. the interaction length of the neutral current candidates and their vertex distribution along the chamber.

Results obtained with method (b) have been reported elsewhere. This report is devoted to method (a). The first estimates of the neutron background have been done in 1972. With simplifying assumptions about the set-up, the equilibrium argument has been applied to get the ratio of the number of non-associated neutrons to the number of associated neutrons taking into account the definitions of these two event categories. A more detailed Monte Carlo calculation has been made, in which the actual geometry, the matter distribution around the chamber, and the radial neutrino flux distribution have been simulated. Also assumptions about the angular distribution and the energy distribution of neutrons emitted in neutrino interactions have been made. The critical part of such a calculation is the propagation of the neutrons in the shielding and their detection in the chamber. Therefore the cascade effect of high-energy neutrons had to be included in the neutron background calculation. In a first attempt this problem was circumvented by attributing to the neutrons in the shielding an effective interaction length.

In this report a more elaborate neutron background calculation is presented. The major improvement compared to previous calculations is the treatment of the neutron cascade. This program was designed in such a way as to ensure an easy study of the sensitivity of the neutron flux to all input quantities. Results were ready for the Bonn Conference, demonstrating that the neutron background can make up at most 10% of the observed neutral current candidates. At the end of March 1974, protons of various energies have been sent into Gargamelle, thus allowing a study of the nucleon cascade. These experimental data offered a valuable test of the critical part in the background calculation. First results have been presented at the American Physical Society Meeting in Washington and are included in this report. The good agreement between experiment and calculation justifies a posteriori the correct estimate of the parameters determining the nucleon cascade.
2. **ASSOCIATED AND NON-ASSOCIATED NEUTRONS**

Interactions of neutrons are observed in the chamber as stars consisting of hadrons only. They are associated or non-associated according to whether the neutrino interaction, their source, is observable or not (see Fig. 1).

![Non-associated neutron](image1)

![Associated neutron](image2)

**Fig. 1** Sketch of associated and non-associated neutrons. The shaded area is the non-visible part of the chamber or the shielding.

Non-associated neutron stars can simulate neutral current candidates and are the background studied in this report.

The understanding of associated and non-associated neutrons involves three processes: the creation, the propagation, and the detection of neutrons:

i) The initial process is:

\[ \nu + \text{nucleus} \rightarrow n + \text{anything} .\]

Another possibility is a two-step process:

\[ \nu + \text{nucleus} \rightarrow h + \text{anything} \]

\[ h + \text{nucleus} \rightarrow n + \text{anything} ,\]

where \( n \) stands for neutron and \( h \) for hadron. Two-step processes are only important if the hadron \( h \) is a proton or a neutron, because nucleon interactions proceed with high elasticity. On the contrary, pion interactions (\( h = \pi \)) lead usually to low-energy nucleons and can be neglected.

Neutrinos from the present neutrino experiment are not an efficient source of high-energy nucleons, i.e. nucleons with kinetic energies above 1 GeV (see Section 3). Neutrinos of 5 GeV, for example, transfer an average of 2.5 GeV to the target nucleon. Part of that energy goes into meson production. Thus the outgoing nucleon shares the transferred energy with other hadrons (typically two to three). Only about 10% of the neutrino interactions in this experiment have energies above 5 GeV.
Neither the angular nor the energy spectrum of the neutrons produced by neutrinos are well known. A safe upper limit of the neutron energy spectrum is 10 GeV.

ii) A high-energy neutron propagating through matter generates a cascade. The structure of the cascade is characterized by the particle multiplicity at each generation. The number of generations depends upon the initial energy, the nature of the particles, and the low-energy cut-off. In a cascade program, particles are followed until their energy is degraded to the cut-off energy. If this low-energy cut-off is chosen as low as 10 MeV, the complexity of the cascade calculation is obviously enormous. Under the conditions of the neutrino experiment, neutral current candidates have more than 1 GeV visible energy. This requirement sets 1 GeV for the low-energy cut-off in the cascade calculation. With this high value the cascade calculation is greatly simplified. Indeed, the meson component in the cascade does not regenerate nucleons with more than 1 GeV. So, at each generation, mesons only contribute to the deposited energy. Consequently, the cascade calculation is reduced to the treatment of the nucleon component.

Figures 2 and 3 illustrate two proton-induced cascades with 6.1 GeV initial energy. Both cascades propagate through the whole chamber, which has a length corresponding to 5 nuclear interaction lengths. Figure 2 is of particular interest as it shows a high-energy neutron carrying away most of the initial energy and cascading successively three times.
Fig. 3 Example of a cascade induced by a proton of 6.1 GeV. At all generations the deposited energy is smaller than the energy carried away by the secondary cascade proton.

iii) The neutrons are detected in the fiducial volume of the bubble chamber through their interactions with the nuclei of the liquid. The difference between the primary neutron energy and the energy deposited in the star can be appreciable in cases where a secondary high-energy neutron propagates the cascade out of the visible volume. A small difference between the deposited and the visible energy in the star arises from missing low-energy neutrons, gammas, and non-detectable excitation energy of the nucleus, which may be of the order of 50 to 100 MeV\textsuperscript{16}.

These considerations show that a reliable prediction of the absolute number of both associated and non-associated neutrons is excluded. This would have required a knowledge of the number, energy, and angular distributions for fast neutrons and protons from neutrino interactions for the whole neutrino spectrum. To date these data do not exist in the necessary detail.

Therefore, another approach has been adopted. The ratio B/AS of non-associated to associated neutrons is predicted. The absolute number of background neutrons is then obtained by multiplying the ratio B/AS with the observed number of associated neutrons.

The phenomena regarding creation and detection of fast neutrons are similar to both associated and non-associated events. The ratio B/AS will only weakly depend upon these phenomena. However, the cascade phenomena influence mainly the flux of neutrons entering the chamber. Thus the cascade plays a prominent role in predicting the ratio B/AS.
3. EXPERIMENTAL CONDITIONS

In this section some aspects of the neutrino experiment relevant to this background study are mentioned.

The set-up of the neutrino experiment at CERN is shown in Fig. 4. The bubble chamber Gargamelle is well shielded all around its surface. This dense material protects the chamber against neutrons coming from the outside. But this matter, being exposed to the neutrino beam, acts as a target giving rise to neutrino-induced background.

The 12 m³ chamber is divided into three zones: the fiducial volume (3 m³), the visible volume (7 m³), and the non-visible volume. Only events with their vertices in the fiducial volume have been collected. Neutral current candidates⁴ are events in which all particles are identified hadrons, and the total visible energy exceeds 1 GeV. If in the same frame there are two or more stars, their correlation is attempted. Upstream events are only considered if their visible energy exceeds 150 MeV. Frames with a neutral current candidate and a possible source in the visible volume, but outside the fiducial volume, are rejected. The other events category, the associated events⁴, have been defined as neutrino (or anti-neutrino) interactions signed by at least one muon and an associated star satisfying the criteria of a neutral current candidate.

---

**Fig. 4** Set-up
Next to the matter distribution around the chamber the neutrino flux is an important ingredient. It determines the neutron source density. The curves in Fig. 5 show the radial flux distribution, which varies with the neutrino energy\textsuperscript{12). Furthermore, the observed associated neutrons provide some information about the emission rate, the angular and energy spectrum of neutrons induced by neutrinos. The statistics of associated events is, however, rather limited. In the neutrino experiment the number of associated events was 15 and has now been increased to 40\textsuperscript{9), whereas in the antineutrino experiment only 14 associated events are available.

4. THE NUCLEON CASCADE

The nucleon cascade has been divided into a nucleon component and a meson component. The meson component is inactive, i.e. does not regenerate cascade nucleons\textsuperscript{a). It will be shown in this section that the nucleon component contains at most one cascade nucleon. Then

\textsuperscript{a) Cascade nucleon = fast nucleon = high-energy nucleon = nucleon with kinetic energy above 1 GeV.}
the cascade calculation is reduced to a linear problem. The key quantity in this problem is the elasticity \( \xi \). The quantity \( \xi \) measures the fraction of the initial energy carried away by the outgoing cascade nucleon. The determination of the elasticity curves for primary energies up to 10 GeV will be the main task of this section.

In the range of 1 to 10 GeV primary energy very little is known experimentally about the differential cross-sections of nucleon-nucleus interactions. For that reason, the data available on nucleon-nucleon interactions have been used. The interaction of the nucleon with the nucleus has been derived from multiple nucleon-nucleon interactions assuming a nuclear model.

In the centre-of-mass system the longitudinal momentum distribution of nucleons from the nucleon-nucleon interaction is symmetrical. Nucleons emitted in the backward hemisphere, i.e. \( p_L^* < 0 \), cannot initiate a cascade. Indeed, if transformed into the laboratory system, those nucleons will have kinetic energies below 1 GeV. So only nucleons emitted in the forward hemisphere are capable of propagating the cascade. Their angular distribution is narrow and can be derived from the transverse momentum distribution which is almost independent of the incident nucleon momentum. The angular distribution is of minor importance, since the mean transverse momentum of nucleons emitted in neutrino interactions is larger than that in nucleon-nucleon interactions.

The energy distribution of the nucleons with \( p_L^* > 0 \) has been extracted from several measurements\(^{11}\), in particular from an experiment at 1 GeV \(^{14}\) and 6 GeV \(^{15}\) incident kinetic energy. In the relevant energy range, 1 to 10 GeV, the total nucleon-nucleon cross-section is roughly constant, whereas the ratio of the elastic to the total cross-section decreases from 50\% at 1 GeV to about 25\% at 5 GeV and remains constant above 5 GeV. It is interesting to note in Fig. 6a that the mean fractional energy carried off by the nucleon emitted in the forward hemisphere does not depend very much upon the initial energy, although the shape of the elasticity curves is quite different. At 1 GeV initial (kinetic) energy the inelastic cross-section is dominated by \( \Delta \) production leading to a broad peak with a mean elasticity of 0.6. With increasing primary energy this particular channel decreases and other inelastic channels \( (1\pi, 2\pi, 3\pi \text{ production}) \) smooth the energy distribution more and more.

These elasticity distributions obtained from nucleon-nucleon interactions have been used as input to deduce the elasticity from a nuclear target, i.e. Fe and CF\(_3\)Br. To evaluate the intranuclear cascade the simplest nuclear model in the high-energy approach has been adopted: the nucleus taken as a uniform sphere with radius \( R = R_0 \sqrt{A} \). The parameters \( R_0 \) and the mean free path in the nuclear matter are chosen to match the measured absorption cross-sections as a function of \( A \) \(^{16}\). In freon, CF\(_3\)Br, a nucleon undergoes typically two inelastic collisions. As an example, Fig. 6b shows the elasticity curve of nucleons with 5 GeV incident energy interacting with CF\(_3\)Br. It appears that the mean elasticity decreased from about 0.7 for a nucleon-nucleon process to about 0.5 for a nucleon-nucleus interaction. The shape of the elasticity curve from nuclear interactions is not very sensitive to the initial energy. This is not so surprising, because at lower energies the higher elastic peak feeds into the hole between \( \xi = 0.6 \) and 1, whereas the resonance peak gets broadened and moved to low elasticities. The detailed shape at small elasticities is unimportant, because the energies of those nucleons are near to or below the cut-off energy (1 GeV). Obviously the area under the elasticity curve for low values must be known in order to ensure the right
Fig. 6a  The shapes of the elasticity distributions for nucleons with 1 and 5.7 GeV incident energy interacting with nucleons.

Fig. 6b  Shape of the elasticity distribution for nucleons with 5 GeV incident energy interacting with CF$_3$Br (freon).
normalization. In conclusion, the net effect of the nuclear interactions in the nucleus is the reduction of the mean value of $\xi$ and the insensitivity of the shape of the $\xi$ curve to variations in the incident nucleon energy in the region from 1 to 10 GeV. The size of the quasi-elastic peak and the mean elasticity are believed to the accurate to 10%.

Each nucleon with more than 1 GeV kinetic energy is propagated through the medium according to its mean free path until its energy is degraded to 1 GeV. The mean free path is calculated as follows:

$$\lambda = \frac{1}{n \sigma_t},$$

where $\sigma_t$ is the difference between the total and the diffraction cross-section and n is the number of nuclei per unit volume. Using the data of Ref. 16 the mean free path in the shielding material is $(16.8 \pm 0.5)$ cm and in the bubble chamber liquid $(72 \pm 3)$ cm. To calculate the last figure, $\rho = 1.538 \text{ g/cm}^3$ has been assumed for the density of freon.

In the shielding and in the non-visible part of the chamber it does not matter whether a neutron or a proton propagates the cascade. But in the visible part of the chamber, proton and neutron cascades can be distinguished. Therefore, at each generation of the nucleon cascade a decision is made whether a cascade neutron (resp. proton) remains a neutron (resp. proton) or is turned into a cascade proton (resp. neutron). The charge exchange rate has been assumed to be 40% of the total inelastic cross-section; the energy distribution is assumed to be similar in shape to the $\xi$ curve excluding the quasi-elastic peak.

5. THE CASCADE EFFECT IN THE SHIELDING AND IN THE CHAMBER

In this section the different aspects of the nucleus cascade are summarized.

If there was no cascade effect at all, the background neutrons would originate essentially from a 1\text{ \lambda} thick shielding layer around the chamber. In reality, the neutron flux gets multiplied by a factor depending upon the cascade length. To demonstrate this, an idealized set-up, as shown in Fig. 7, is chosen. Furthermore, the elasticity curve is simplified to a two-step function with $\langle \xi \rangle = 0.67$ (Fig. 8). Nucleons sources are generated uniformly over the shielding. Nucleons emitted with $5 \text{ GeV}$ are propagated through the shielding. They are recorded, if they enter the chamber with $E > 1 \text{ GeV}$. Figure 9 shows the relative contribution of nucleon sources at a given shielding depth (measured in units of one mean free path) to the flux of nucleons entering the chamber as a function of the shielding depth L. The cascade factor measured by the integral of Fig. 9 amounts in this idealized example to 3.5. The

\begin{center}
\textbf{Fig. 7} Idealized set-up  \hspace{1cm} \textbf{Fig. 8} Idealized elasticity curve
\end{center}
cascade leads to an increased neutron flux, but softens also the energy spectrum. Figure 10 displays how the originally monochromatic spectrum is distorted as a function of the shielding depth.

Not all nucleon cascades leaving the shielding simulate neutral current candidates. First of all, it must be a neutron which enters the visible volume. This trivial requirement reduces by about 50% the cascades in the visible volume which have their neutrino source deep in the shielding. In fact, after two or three interactions the cascade is transported with equal probability by a proton or a neutron regardless of whether it was initiated by a proton or a neutron. Another restriction is that the neutron must not interact in the visible volume outside the fiducial volume. This requirement is efficient for those neutrons entering through the side of the cylindrical visible volume.

The mean free path of neutrons in the visible part of the chamber is not simply the inelastic interaction length, but slightly larger. An interaction with a high elasticity remains undetected. It was therefore required (see Section 3) that neutron interactions are only taken into account if at least 150 MeV are visibly deposited (to a proton of 150 MeV corresponds a track length of $= 4$ cm in projection). The mean intervertex distance of neutron interactions satisfying this condition is called the apparent interaction length $\lambda_a$. It is about 10% higher than the inelastic interaction length. The increase is mainly due to the quasi-elastic scattering (see Fig. 6). There is a small energy dependence between 1 and 5 GeV. Above 5 GeV $\lambda_a$ remains constant (cf. Fig. 16).

The energy deposition in a neutron interaction is governed by the elasticity curve. As opposed to the considerations in the shielding, the charge exchange now plays an important role. As a matter of fact, the cascade can be considered terminated if the neutron turns into a high-energy proton. In this case, the incident energy is nearly equal to the deposited energy plus the energy of the proton. In the other case, as mentioned already in Section 2 (iii), the deposited energy accounts for only part of the incident neutron energy.
On the average, the potential path available to a neutron associated with a neutrino interaction amounts to 150 cm. Because this length is not appreciably larger than $\lambda_n$ it is to be expected that the associated events will consist in general of only one star, independent of whether the neutron has high or low energy.
6. **SENSITIVITY OF B/AS TO VARIOUS PARAMETERS**

The input quantities required to the calculation of the ratio B/AS (i.e. the ratio of non-associated to associated neutrons) are the following:

- **Geometry**: distribution of the material around the chamber as displayed in Fig. 4.
- **Neutrino flux**: Figure 5.
- **Nucleon cascade**: Section 4.

- **Energy and angular spectrum of nucleons from neutrino interactions**:
  Information about these spectra comes from the associated events and from high-energy protons\(^{19}\) emitted in neutrino interactions. Due to the low statistics an assumption about the form of the spectra has been made:

\[
\frac{dN}{dE} \sim E^{-n} \quad \frac{dN}{d\Omega} \sim \exp \left( -\theta^2 / 2\theta_0^2 \right)
\]

Agreement with the data is obtained for \( n = 2.4 \pm 0.4 \) and \( \theta_0 = 0.35 \pm 0.05 \).

If these input quantities were taken for granted, B/AS would come out to be 0.6. It remains now to be investigated to what extent B/AS is sensitive to variations of the input quantities. In this study the geometry of the set-up and the neutrino flux are considered to be well known and are not subject to variations.

6.1 **Angular distribution**

Using the cascade parameters as determined in Section 4 and fixing the energy distribution to a monochromatic spectrum of energy 5 GeV, the parameter \( \theta_0 \) in the angular distribution is varied from 0 to 500 mrad. The mean angle characterizing the angular spectrum is varied over a much larger range than would be expected in order to illustrate the sensitivity of the ratio B/AS to the variation of \( \theta_0 \). The result is shown in Fig. 11. The general trends are quite obvious: sources in front of the chamber are most efficient for narrow angular distributions (small \( \theta_0 \)), as opposed to the sources at the side of the chamber which are prevailing for broad angular distributions (large \( \theta_0 \)). It appears that the total number of background events (B) varies little with \( \theta_0 \). The number of associated events (AS) decreases with increasing \( \theta_0 \), because the available path length to detect the neutrons gets more and more reduced.

Genuine neutral current events should be distributed uniformly along the chamber assuming uniform detection efficiency. Could not neutron-induced background events reveal their nature by a spatial distribution with a characteristic fall-off at the beginning of the chamber? The answer to this question is closely related to the angular distribution of fast nucleons in neutrino reactions. Neutrons entering at the front produce indeed an exponential fall-off along the neutrino beam axis. This can be seen in Fig. 12. But neutrons entering through the side produce a flat distribution, just as neutral current events would do. In reality, the detection efficiency along the chamber is not uniform. For that reason, the spatial distribution can only give a hint to the nature of the neutral current candidates, if the angular distribution is sufficiently narrow, i.e. \( \theta_0 \lesssim 300 \) mrad.
Fig. 11  Number of associated (AS) and non-associated (3) neutrons versus mean angle $\theta_0$ for fixed energy spectrum. The dashed lines indicate the front and the side contributions to the non-associated neutrons.

Fig. 12  Distribution of the vertices of non-associated neutrons along the chamber (neutrino beam direction). Uniform detection efficiency is assumed. The dashed curves indicate the front and the side contributions.
6.2 Energy distribution

Using the cascade parameters as determined in Section 4 and a fixed angular distribution, \( \theta_0 = 300 \text{ mrad} \), the number of associated and non-associated neutrons are determined for monochromatic sources of various energies and displayed in Fig. 13. The fall-off near 1 GeV reflects the energy cut-off (cf. Section 3). The number of associated neutrons (AS) saturates with increasing energy. On the contrary, the number of non-associated neutrons (B) increases steadily with increasing source energy, because deeper and deeper layers of the shielding can contribute to the neutron background (cf. Section 5). In conclusion, the ratio B/AS is a rapidly increasing function with increasing energy assuming monochromatic source spectra.

In reality, the neutron source spectrum is not monochromatic, but falls off rapidly towards high energies reflecting the energy dependence of the neutrino spectrum. A reasonable assumption would be a power law \( E^n \) with \( n \approx 2.5 \). A variation of \( \pm 0.5 \) in \( n \) would induce only a variation of \( \pm 0.05 \) in B/AS.

6.3 Shape of the elasticity curve

Keeping fixed the angular distribution by choosing the free parameter \( \theta_0 = 350 \text{ mrad} \) and the energy distribution by choosing a monochromatic spectrum with the extreme energy 10 GeV, the sensitivity of the number of associated and non-associated neutrons to elasticity curves of three different shapes (see Fig. 14) is studied.

The mean elasticity (\( \xi \)) covers the wide range from 0.45 to 0.65. Figure 15 shows that the ratio B/AS changes over that range by a factor of 2, namely from 0.75 to 1.5. The increase is essentially due to the increasing cascade length.
The elasticity curves derived in Section 4 have a mean value of about 0.5. Allowing for a variation of 0.05 would result in an uncertainty of 20% in the ratio B/AS.

6.4 Charge exchange

The fact that the carrier of the nucleon cascade may be a neutron as well as a proton implies the ratio B/AS to depend weakly upon the probability $\beta$ that, in neutrino interactions
which produce cascade nucleons, this nucleon is a neutron. Values of \( \beta \) near to 0 or 1 are excluded, because the cascade nucleon emerges from a nucleus. Although the number of associated events changes almost linearly with \( \beta \), the ratio \( B/AS \) varies by less than 20%, if both \( \beta \) is varied between 0.3 and 0.7 and the charge exchange rate is varied between 0.2 and 0.6.

7. TESTS OF THE CASCADE CALCULATION

Although the basic concepts in predicting \( B/AS \) are simple, it was desirable to check them with experimental facts. To this purpose Gargamelle, filled with freon, was exposed at the end of March 1974 to protons of 4, 7, 12, and 19 GeV/c momentum. About 800 proton-induced cascades have been analysed in the five interaction lengths long detector\(^{20} \). Two examples are shown in Figs. 2 and 3.

The simplest quantity to measure is the apparent interaction length \( \lambda_a \) introduced in Section 5. It is by definition the mean distance to the first interaction in which the proton deposits more than 150 MeV. The measured values agree well with the calculation (Fig. 16). These measurements test the elasticity curve near to \( \xi = 1 \). The calculated curve increases below 4 GeV/c proton momentum owing to the increasing elastic nucleon-nucleon cross-section. The accuracy of the calculation amounts to 5%, where the main contribution comes from the uncertainty in the inelastic interaction length in freon. There exists also a measurement of \( \lambda_a \) obtained with neutrons (see in Ref. 2, the paper by F.J. Hasert et al.), which is compatible with the data shown in Fig. 16.

In order to check the elasticity curve also at values of \( \xi < 1 \) the cascade length \( \lambda_c \) has been measured and predicted simulating the experimental conditions. Owing to the big extension of Gargamelle in beam direction the development of the whole cascade can be observed.

![Diagram showing \( \lambda_a \) versus momentum](image)

**Fig. 16** The measured and calculated apparent interaction length in freon versus proton momentum.
in most cases. The cascade length $\lambda_c$ is by definition the mean distance to the last observable interaction of a cascade proton depositing more than 1 GeV. Invoking charge symmetry $\lambda_c$ measures the average range of neutrons simulating neutral current candidates. It should be noted that $\lambda_c$ and $\lambda_{\text{eff}}$, as defined in Ref. 2, are quite different quantities. Figure 17 shows the measurements together with the prediction. The accuracy of the calculated cascade length depends upon the charge exchange rate and the shape of the elasticity curves. The charge exchange rate has also been measured at all four momenta by counting in how many cases the proton-induced cascade is prolonged by a cascade neutron instead of a cascade proton. The result is $(41 \pm 3)\%$; there is no indication of an energy dependence between 4 and 19 GeV/c. Allowing for an uncertainty of 0.05 in the mean elasticity the predicted cascade length $\lambda_c$ varies by 8\%.

In conclusion, the parameters determining the nucleon cascade have been estimated realistically.
8. CONCLUSION

After all these considerations, an answer to the fundamental question, whether the observed neutral current candidates are due to non-associated neutrons, can now be given. The determination of the absolute number of background neutrons involves the calculated ratio B/AS and the observed number of associated events (AS).

i) B/AS: Choosing the input quantities as follows:
- Cascade : Elasticity curves as derived in Section 4
- Source spectra: dN \sim \exp (-\theta^2/2\sigma^2_0) d\theta \quad \theta_0 = 0.35 \pm 0.05
  \quad dN \sim E^{-n} dE \quad n = 2.4 \pm 0.4,

the ratio of non-associated neutrons to associated neutrons is: B/AS = 0.6 \pm 0.3.

The reliability of the calculation of B/AS has been checked by comparison with experimental data (Section 7). The fact that the cascade parameters are so tightly bound implies B/AS < 1 even for unrealistic assumptions about the angular and energy spectra of high-energy neutrons produced in neutrino and antineutrino interactions. This is well demonstrated by Figs. 11 and 13.

ii) AS: The number of associated events per film (one film consists of 750 pictures) is, according to Table 1, 15/111 = 0.135 \pm 0.037. In order to exclude a big statistical fluctuation the number of associated events has been increased substantially:

\[
\frac{AS}{\text{film}} = \frac{40}{277} = 0.144 \pm 0.025.
\]

In conclusion, the number of associated events per film remained unchanged.

Combining the observed number of associated events, 15 in the neutrino experiment and 12 in the antineutrino experiment (cf. Table 1), with the ratio B/AS the absolute number of background neutrons amounts to:

9 \pm 5 (\nu) \quad \text{and} \quad 7 \pm 4 (\bar{\nu}) .

These figures have to be compared with 102 (\nu) and 64 (\bar{\nu}), the number of neutral current candidates in the neutrino and antineutrino experiments. Conclusion: The observed neutral current candidates cannot be explained by non-associated neutrons.

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