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SCALING VARIABLE DISTRIBUTIONS FOR ANTINEUTRINO-NUCLEON SCATTERING IN THE 15-FT BUBBLE CHAMBER AT FERMILAB*

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ABSTRACT

This paper continues the discussion of high energy (10-200 GeV) antineutrino interactions with nucleons in the hydrogen-neon filled 15-ft bubble chamber. The earlier paper at this meeting presented by V. Kolganov discussed the limit in this experiment for the reaction $\bar{\nu} + N \rightarrow \mu^+ e^- X$. Herein we present the Bjorken scaling variable distributions y and x. The y distributions are fitted with a parameter B which in the quark-parton model is related to the relative antiquark content in the nucleons. The antiquark content is determined to be (10 ± 3)% and shows no antineutrino energy dependence. A comparison is made of fitted B values for this experiment and other antineutrino experiments discussed at this meeting. The x distributions for x > 0.2 are consistent in shape with the structure functions extracted from e-d scattering data.

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INTRODUCTION

In this paper we investigate the behavior of antineutrino interactions with nucleons at high energies with the goal of trying to better understand the constituent nature of the nucleons. The antineutrino-nucleon scattering process

$$\bar{\nu}_\mu + N \to \mu^+ + \text{hadrons}$$

is investigated using the Bjorken scaling variables $x = Q^2/2m\nu$ and $y = \nu/E$ where ν and Q^2 are the energy and momentum transfer between the leptons and the hadrons, E is the antineutrino energy and m is the nucleon mass. In particular, within the framework of the quark-parton model, the antiquark contribution in the antineutrino interactions can be determined by investigating the behavior at high y ($y \simeq 1$).

Previous neutrino experiments have suffered from muon acceptance losses and systematic uncertainties in the selection of the muon at large y values. Even so an anomaly in the antineutrino y-distribution has been reported[1] in a counter neutrino experiment. The present bubble chamber experiment with good muon acceptance and good muon identification is an important test of the reported anomaly using an independent technique.

EXPERIMENTAL CONFIGURATION

This experiment utilized the 15-ft bubble chamber filled with a hydrogen-neon mixture exposed to the horn focussed antineutrino beam. The External Muon Identifier[2] (EMI) provided the muon identification.

The bubble chamber filled with a 21% atomic neon-hydrogen mixture had a radiaiton length of 110 cm. Approximately 52,000 pictures were taken using the "hadron camera triad" during the May 1975 bubble chamber run. The relative quality of the film with respect to parasitic boiling, track quality, and magnitude of background muon and hadron tracks was bad.

The antineutrino flux was produced by 300 GeV protons striking the Al target of the two horn system[3] which focussed negative particles and defocussed positive particles. The primary proton beam had an average intensity of 8.5×10^{12} ppp and had a duration of 20 μsec (single turn extraction). The good focussing time of the horn system and the beam width were optimally matched during this run. To suppress even more the neutrino background in the antineutrino beam a "absorptive plug" was placed downstream of the first horn to remove the wrong sign mesons from the beam. Figure 1 shows the relative importance of the "absorptive plug" in reducing the neutrino background.

The EMI has been extensively described in presentations at this meeting by M. Peters[4] and V. Stenger[5]. I refer the reader to those talks for the EMI description. Later I will discuss how we use the EMI information in the data analysis.

Because of the geographical scale of this collaboration and our desire for a speedy result the bubble chamber film distribution received special attention. The entire quantity of film was copied using the direct reversal technique[6]. There are no identified differences in measurements from the original or copied film. Each nation received 50% original film and 50% copied film but was responsible for scanning and measuring only the original film. The copied film was used for cross checking.

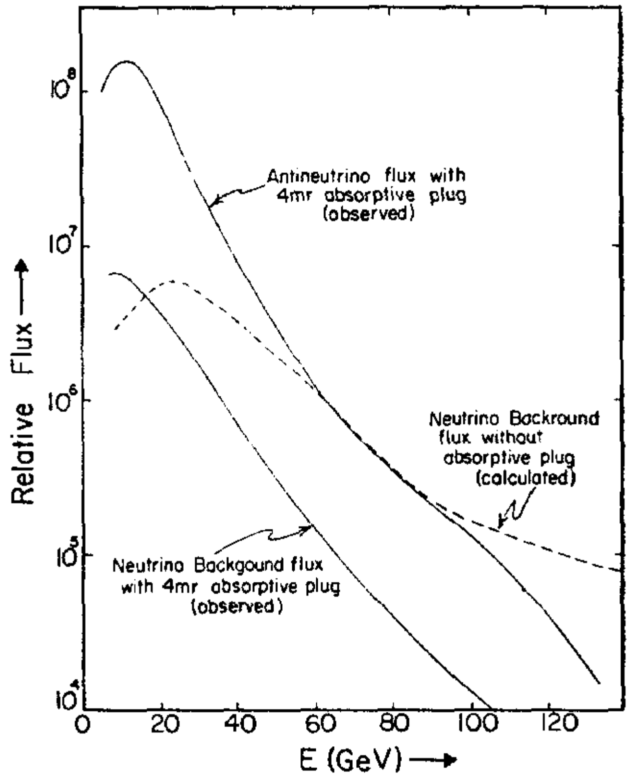


Figure 1: Relative neutrino background flux with and without use of 4mr absorptive plug compared with the antineutrino flux.

DATA ANALYSIS

<u>Event Scan Selection</u>: The film was scanned for all events with a total momentum, (charged plus neutral), ΣP_x, along the neutrino beam direction greater than ~1 GeV within the visible volume (~27m^3) of the bubble chamber. Events consisting of a single charged track only were not sought. Therefore the elastic events $\bar{\nu} + p \rightarrow \mu^+ + n$ were not detected but those with observed V^o were recorded. About 2500 neutral candidates were found in the scan. Each of the four groups was responsible for scanning and

measuring 25% of the total data. The Hydra Geometry program[7] was used for geometrical reconstruction.

Muon Selection: The EMI is used to identify the muon tracks. After the event is measured in the bubble chamber all tracks which could be muons are extrapolated to the EMI. From the extrapolated position in the EMI, the multiple scattering circle (the tracks penetrate about ~600 g/cm^2 of absorber between the fiducial volume and the EMI) and the position of the nearest actual recorded hit in the EMI, the confidence levels C_H of the track being a hadron and C_μ of the track being a muon are calculated. The track is taken as an identified muon if it has $C_H <$ 10% and $C_\mu > 4\%$.

Antineutrino Energy Determination: In the charged current events the antineutrino energy is the sum of the momenta in the neutrino direction of the muon, charged hadrons and neutral hadrons. For antineutrino interactions on the average only ~20% of the total energy goes into hadrons ($\langle y \rangle \sim 0.2$) and only about one-third of that into neutral hadrons. In this experiment a large fraction of the neutral energy is undetected. The following is a procedure to correct the antineutrino energy for the energy missing in neutrals.

Assume that on the average the neutral hadrons in the hadron shower are symmetrically distributed around the mean charged hadron direction. Then for a sample of events, with a certain average fraction of the hadronic shower momentum undetected, on the average the same fraction of longitudinal momentum, P_L^H, and transverse momentum, P_T^H will be undetected. Due to Fermi motion and undetected nuclear fragments we do not expect transverse momentum balance in individual events. However for a sample of events if there were no missing neutrals the mean transverse momentum of the muon $< P_T^{\mu} >$, and hadrons $< P_T^{H} >$ should balance in the antineutrino-muon plane. Therefore the mean transverse imbalance in the neutrino-muon plane is used to correct for the hadronic missing longitudinal momentum.

We calculate the corrected antineutrino energy as follows. The uncorrected energy transfer between the leptons and hadrons ν_u from the visible energy deposited in the detector is given by

$$\nu_u = P_L^{\mu} + \Sigma\ P_L^{H} - E^{\mu}$$

where P_L^{μ} and P_L^{H} are the longitudinal momentum of the muon and hadrons and E^{μ} is the muon energy.

For fixed intervals of ν_u calculate $\left\langle \frac{P_T^H}{P_T^{\mu}} \right\rangle$ in the antineutrino-muon plane and $< \nu_u >$. The mean corrected energy transfer ν_c for each interval is given by

$$< \nu_c > = \frac{< \nu_u >}{\left\langle \frac{P_T^H}{P_T^{\mu}} \right\rangle}$$

The mean corrected energy transfer for intervals of the mean uncorrected energy transfer is given in Fig. 2. The distribution is well fitted by the correction formula $\nu_c = 1.2(\nu_u + 1.0)$.

All events are corrected for missing hadronic energy using the correction formula. We see the correction involves a 20% scaling plus an additive 1.2 GeV which could account for unseen nuclear recoil and spallation nucleons. The antineutrino energy is then the sum of the muon energy and the corrected hadronic energy.

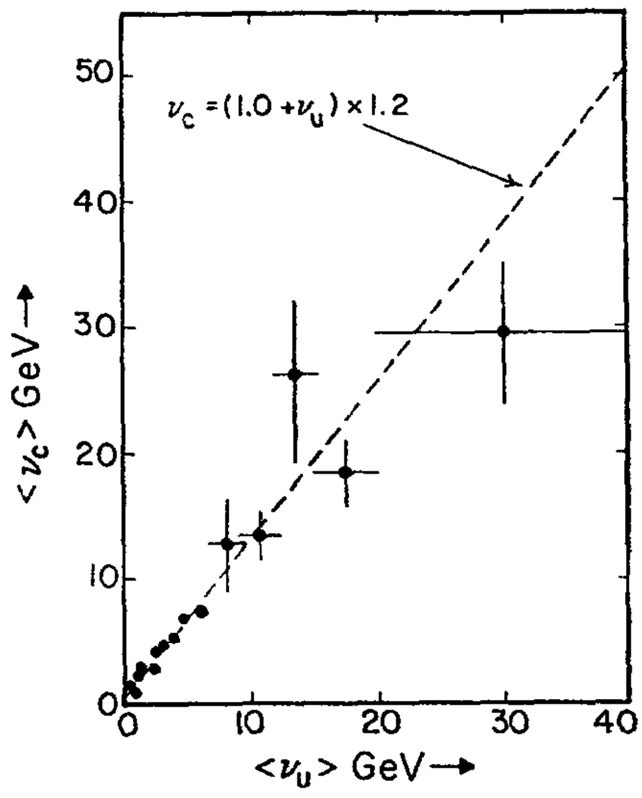


Figure 2: Correction for missing hadronic energy.

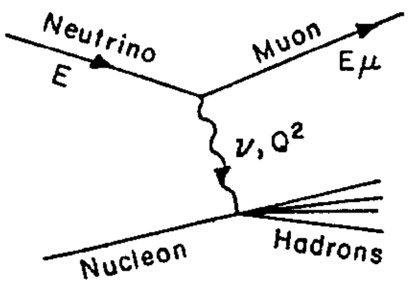
Data Cuts: To produce a clean antineutrino data set with well determined parameters the following cuts were applied:

1. Identify μ^+: one positive track must be identified by the EMI as a muon, i.e., $C_H < 0.10$ and $C_\mu > 0.04$.
2. Cut neutral background (n, K^o, etc.): Previous studies[8] show that most of the neutron, K^o, and other neutral background has an energy of less than 10 GeV. Therefore we require $E_c > 10$ GeV.
3. Well measured events: Require the event be greater than 65 cm. from the downstream wall of the chamber to allow adequate measurement length for the tracks.

4. Good EMI Efficiency: For good EMI acceptance and to reduce hadron background we requre that the muon candidate have a momentum greater than 4 GeV.

5. Good resolution of ν_c: Events with ν_u < 1 GeV are cut from the sample (1) because of the large fractional correction for missing hadron energy[9] and (2) because the small ν region is biased from the scanning loss of elastic events.

THEORETICAL GUIDE



Consider the antineutrino-nucleon interaction as shown where the neutrino and muon energies are E and E_μ and the virtual boson propagator carries the energy $\nu = E - E_\mu$ and four momentum $Q^2 = 4EE_\mu \sin^2 \frac{\theta\mu\nu}{2}$. The scaling variables are defined as $x = Q^2/2m\nu$ and $y = \nu/E$. In the scaling region the cross section for "neutrino" - nucleon scattering is of the form

$$\frac{d\sigma^{\nu,\bar{\nu}}}{dxdy} = \frac{G^2 ME}{\pi} \left[F_2(x)\ (1-y) + 2xF_1(x)\frac{y^2}{2} \mp xF_3(x)y(1 - \frac{y}{2})\right]$$

where F_1, F_2 and F_3 are the hadronic structure functions. Assuming charge symmetry invariance and the Callan-Gross relation ($F_2(x) = 2\ x\ F_1(x)$) the cross section can be written:

$$\frac{d\sigma^{\nu}}{dxdy} = \frac{G^2ME}{\pi}\left[q(x) + \bar{q}(x)\ (1 - y)^2\right] \quad (1)$$

$$\frac{d\sigma^{\bar{\nu}}}{dxdy} = \frac{G^2ME}{\pi}\left[q(x)\ (1 - y)^2 + \bar{q}(x)\right] \quad (2)$$

with $q(x) = \frac{1}{2}\left[F_2(x) - xF_3(x)\right]$ and $\bar{q}(x) = \frac{1}{2}\left[F_2(x) + xF_3(x)\right]$.

Within the quark-parton model $q(x)$ and $\bar{q}(x)$ are interpreted as the probabilities of the quark and antiquark being involved in the interaction and carrying the momentum fraction x. The relative momentum fraction of the nucleon carried by the antiquarks is expressed in the jargon of this subject by

$$B(x) = \frac{xF_3(x)}{F_2(x)} = 1 - \frac{2\ \bar{q}(x)}{q(x) + \bar{q}(x)}\ .$$

Re-expressing equations 1 and 2 in terms of B and integrating over x gives

$$\frac{d\sigma^{\nu}}{dy} = \frac{G^2ME}{\pi}\int F_2(x)dx\left[\left(1 - y + \frac{y^2}{2}\right) + BY\left(1 - \frac{y}{2}\right)\right] \quad (3)$$

$$\frac{d\sigma^{\bar{\nu}}}{dy} = \frac{G^2ME}{\pi}\int F_2(x)dx\left[\left(1 - y + \frac{y^2}{2}\right) - BY\left(1 - \frac{y}{2}\right)\right] \quad (4)$$

As seen from equations 1 and 2 if the antiquark contribution to the interaction is negligable then the neutrino y-distribution will be constant and the antineutrino y-distribution will be $(1 - y)^2$. A sensitive determination of B comes from the antineutrino y-distribution in the high-y region which is dominated by the antiquark contribution. We also expect the relative antiquark contribution to effect primarily the low x region ($x \lesssim 0.2$) because of the rapidly decreasing ratio of $xF_3(x)/F_2(x)$ for small x.[10]

EXPERIMENTAL DATA

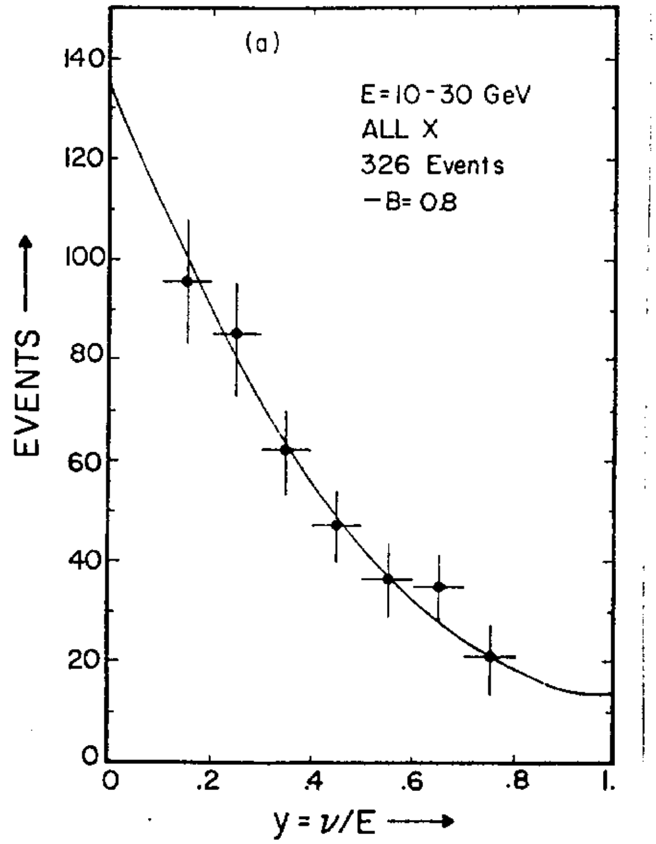
y-Distributions: Applying the data cuts to the antineutrino candidates produced 493 charged current antineutrino events between 10 GeV and 200 GeV. The y-distribution for these events has been corrected for the EMI geometrical efficiency which was calculated using the events themselves. The EMI geometrical efficiency as a function of x and y is given in Table I.

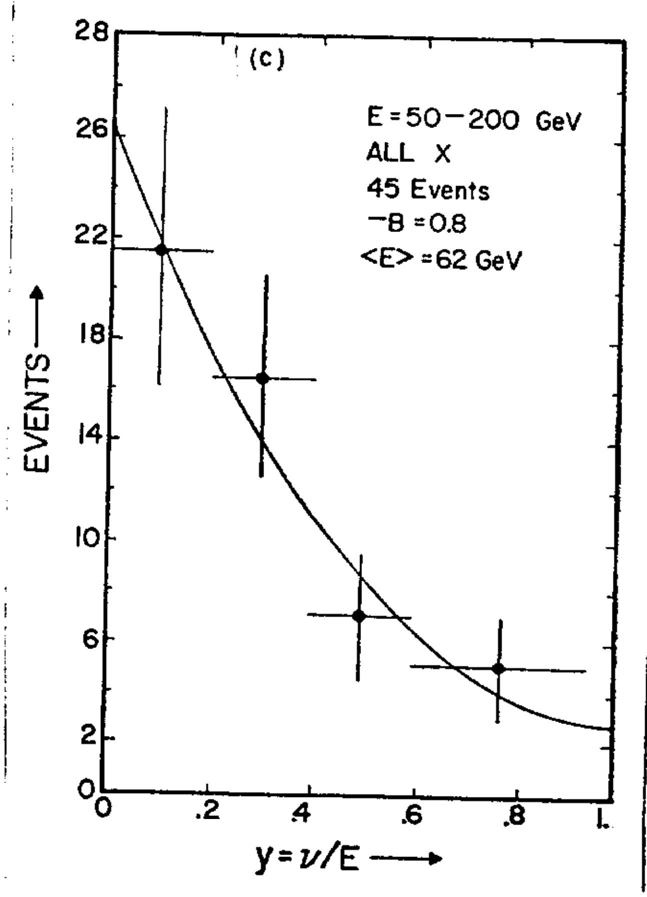
TABLE I

EMI Geometrical Acceptance Variation with x and y for Mean Antineutrino Energy of 20 GeV

y \ x	0-.2	.2-.4	.4-.6	.6-.8	.8-1.0
0- .2	.98	1.0	.95	.94	.96
.2- .4	.94	.99	.93	.88	.96
.4- .6	.93	.94	.93	.81	.80
.6- .8	.96	.96	.79	.75	.73
.8-1.0	.43	.36	.25	.21	.19

The y-distribution for all events between 10 GeV and 200 GeV with $0.0 < x < 1.0$ is inconsistent with a pure $(1 - y)^2$ distribution. A maximum likelihood fit gives $B = 0.79 \pm 0.06$. The y-distributions for $0.0 < x < 1.0$ and the different antineutrino





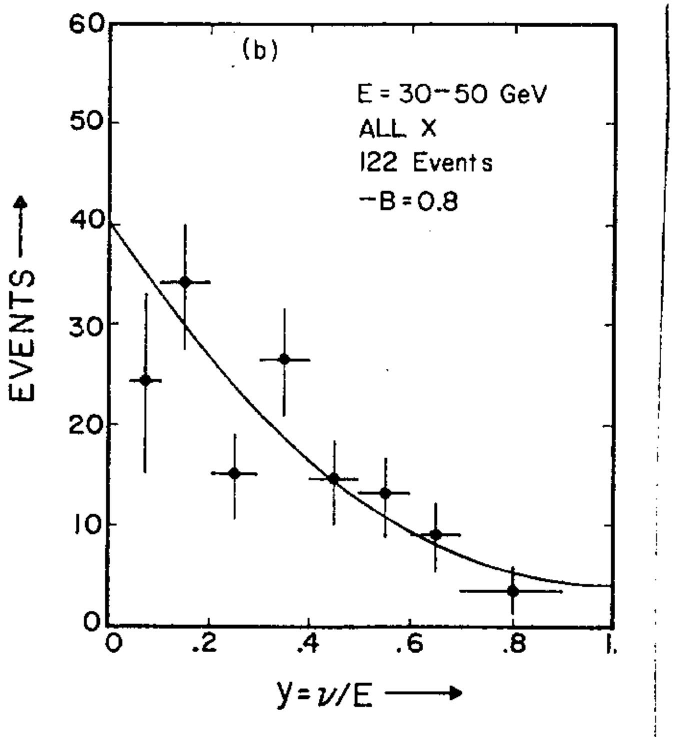


Figure 3: Antineutrino y-distributions for events with $0 < x < 1.0$ in the antineutrino energy intervals:

(a) $10<E<30$ GeV

(b) $30<E<50$ GeV

(c) $50<E<200$ GeV

The solid line is from Eq.4 normalized to the data and with B = 0.8.

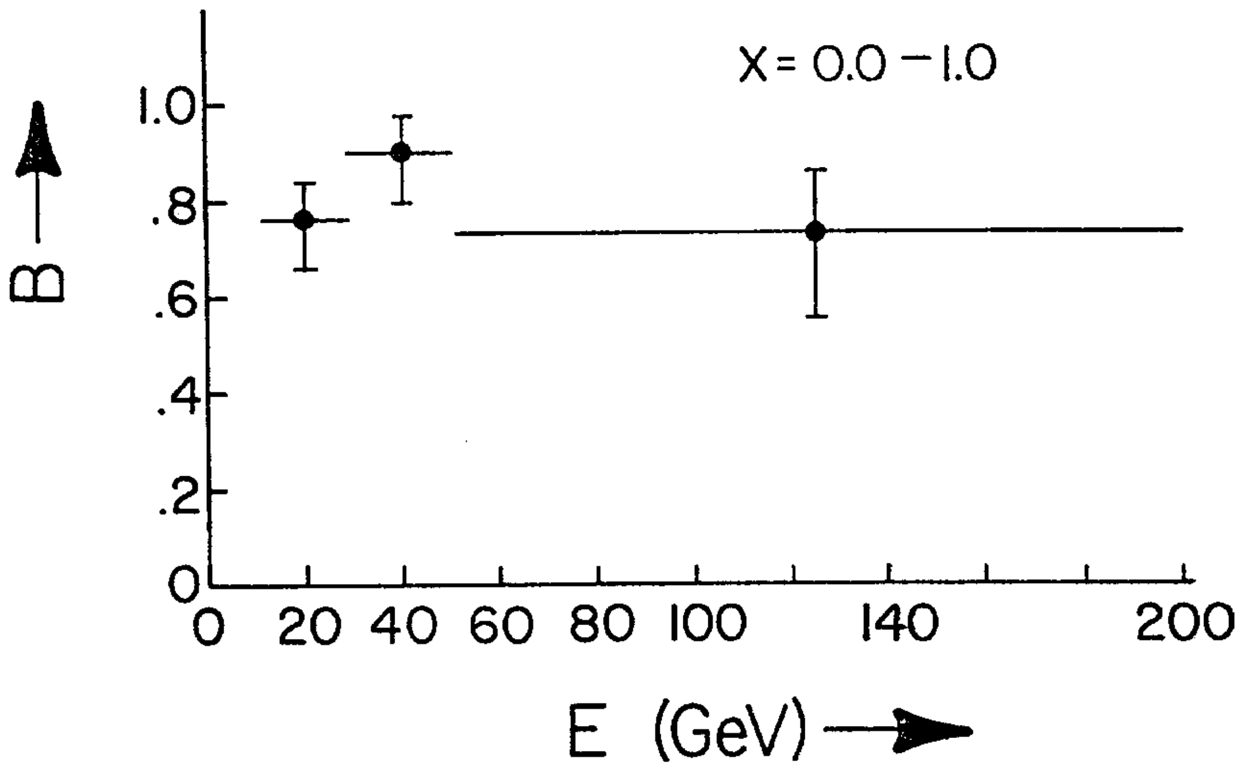


Figure 4: B values as a function of antineutrino energy from maximum likelihood fits to data of Fig. 3a, 3b and 3c. The data are plotted in the middle of the energy intervals.

energy intervals 10-30 GeV,,30-50 GeV and 50-200 GeV are given on Fig. 3a, 3b and 3c respectively and are compared with the theoretical y-distribution with B = 0.8. No apparent variation with energy is observed. The mean antineutrino energy in the 50-200 GeV distribution is about 62 GeV. Note that the fitted range of the y-distribution as shown by the data points on Fig. 3 vary with antineutrino energy consistent with the $\nu_\mu > 1$ GeV and $P_\mu > 4$ GeV data cuts. The maximum likelihood fit to the y-distributions in the three energy intervals was made and the B values are given as a function of energy on Fig. 4. From these data alone there is no evidence of an energy dependence of B.

The data are consistent with B = 0.79 ± 0.06 independent of energy which gives a relative antiquark contribution to the interaction of $\frac{\bar{q}}{q + \bar{q}} = 0.10 \pm 0.03$.

Let us compare the world data on B values for antineutrino interactions as a function of energy. Table II summarizes the present situation.

TABLE II

B Values from Antineutrino Experiments
Reported at this Meeting

Experiment	Approximate Mean Energy (GeV)	Fitted B Value $B = 1 - \frac{2\bar{q}}{q + \bar{q}}$
This experiment FIMS[11]	20	$0.76 \, ^{+.08}_{-.10}$
	40	$0.90 \, ^{+.08}_{-.10}$
	62	$0.73 \, ^{+.12}_{-.18}$
Gargamelle (Krenz this meeting)	1.5	0.90 ± 0.04
CF (Barish this meeting)	50	$0.64 \, ^{+0.22}_{-0.26}$
	150	$0.36 \, ^{+0.30}_{-0.36}$
HPWF (Benvenuti this meeting)	25	0.95 ± 0.10
	78	$0.45 \, ^{+0.15}_{-0.10}$

All the B values in Table II have been presented at this meeting. The CF data were given in terms of α where $B = 1 - 2\alpha$. The graphical presentation of these data is given in Fig. 5. A least squares fit[14] give $B = (0.92 \pm 0.04) - (3.9 \pm 1.2)E\times10^{-3}$.

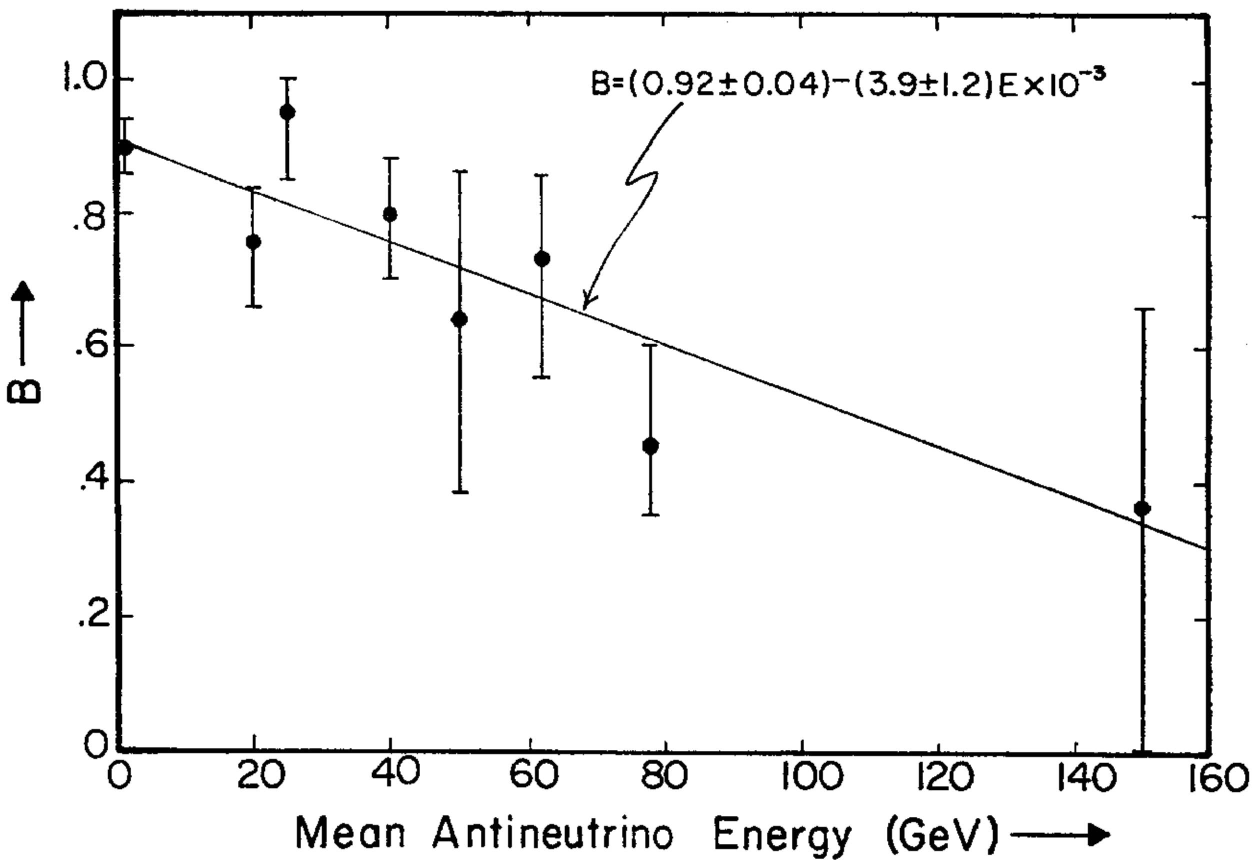
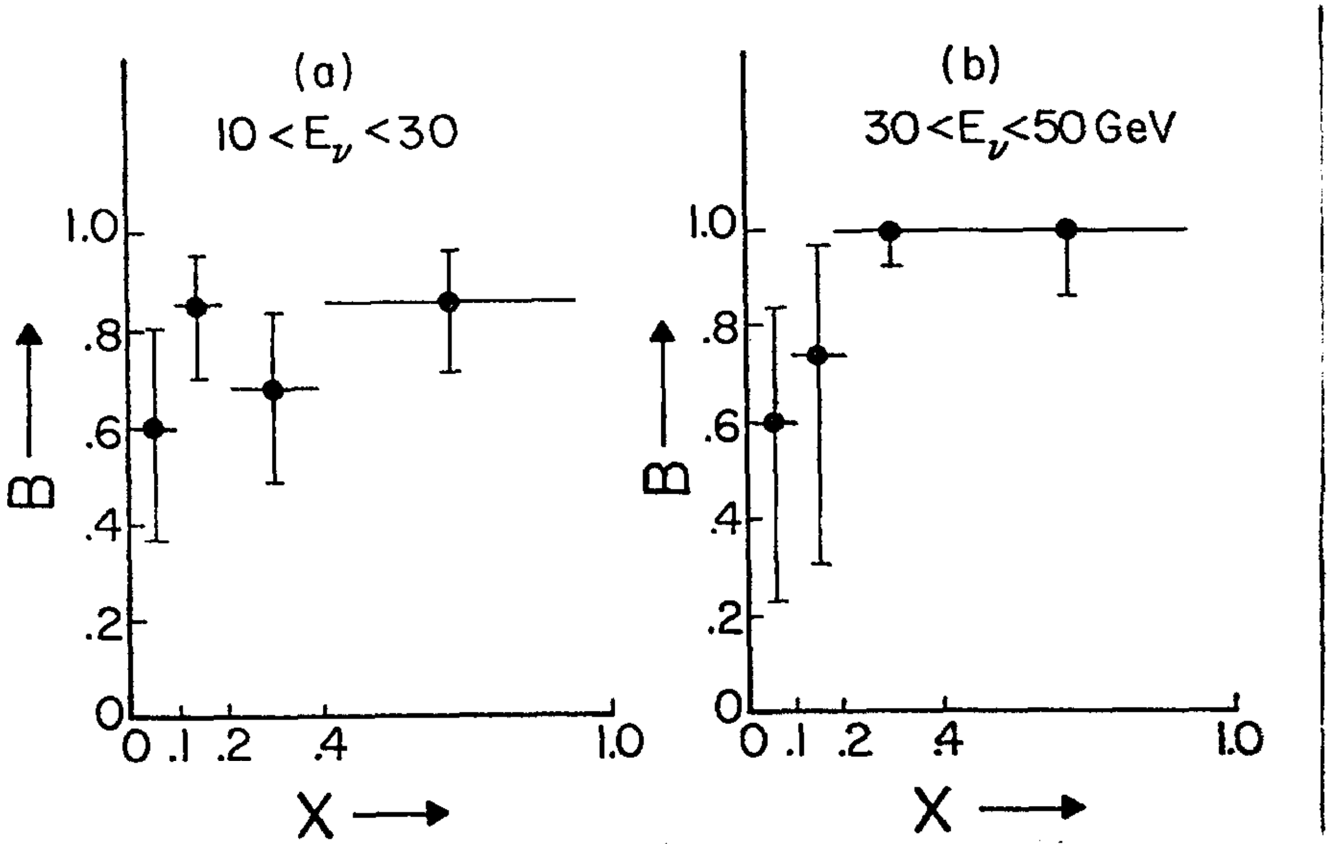


Figure 5: B valves as a function of antineutrino energy from Table II. The data are plotted at the mean of the energy interval. Solid curve is a least squares fit to the world data.

Let us now pursue the x dependence of B determined from the y-distribution. For each of the three energy intervals of Fig. 3 a maximum likelihood fit to B was made to the y-distributions for the x intervals 0-0.1, 0.1-0.2, 0.2-0.4 and 0.4-1.0. The



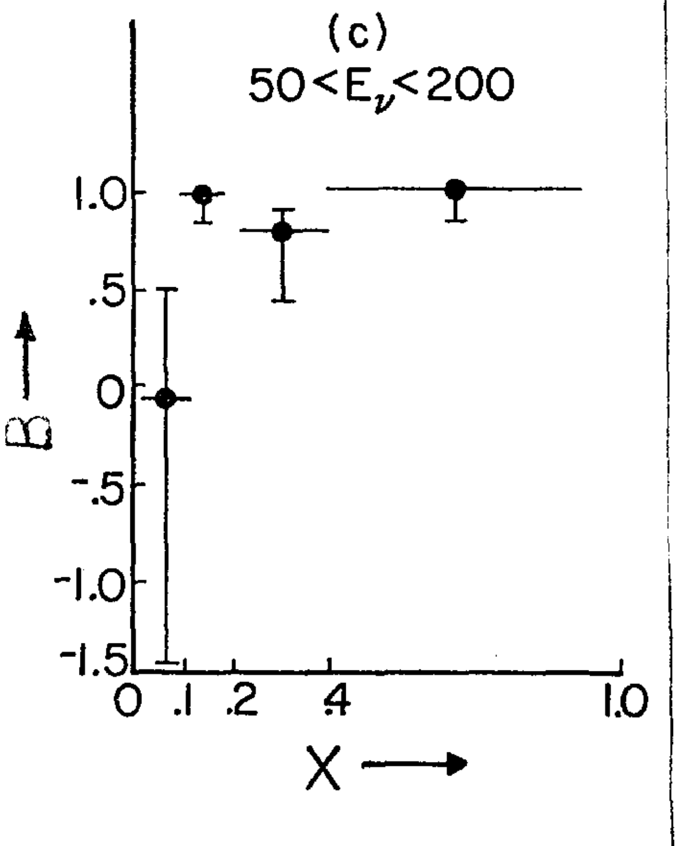


Figure 6: B values as a function of x from fitting the y-distributions in the antineutrino energy inter vals:

(a) 10<E<30 GeV

(b) 30<E<50 GeV

(c) 50<E<200 GeV.

The data are plotted in the center of the x intervals.

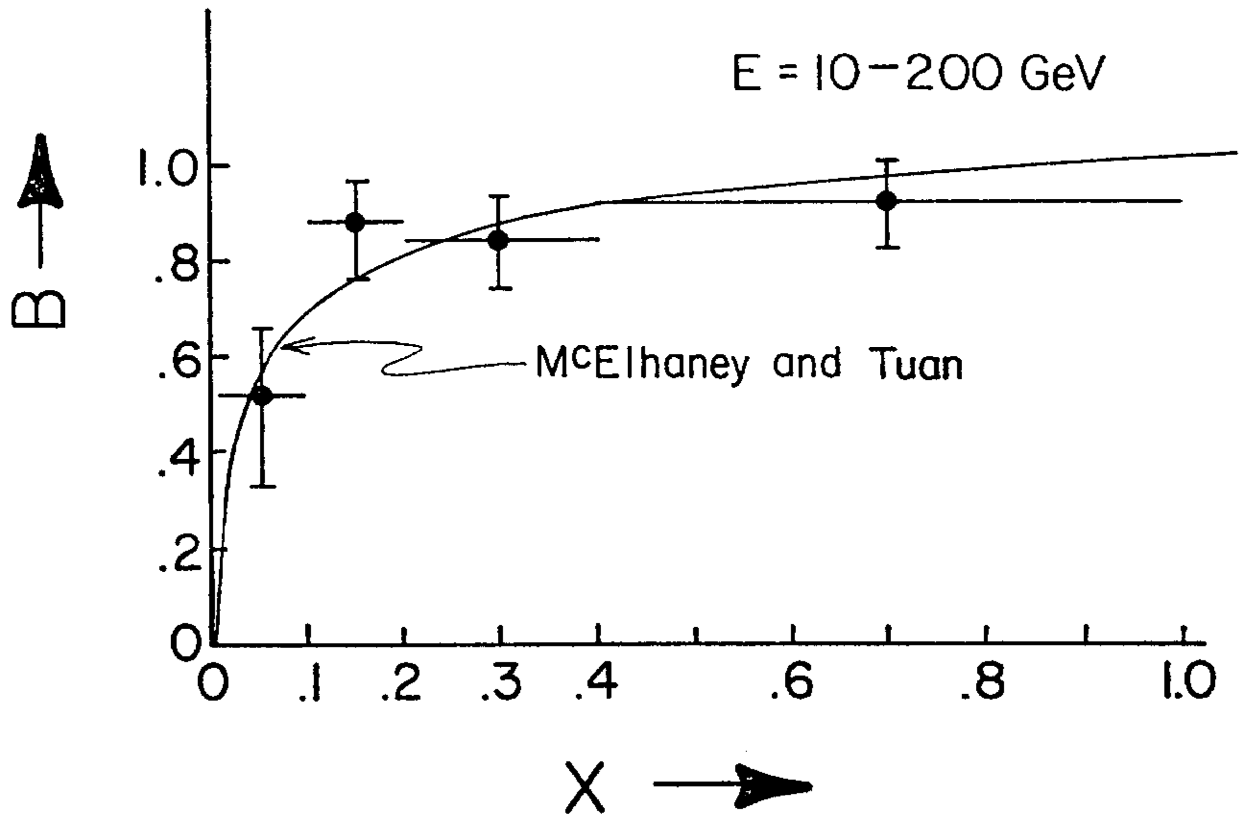
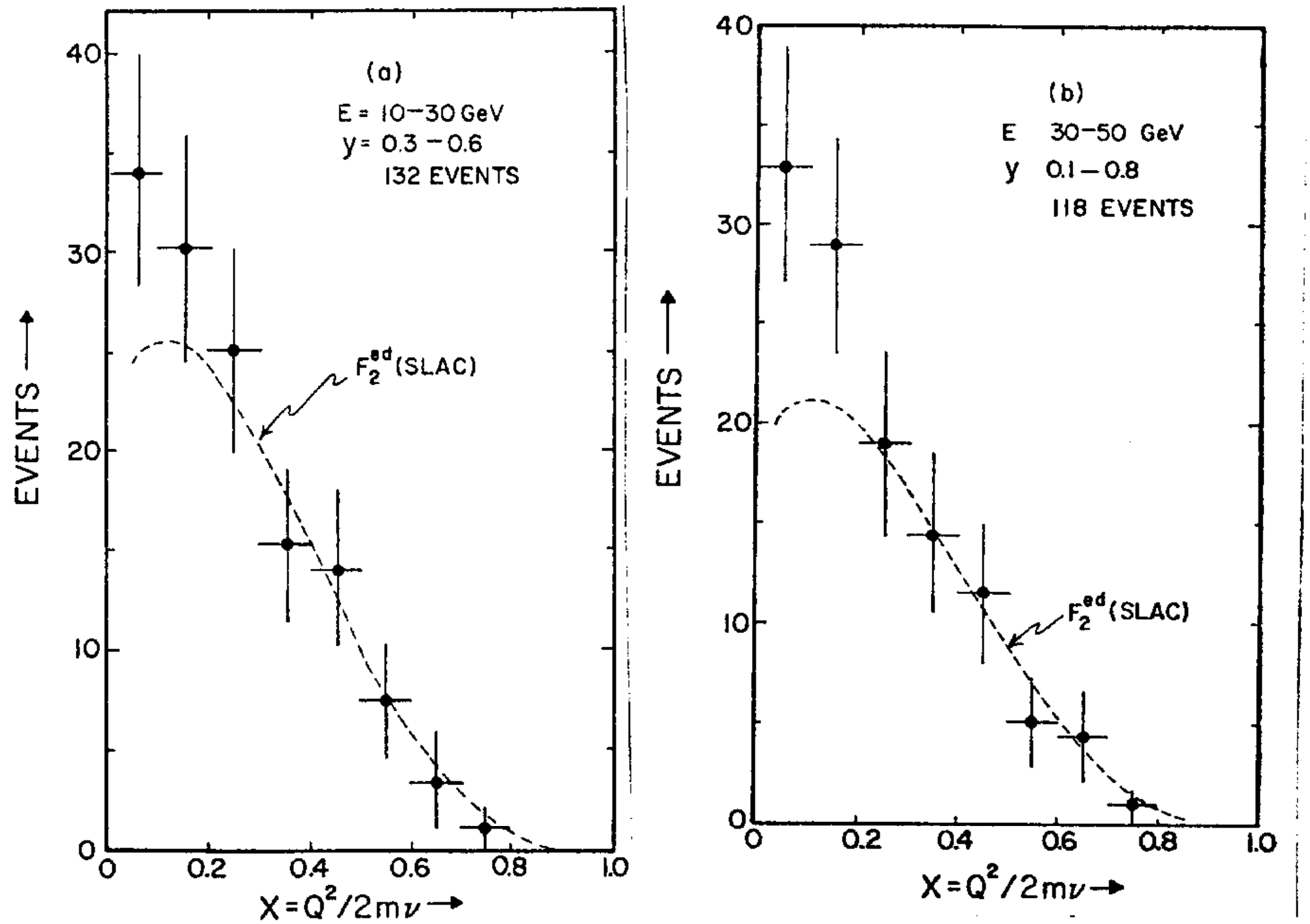


Figure 7: Fitted B values as a function of x for antineutrino events for all energies, 10 < E < 200 GeV.

fitted B values are given in Fig. 6. Assuming that B is not a function of antineutrino energy, the data of Fig. 6 are folded together to give the x dependence of Fig. 7. Also given in Fig. 7 is the x dependence of B as predicted by McElhaney and Tuan[12] which also fits well the Gargamelle data.[10] Even at high energies the antiquark contribution to the interaction is dominant at small x, ($x \lesssim 0.15$).

X-distribution: The $x = Q^2/m\nu$ distribution (quark momentum distribution) will be examined for three antineutino energy intervals; 10-30 GeV, 30-50 GeV and 50-200 GeV. The x-distributions are corrected for EMI geometrical acceptance. For



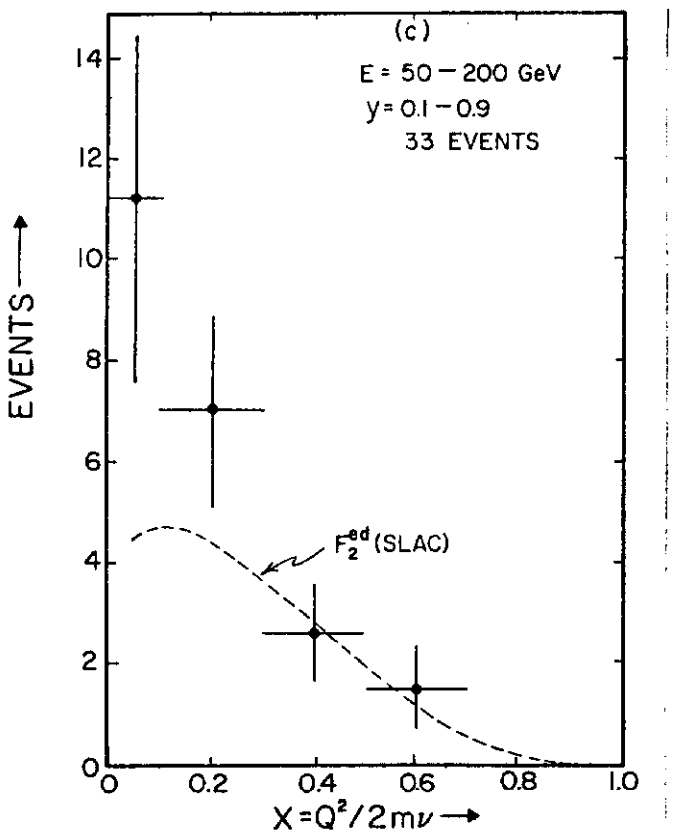


Figure 8: Antineutrino x-distributions for the energy intervals:

(a) $10<E<30$ GeV

(b) $30<E<50$ GeV

(c) $50<E<200$ GeV.

The data are compared to F_2^{ed} (SLAC).

each energy interval only the events in the y-range unaffected by the P_μ and ν_u cuts are used. For example in the $10 < E < 30$ GeV ($50 < E < 200$ GeV) range $y_{min} = \nu_c^{min}/10$ GeV $= 2.4/10 = 0.3$ (0.1) and $y_{max} = E - P_\mu^{min}/E = 10-0.4/10 = 0.6$ (0.9). The x-distributions for the three energy intervals are given in Figure 8. The data are compared with F_2^{ed} (SLAC)[13] normalized for $x > 0.2$ where the antiquark contribution in the antineutrino data is negligable. In all three x-distributions, the data show an excess of events compared to F_2^{ed} for $x < 0.2$ and good agreement for $x > 0.2$. Is this low x behavior an anamoly? Probably not!

Expressing the differential cross section for antineutrino-nucleons and electron-nucleons in terms of the weights of up quarks (u) down quarks (d) and strange quarks (s) gives

$$\frac{d\sigma^{\bar{\nu}N}}{dx} \propto u + d + 3(\bar{u} + \bar{d}) + 6\,\bar{s}\tan^2\theta_c$$

$$\frac{d\sigma^{eN}}{dx} \propto u + d + (\bar{u} + \bar{d}) + \frac{2}{5}(s + \bar{s}).$$

Assuming all the sea components have equal weight gives;

$$\frac{d\sigma^{\bar{\nu}N}}{dx} \propto u + d + 3(\bar{u} + d)$$

$$\frac{d\sigma^{eN}}{dx} \propto u + d + \frac{7}{5}(\bar{u} + \bar{d})$$

Therefore in the region where the antiquark contribution is negligable ($x \gtrsim 0.2$) we expect agreement between the antineutrino x-distribution and the electron x-distribution. As the antiquark contribution becomes important ($x < 0.2$) we expect the antineutrino x-distribution to lie above $F_2^{ed}(x)$. The B values determined from the antineutrino excess at low x are in agreement (within errors) with the B values determined from the y-distributions.

CONCLUSION

In the study of antineutrino-nucleon interactions in the neon-hydrogen filled 15-ft bubble chamber the following has been determined.

1. The y-distributions are inconsistent with $B = 1.0$
2. No energy dependence of the y-distribution is observed.
3. Fitting the y-distribution for $10 < E < 200$ GeV and $0 < x < 1.0$ gives $B = 0.79 \pm 0.06$ which means a relative antiquark content of the nucleon of $\frac{\bar{Q}}{Q + \bar{Q}} = 0.10 \pm 0.03$.
4. The antiquark contribution is primarily at small x ($x < 0.2$).
5. The x-dependence of B is consistent with the prediction of McElhaney and Tuan which also fits the Gargamelle data.
6. The x-distributions are energy independent.
7. The x-distributions for $x > 0.2$ agree in shape with F_2^{ed} (SLAC).
8. The departure of the x-distribution for $x < 0.2$ from

F_2^{ed} (SLAC) is consistent with $\frac{\bar{Q}}{Q + \bar{Q}} = 0.10$

9. Including our fitted B values at mean energies of 20 GeV, 40 GeV and 62 GeV to the world antineutrino data and making a least squares fit gives[14]

$$B = (0.92 \pm 0.04) - (3.9 \pm 1.2)E \times 10^{-3}.$$

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$$B = (0.88 \pm 0.05) - (3.2 \pm 1.4)E \times 10^{-3}.$$

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