PRELIMINARY ESTIMATES OF RATES OF $\nu$ AND $\bar{\nu}$ EVENTS TO BE EXPECTED WITH PROPANE IN THE H.I.B.C.

Improved experimental conditions (increased intensity of the PS-beam; larger volume of the H.I.B.C.) open the possibility of carrying out experiments on neutrinos and antineutrinos with propane in place of freon.

The main advantages of propane ($\text{C}_3\text{H}_8$) with respect to freon ($\text{C}_2\text{F}_5\text{Br}$) are:

1) The momentum determination on charged tracks can be carried out to a higher degree of precision.

2) The inelastic reactions on free protons can be studied, without interference from subsequent absorption or scattering of the final products in nuclear matter.

The main disadvantages are:

3) The longer mean free path for $\gamma$ conversion. The detection of $\pi$'s would be possible only in a few cases.

4) The longer mean free path for collision on which the separation of $\pi$'s from $\mu$'s is based.

5) Lower rates for $\delta$-rays, on which the separation between protons and pions is based.

The rates and most of the conclusions given in the following are still preliminary and incomplete. They depend in an essential way on the neutrino and anti-neutrino spectra in the various experimental conditions which are discussed. The spectra calculated (and kindly supplied) by Van der Meer have been used.

I) Constants used in the computation

Liquid propane ($\text{C}_3\text{H}_8$)

$\lambda_{\text{coll}} = 119.3$ cm

$\lambda_{\text{rad}} = 109$ cm

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Density = 0.41 g/cm³
Fiducial volume = 700 l
Number of nucleons in the fiducial volume = 1.69 \times 10^{29}
Number of free protons = 0.304 \times 10^{29} (18 \%)
Number of bound protons (or neutrons) = 0.691 \times 10^{29} (41 \%)
Accelerated primary protons = 10^{12} \text{ burst}^{-1}
On 1 burst/3 sec = 2.68 \times 10^{16} \text{ acc. protons/day.}

II) Expected rates of events

Rates of elastic and inelastic N's events are given in table 1 and 2. They have been calculated, on theoretical cross section and computed spectra, for the following conditions:

a) \( E_p = 24.8 \text{ Gev} \)
   \( I_h = \text{ current in the horn} = 300 \text{ KA} \)
   \( \Delta = \text{ shielding thickness} = 23 \text{ m} \)
   \( R = \text{ repetition rate} = 1 \text{ burst/3 sec} \)
   \( \) neutrinos

b) \( E_p = 17.8 \text{ Gev} \)
   \( I_h = 200 \text{ KA} \)
   \( \Delta = 16 \text{ m} \)
   \( R = \text{ repetition rate} = 1 \text{ burst/3 sec} \)
   \( \) neutrinos

c) \( E_p = 24.8 \text{ Gev} \)
   \( I_h = 300 \text{ KA} \)
   \( \Delta = 23 \text{ m} \)
   \( R = \text{ repetition rate} = 1 \text{ burst/3 sec} \)
   \( \) antineutrinos

Antineutrino rates with lower primary energy and smaller shielding could not be calculated as the expected spectrum is not yet available.

The cross sections are taken from Yamaguchi's paper (Prog. Theor. Phys. 23, 1117, 1960) for the elastic processes, assuming the axial form factor to be equal to the vector ones \( F_1(q^2) = F_2(q^2) = F_A(q^2) \); and from Berman and Veltman's calculations (CERN report, 9276/TH. 455, 29th July 1964) for N production, assuming the axial form factor \( F_A = \frac{1}{(1 + q^2/M_A^2)^2} \) and \( M_A = 0.9 \text{ Gev/c}^2 \).
At present, it is not possible to give an estimate of the total rate of inelastic events nor experimental data (on hydrogen) to compare with.

III) Background from $\bar{\nu}$'s in $\nu$ - runs and from $\nu$'s in $\bar{\nu}$ - runs

Both in $\nu$ - and $\bar{\nu}$ - runs we expect a background of the conjugate particle of about 10 o/o. As we have already experienced in the analysis of events produced in $\text{CF}_2\text{Br}$ ambiguities may arise in $\text{C}_2\text{H}_8$ between events such as

1) $\nu + n \rightarrow l^- + p$ and $\bar{\nu} + n \rightarrow n + \pi^- + l^+$
2) $\nu + n \rightarrow l^- + \pi^+$ and $\bar{\nu} + n \rightarrow n + \pi^- + l^+$
3) $\nu + p \rightarrow l^- + p + \pi^+$ and $\bar{\nu} + p \rightarrow \pi^- + p + l^+$

and others associated with more than one pion. In case (1) the two processes can be distinguished from one another when the positive track is sufficiently above minimum ionization to allow an evaluation of the mass of the particle. Moreover, in some cases, the dynamical analysis of the events and the detection of the neutrons through their recoil will permit an estimate of the relative cross section on a statistical basis. Cases (2) and (3) will present a harder problem. The final states differ only for the relative charge of a $\mu$ and $\pi$ thus being indistinguishable in a propane bubble chamber. The relative frequencies to be expected in a $\nu$ - and $\bar{\nu}$ - run of the two competing processes are given in table 2.

IV) The separation of hydrogen events from those occurring in heavy nuclei

One of the main advantages in performing a neutrino run with propane (or a propane-freon mixture) in the bubble chamber, is related to the study of the reaction:

$$\nu + p \rightarrow \mu^- + \pi^+ + p$$

free from effects due to Fermi motion and secondary nuclear interactions.

The selection of free proton events would be made on the basis of the following criteria:

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1) Charge balance
2) Not more than one proton track leaving the vertex
3) Momentum unbalance consistent with zero (say within two standard deviations).

In order to estimate the contamination from heavy nucleus events, the events obtained in the freon runs were subjected to the same selection criteria. Only events with visible energy greater than 1 GeV were considered, since this is likely to be the region of most physical interest. It was found that there were 23 events ($\mu^-\pi^+p$) in the fiducial volume. The total momentum unbalance and its error were calculated in each case. Typical values were an unbalance of 0.4 GeV/c and an error of 0.15 GeV/c. It was found that 9 of the events had an unbalance within two standard deviations of zero. Then that part of the error which was not due to the uncertainty in the neutrino direction was halved. (This would approximate the situation in an 88 % propane, 12 % freon mixture, radiation length 50 cm). In 5 cases the unbalance was still compatible with zero. These 5 events represent the contamination.

In order to estimate the number of true free proton events to which this background corresponds it was assumed that the original sample contained 130 one-pion events. If $N^*$ (33) production is dominant 98 of these events would have occurred on bound protons. In the propane-freon mixture mentioned above, the ratio of free protons to bound protons is 0.29. Therefore the corresponding number of free proton events is 28. These would be reduced to 26.5 by the application of criterion (3). Hence of a total of 31.5 events, 5 are contamination i.e. 16 o/o. In pure propane one would expect a contamination of less than 10 o/o.

V) Preliminary conclusions

V.1 Experimental conditions

In table 1 the expected rates of neutrino induced elastic events and $N^*$ producing events (hereafter referred to as $N^*$ events) have been calculated for two experimental conditions:

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a) the P.S. is operated – as it has been almost all the time so far to produce 24.5 Gev/c protons;

b) the P.S. is operated at 17.5 GeV/c.

Under condition a) only one burst every 3 second is possible. The horn works with a current of 300 KA and the shielding imposes a distance $D \sim 25$ m between the end of the decay tunnel and the bubble chamber.

Under condition b) one burst every 1.5 seconds are possible. However the bubble chamber may not be able to stand such a rate of expansion and a more realistic rate of 1 burst every 2 seconds has been considered. Moreover, the horn will have to be operated at 200 KA and the distance $D$ may be reduced to make $D \sim 18$ m.

The consequences are:

1) The $\nu$ - spectrum is made richer in neutrinos in the energy region below 3 Gev by a factor $\sim 40$ o/o and poorer above 3 Gev by about the same factor.

2) The total number of interactions of the above mentioned type is increased by a factor 2, because of the reduction of the shielding and the increase in the repetition rate.

3) The total number of muon events (2 $\pi$'s or more) will be probably reduced by a factor not higher than $\sim 30$ o/o. This cannot be calculated on any theory and is estimated only on the total rates observed in the previous neutrino experiments.

For experiments on antineutrinos the corresponding rates have been calculated only for the PS operated at 24.5 Gev/c: data on the $\bar{\nu}$ spectra at lower energy are not available.

However, if the effect of running at lower energy on the $\bar{\nu}$ - spectrum is comparable with that calculated for the $\nu$ - spectrum, the following conclusions can be drawn:

4) The increase in total number of elastic and $N^\pi$ events per day is substantial – though not as spectacular as for the neutrino: in fact an increase of $\sim 50$ o/o can be expected. This is due to the
shape of the corresponding cross sections which is comparatively small at low energy where - one the other hand - the $\bar{\nu}$ spectrum gains most.

5) The increase in the number of events, both for $\nu$ and $\bar{\nu}$ interactions in the region below 3 Gev is of great importance as this is the region where the elastic cross sections $\sigma_{e1}(\nu)$ and $\sigma_{e1}(\bar{\nu})$ differ most. This difference is directly related to the axial form factor which can thus be determined assuming C.V.C. theory.

In conclusion, in so far as elastic and $N^*$ events are concerned, running at lower energy seems to offer a considerable advantage. The above holds both for experiments with propane and freon even if the rates are substantially different.

V. 2 Conclusions pertinent to experiments on propane

$\nu$ - runs. For elastic reactions

$$\nu + n \rightarrow l^- + p$$

which will take place on bound nucleons, the use of propane will give comparatively little advantage with respect to freon. The contamination from inelastic events - in which the pion is re-absorbed in the nucleus - will be smaller than in freon ($\sim 25$ o/o) due to the larger escape probability for pions from carbon nuclei with respect to bromine. This will be partially compensated by the fact that $\pi^0$'s will be detected only in about $50$ o/o of the cases. Thus the reaction

$$\nu + n \rightarrow l^- + p + \pi^0$$

may contribute to the background of disguised inelastic events with $\sim 5$ o/o of the expected rate of elastic. More detailed calculations are being attempted.

Antineutrino background will not interfere.

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As stated in section IV, the main interest in a propane exposure concerns the study of the reaction

$$\nu + p \rightarrow \mu^- + \pi^+ + p$$
on free protons. All the final products being charged, a precise determination of the $m(\pi^+, p)$ invariant mass will be possible. In the enlarged bubble chamber under condition a) (see table 1) we expect $\sim 1.4$ events of such a type per day; under condition b) we expect 2.5 events per day. Thus a 40 day exposure in propane will yield 100 such events on free protons.

The background from antineutrinos will be negligible. Contamination of similar events taking place in heavy nuclei is expected to be $\sim 16\%$ in a propane - freon mixture (12% freon) and probably less than $\sim 10\%$ in pure propane.

The total cross section for inelastic events is not known and no meaningful estimate is possible. An order of magnitude may be guessed from the rates observed in the experiments carried out in freon. If single pions are all attributed to $N^*$ production and the relative proportion of $(1\pi)$ to $(>1\pi)$ events is taken to be the same in freon and propane, then we can expect $\sim 5$ multipion events/day under condition a). This figure is, probably, an overestimate. The contamination of (undistinguishable) $\bar{\nu}$ events will be $\sim 12\%$.

In a similar way we can estimate the number of events containing strange particles from the observed rates in freon. The result is 0.2 events/day under condition a).

### $\bar{\nu}$ - runs. Elastic events

$$\bar{\nu} + \bar{p} \rightarrow \bar{l}^+ + n$$

may occur both on free protons as well as on bound protons. Those on free protons are of interest as they would be unaffected by limitations imposed by the Pauli principle and thus allow a better determination of the elastic form factors.

However, they are indistinguishable from elastic events on bound protons, when the final neutron fails to disrupt the nucleus in which it originates. Then, discrimination between the former and latter type of events is impossible.
on the basis of kinematical analysis as all particles of the final state are neutral except the $\mu^+$ and the neutrino momentum not known a priori. We estimate that this will be the case for at least 50 o/o of the elastic reactions in carbon. From table 1 one can conclude that of the "single-$\mu^+$-events" not more than 45 o/o will be on free protons. A small contamination of inelastic events of the type

$$\bar{\nu} + p \rightarrow l^+ + n + \pi^0,$$

may also be present. ($\sim 4$ o/o of the cases).

Inelastic $\bar{\nu}$-events will be heavily contaminated by inelastic $\nu$-events. (see table 2). The background—averaged over all the $l \pi$-events—amounts to 40 o/o of the genuine $\bar{\nu}$ ($l \pi$)-events. Thus, $\sim 30$ o/o of the detected $l \pi$-events in an $\bar{\nu}$-run under condition 0) will be due to neutrinos. Moreover, not more than 12 o/o will take place on free protons.

Strange particle production is difficult to predict. The theoretical predictions are—at present—based on uncertain hypothesis. If we take Block's figures (K.M. Block, Nov. 1953) the number of hyperons produced in reactions

$$\bar{\nu} + N \rightarrow Y + \mu^+$$

(corrected for phase space effects, should amount to $\sim 10$ o/o of the elastic reaction. Single production of hyperons can be unambiguously detected against associated production only below the threshold for the latter process, i.e. in the interval between $E_\nu = 0.35$ and $E_\nu = 1.1$. Taking into account neutral decays and detection probability for $\gamma$'s, on the basis of the above prediction we should observe $\sim 0.035$ events of type(a) per day. Above $E_\nu = 1.1$ a comparable number of hyperons from associate production will probably be present.

In conclusion, neutrino experiments on protons will allow a more precise study of inelastic interactions on protons and yield valuable information especially in connection with $N^*$ production. Experiments with $\bar{\nu}$ are less advantageous than for $\nu$ and probably will not supply much more information than

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(o) $Y^*$ production has not been included.

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those of $\bar{\nu}$ in freon, where the event rate per day is about 3 times greater.

Discussions with S. van der Meer and M. Veltman are gratefully acknowledged.

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G. Myatt

Distribution : (open)
Scientific staff of N.P.A.
TABLE 1 - Rates of events  
Elastic and $N^+$ production  
(slide rule calculations)

<table>
<thead>
<tr>
<th>Exposure</th>
<th>$\nu$ - run</th>
<th>$\bar{\nu}$ - run</th>
<th>$\bar{\nu}$ - run</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_p$ = 24.5 Gev</td>
<td>$\nu + n \rightarrow l^- + p$</td>
<td>$\bar{\nu} + p \rightarrow n^- + l^+$</td>
<td></td>
</tr>
<tr>
<td>$I_h$ = 300 KA</td>
<td>$\nu + n \rightarrow l^- + p + \pi^0$</td>
<td>$\bar{\nu} + n \rightarrow n^+ + \pi^0$</td>
<td></td>
</tr>
<tr>
<td>1 burst/3 s</td>
<td>$l^- + n + \pi^+$</td>
<td>$p + \pi^- + l^+$</td>
<td></td>
</tr>
<tr>
<td>$\Delta = 23$ mts</td>
<td>11.7</td>
<td>15.5</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>3.4</td>
<td>6.7</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>3.4</td>
<td>6.7</td>
<td>0.75</td>
</tr>
</tbody>
</table>

- $E_p$ = Energy of the primary proton beam
- $I_h$ = Current in the horn
- $\Delta$ = Shielding thickness. The distance $\Delta$, quoted in the text, between the end of the decay tunnel and the bubble chamber is $\Delta \sim \Delta + 2$ m.
<table>
<thead>
<tr>
<th>Event</th>
<th>Background</th>
<th>0/o Bkg/Event rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v + n \to \mu^- + p$</td>
<td>$\bar{v} + n \to n + \pi^- + \mu^+$</td>
<td>2 o/o</td>
</tr>
<tr>
<td>$\mu^- + n + \pi^+$</td>
<td>$\bar{v} + n \to n + \pi^- + \mu^+$</td>
<td>20 o/o</td>
</tr>
<tr>
<td>$v + p \to \mu^- + p + \pi^+$</td>
<td>$\bar{v} + p \to \mu^+ + p + \pi^-$</td>
<td>neglig.</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Event</th>
<th>Background</th>
<th>0/o Bkg/Event rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{v} + n \to n + \pi^- + \mu^+$</td>
<td>$v + n \to \mu^- + p$</td>
<td>28 o/o</td>
</tr>
<tr>
<td>$\bar{v} + n \to n + \pi^- + \mu^+$</td>
<td>$v + n \to n + \mu^- + \pi^+$</td>
<td>3 o/o</td>
</tr>
<tr>
<td>$\bar{v} + p \to p + \pi^- + \mu^+$</td>
<td>$v + p \to p + \mu^- + \pi^+$</td>
<td>260 o/o</td>
</tr>
</tbody>
</table>