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ON THE MEASUREMENT OF ELECTRONS IN THE 5-20 MeV RANGE IN LIQUIDS

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ABSTRACT

Recent approaches to solve the solar neutrino problem comprise both, new theoretical ideas and newly developed techniques for huge underground detectors. The investigation of electrons produced by neutrinos from the ${}^8\text{B}$ decay is particularly interesting. Earlier bubble chamber photographs of electron tracks (5-20 MeV) in two liquids, the measurement of their energy and direction, may help to optimize the design of these detectors.

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1. INTRODUCTION

Solar neutrinos are studied in the ^{37}Cl experiment by Davis et al. [1] over the last two decades. The neutrino flux is found consistently smaller by about a factor of three than expected from theoretical calculations based upon standard models how the sun shines. Recently a mechanism was discovered by which a large fraction of the neutrinos ν_e emitted in the sun may be converted into ν_μ when traversing the sun [2, 3], and thereby be rendered unobservable in the Davis detector. Therefore, any further measurements of the flux with other techniques are of great interest. Two large gallium detectors are currently under development (Baksan (USSR) ~ 60 t and Gran Sasso (Italy) 30 t) and they might be able to distinguish between one of the two solutions of the resonance condition proposed in ref. [2], the first one discussed in detail in ref. [3]. However, as pointed out in refs [4, 5], simply seeing 110 SNU in a gallium detector would be consistent with the first solution [3], but also consistent with mechanisms other than neutrino oscillation. However, unambiguous evidence for adiabatic resonance oscillation would come from the knowledge of the energy spectrum of these neutrinos. An important feature of a 4500 m³ continuously sensitive liquid argon (methane) imaging detector – now under construction – will be the practicability of an accurate calorimetry [6, 7], which could allow for the required determination of the neutrino spectrum. By this virtue the detector is possibly superior to a liquid argon bubble chamber [8], which had been proposed earlier for nucleon decay studies.

Neutrinos from: (i) the decay of ^8B in the solar interior can produce absorption (^{40}Ar goes to ^{40}K), and neutrino-electron scattering in a liquid argon detector. Cross sections for these reactions and energy spectra for electrons can be found in refs [9, 10]. Other sources for (electron) neutrino and/or antineutrino production are (ii) supernova collapse, (iii) relic supernova and (iv) nuclear reactors. The approximate range of neutrino energies and their mean value, expected from these sources, is taken from refs [2, 3], and are shown in table 1. The background from reactors (iv) appears to be negligibly small [9].

The neutrinos interact with electrons and determine their energy and initial direction. These electrons will then be subjected during their passage through the detector material to multiple scattering, energy loss by ionization and bremsstrahlung. Computer simulations for electrons in the energy range from 5 to 15 MeV have been made [10], taking into account the expected spatial resolution of the argon detector.

We present here results from an earlier bubble chamber experiment, which are pertinent for the measurement of electrons produced by solar neutrinos. During this experiment electrons with energies between 5 and 20 MeV had been photographed in two liquids with quite different radiation lengths and densities [11, 12]. Results of the measurement of the path lengths of such electrons [13, 14] and their relevance to the determination of the electron's energy, will be reviewed. The effect of energy losses by ionization and bremsstrahlung upon the track length is treated by a theory [15], which fits well our experimental data. In addition as yet unpublished results on theoretical path length distribution for various electron energies and its Z-dependence [16], as well as more numerical data from the evaluation of electron tracks (total track lengths, penetration depth (range), angular distribution) [17] are reported.

2. REVIEW OF THE BUBBLE CHAMBER RESULTS

The bubble chamber, a cylinder with a diameter of 97 mm and a depth between the two windows of 70 mm [7], was filled with propane and a heavy freon and exposed to an electron beam extracted from a 35 MeV betatron. In table 2(a) the liquid density and radiation length of C_3H_8 and CF_3Br at chamber operating conditions (temperatures 65°C and 35°C, respectively) are given, together with the corresponding data of methane and argon at the normal boiling point (NBP). Table 2(b) gives the mean square of small angle multiple scattering for electron energies of 6.9 and 19.6 MeV calculated according to formula

$$\langle \Theta^2 \rangle_{av} = (21/E_0)^2 \cdot x/X_0 \text{ with}$$

X_0	= radiation length [cm],
x	= thickness of material [cm],
E_0	= initial energy [MeV].

It is valid only for a small absorber thickness (small energy loss), and neglects single processes in which a large angular deflection occurs.

The beam passed through a beta-spectrometer for momentum analysis and a 5 mm diameter aperture. In front of the chamber the beam had an angular divergence of $\sim \pm 1^\circ$ and an energy spread of $\sim 1\%$. The effect of the beam entrance window (4 mm Be and 0.6 mm Al) upon energy loss (ionization and bremsstrahlung) and multiple scattering has been calculated for two energies and is given in table 3.

For the propane experiments the effect of the window can best be approximated by adding to the visible track lengths ≤ 20 mm liquid equivalent; for the freon experiment to subtract 1 MeV from the initial energy E_0 and by adding 2 mm liquid equivalent. This procedure takes into account the different ratio of bremsstrahlung to ionization losses in the two experiments.

On the average only 3 electrons per expansion were injected into the chamber to facilitate the measurements of the tracks in the two views. In addition, a series of pictures with $50 \div 100$ electrons per pulse and various energies were photographed in propane. This gives a more qualitative picture of their behaviour, mainly in view of medical applications [11, 12]. We reproduce photographs taken in propane at two energies (9.3 and 5.8 MeV) (figs 1 and 2): they show particularly well the effect of multiple scattering. Examples for single large angle scattering are given in fig. 3 (propane 5.8 MeV) and fig. 4 (freon 19.6 MeV). The effect of bremsstrahlung losses and successive pair and Compton-electron production is seen from fig. 5 (freon 19.6 MeV). The bubble size in the chamber (figs 1-5) is $\leq 200 \mu\text{m}$.

Fig. 6 indicates the procedure for the measurement of our samples of 439 electron tracks in propane ($E = 6.9$ MeV) and 299 tracks in freon ($E_e = E_0 - 1 \text{ MeV} = 19.6$ MeV): corresponding points were determined in the two stereo views, the track approximated by a polygon, and reconstructed in space. This allowed for the measurement of several quantities: the actual path length L , the total path length GL (energetic delta electrons added to L), the maximum penetration depth T (normally defined as "range"), the penetration depth of the end-point of the track T_E , and its angle Θ with the direction of the incoming beam. These quantities are tabulated for each electron [17], together with their mean values and deviations. Also given are various derived quantities, which characterize the penetration of electrons through thick layers. Figs 7-11 show the histograms for L , GL , T , T_E and Θ for the two experiments.

The path length distributions were compared with theory [15] and showed excellent agreement [14]. Since they covered a wide range of the ratio $\Delta E_{\text{rad}} / \Delta E_{\text{ion}}$ and initial electron energies, it can be concluded that the theory is generally valid, i.e. for other materials and energies up to a few hundred MeV. Fig. 12 shows the mean path length for propane and freon as function of energy and Figs 13 and 14 the distributions divided by the mean path length. More theoretical curves, at other energies and in these and also other materials, including C, H_2O , and Pb can be found in ref. [16].

3. DISCUSSION OF THE RESULTS

3.1 Energy measurements

The path length of an electron, even including large delta electrons, can only be a "measure" for its energy in very low-Z material and at fairly low energies, when bremsstrahlung losses are still negligibly small. This condition is not fulfilled in freon or argon in the energy range we discuss. Even if a detector is large enough to detect in addition to the primary electron all converted gammas and having a perfect time correlation between these tracks, the uncertainties in the energy determination from the track lengths alone remain large. Even the momentum measurement of GeV-electrons in a heavy liquid bubble chamber by curvature in the magnetic field remain unsatisfactory, if converted bremsstrahlung is not considered appropriately [18].

Therefore, a detector, which uses instead of path length measurements imaging technique and calorimetry together, could be superior to a bubble chamber. For an underground experiment, aiming at the detection of relatively rare electron events, it should be possible to correlate in time primary electrons with their converted bremsstrahlung and collect all free charges. For such a detector the inevitable losses of free charges by capture processes, when drifting over large and different distances, will ultimately limit the precision of energy measurements.

3.2 Angular measurement

The determination of the direction of a neutrino poses a problem for energies in the few to tens MeV range, most pronounced for the heavier liquid. An unambiguous distinction between start and end of an electron track requires a very high "optical" resolution, otherwise any increase of the frequency of large angle scattering towards its end may not be recognizable. Ionization measurements are of little or no help in this context, since the energy loss changes only significantly in the last (few) millimeter(s) of the track. Such a variation can be faked by delta-electrons at the start or anywhere along the track.

Even with the start and end of a track known, the determination of the initial direction suffers from many small and, not so infrequent, large angle scattering. Therefore, the resolution should be a fraction of a millimeter, as can be deduced from our bubble chamber photographs. The measured angles Θ , given in fig. 11, have a mean value of $26.4^\circ \pm 14.5^\circ$ and $23.8^\circ \pm 12.3^\circ$ for the freon and propane bubble chamber experiments, respectively. This quantity is probably the easiest to access

in any underground detector. It is, however, about four times as large as the theoretical value obtainable under ideal measurement conditions from the first centimetre of a track (table 2(b)).

4. CONCLUSIONS

The goal to measure neutrinos from solar ${}^8\text{B}$ decay, and also of supernova collapse and relic supernova, to distinguish between these sources and the (small) background radiation from nuclear reactors is a great challenge for any new underground detector and deserves all attention. In particular, an argon (methane) imaging detector with charge collection has the potential of measuring neutrino spectra, thus making it superior to gallium detectors. Bubble chamber photographs of MeV-electrons show, that care has to be taken to optimize both, calorimetry and imaging techniques.

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TABLE 1

Source	Energy spectrum (approx. limits) ^(*)	Mean energy
1a	1 - 9 MeV	5 MeV absorption
1b	1 - 14 MeV	scattering
2	4 - 60 MeV	10 MeV
3	2 - 25 MeV	6.6 MeV
4	2 - 9 MeV	4.1 MeV

(*) For details of spectra, see refs [2, 3, 7, 8] and references therein.

TABLE 2(a)

	CH ₄ NBP	C ₃ H ₈ BC	NBP	Ar NBP	CF ₃ Br BC	NBP
Density [g/cm ³]	0.425	0.43	0.585	1.39	1.48	2.0
Rad.Length [cm]	110	110	81	14	11	8.3
$\Sigma Z/n$	2.0	2.5		18	11.8	
$\Sigma Z^2/n$	8	10.5		324	301	

NBP: at normal boiling point, BC: at bubble chamber temperature

TABLE 2(b)

E [MeV]	6.9	6.9	19.6	19.6
$\langle \Theta^2 \rangle_{av}$ (1.0 cm)	4.83°	4.83°	4.70°	5.98°

TABLE 3

E ₀ [MeV]		6.9		20.6
$\langle \Theta^2 \rangle_{av}$ (0.40 cm Be) $\langle \Theta^2 \rangle_{av}$ (0.06 cm Al)		4.32° 3.25°		0.48° 0.36°
ΔE_{ion} [MeV] ΔE_{rad} [MeV]		1.42 0.13		1.48 0.36

FIGURE CAPTIONS

- Fig. 1 Electron tracks ($E_0 = 9.3$ MeV) in propane (C_3H_8). Scattering and energy loss by ionization in the beam entrance window (4 mm Be, 0.6 mm Al) are equivalent to a layer of ~ 20 mm propane.
- Fig. 2 Electron tracks ($E_0 = 5.8$ MeV) in propane (C_3H_8).
- Fig. 3 Examples for backward scattering and electron-electron scattering (large δ -electron). Electrons ($E_0 = 5.8$ MeV) in propane (C_3H_8).
- Fig. 4 Large angle scattering of electrons ($E_e = E_0 - 1$ MeV = 19.6 MeV) in freon (CF_3Br).
- Fig. 5 Bremsstrahlung, pair production and Compton effect. Electron ($E_e = 19.6$ MeV) in freon (CF_3Br).
- Fig. 6 Electron track (schematically): measurement points (corresponding points in two views) are connected by straight lines. Polygons have been added between large δ -electrons (the more energetic partner is considered to be the primary electron). $L = \sum l_i$ = path length. T = maximum penetration depth (range). T_E = distance of end point of track from entrance plane. R_E = distance end point from entrance point into window. Θ = angle between R_E and initial direction of electron beam.
- Fig. 7 Pathlengths L : (a) propane 6.9 MeV, (b) freon 19.6 MeV.
- Fig. 8 Total track lengths GL : (a) propane 6.9 MeV, (b) freon 19.6 MeV.
- Fig. 9 Maximum penetration depths: (a) propane 6.9 MeV, (b) freon 19.6 MeV.
- Fig. 10 Penetration depth of end points: (a) propane 6.9 MeV, (b) freon 19.6 MeV.
- Fig. 11 Angle end point - entry point with primary direction Θ : (a) propane 6.9 MeV, (b) freon 19.6 MeV.

FIGURE CAPTIONS (Cont'd)

- Fig. 12 Calculated mean path length for propane (C_3H_8) and freon (CF_3Br) as function of energy.
- Fig. 13 Calculated path length distributions (divided by mean path length) for initial energies of 1, 20 and 60 MeV in propane (C_3H_8).
- Fig. 14 Calculated path length distributions (divided by mean path length) for initial energies of 1, 8 and 20 MeV in freon (CF_3Br).

Fig. 1

Fig. 2

Beam
Window

Bubble Chamber Liquid: Propane (C_3H_8)

$E_0 = 5.8 \text{ MeV}$

4 mm Be
0.6 mm Al

97 mm

= 20 mm
Propane

Fig. 3

Bubble Chamber Liquid: Freon (CF_3Br)

$E = 19.6 \text{ MeV}$

50 mm

Fig. 4

Bubble Chamber Liquid: Freon (CF_3Br)

$E = 19.6 \text{ MeV}$

50 mm

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Angle end point - entry point with primary direction θ

Fig. 11

Fig. 12

Fig. 13

Fig. 14