COHERENT NEUTRINO–NUCLEUS ELASTIC SCATTERING
IN ULTRALOW-TEMPERATURE CALORIMETRIC DETECTORS

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ABSTRACT

We speculate on the measurement of the coherent forward peak in the neutrino–nucleus elastic scattering, using ultralow-temperature calorimetric techniques for the determination of the recoil energies down to below 1 keV. The detector would consist of an array of relatively large single-crystal calorimeters made of various elements and compounds, cooled to below 100 mK temperature. The detector should be surrounded by veto track detectors for the elimination of the background events due to cosmic rays and neutrons and charged beam particles. The coherent event rate for some existing or projected neutrino beams and sources is calculated for a Ge detector.

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1. INTRODUCTION

The neutral-current elastic scattering of neutrinos on nuclei is predicted to have a pronounced forward peak in analogy with electron scattering. For a momentum transfer which is small compared with inverse target size, the relative phase factors of the waves scattered from the individual constituents of the target are small, and the waves add coherently [1] to make the amplitude

\[ F(k',k) = Ge^{-q^2r^2} [Z(a_0 + a_1/2) + N(a_0 - a_1/2) + (Z_i - Z_f)(b_0 + g_s b_i/2) + (N_i - N_f)(b_0 - g_s b_i/2)] \times \times \bar{u}(\nu')\gamma^0 \gamma^\mu u(\nu). \]  

Here \( a_0, a_1, b_0, \) and \( b_1 \) are the general phenomenological parameters of the electroweak interactions, which take the values \( a_0 = -\sin^2 \theta_w, a_1 = 1 - 2 \sin^2 \theta_w, b_0 = 0, \) and \( b_1 = -1, \) in the Weinberg-Salam (WS) model. The spin-dependent terms in Eq. (1) are small for nuclei with large mass and low spin and are exactly zero for nuclei with zero spin. There are several other models which cannot be ruled out as yet, although the WS model is the most popular one.

The range of momentum transfers where the coherence occurs is determined by the nuclear size \( R \) and is around \( |q| < 100 \text{ MeV}/c; \) for heavier nuclei this corresponds to such small recoil energies that the events are below the threshold in any existing detector of reasonable size.

A new detector, based on thermal calorimetry in pure dielectric diamagnetic single-crystal materials, shows promise for reaching good energy resolution and threshold even in a rather massive combined-function target-detector.

The principle of the thermal detection of particles relies on the conversion of the deposited energy into heating of the phonons in the material, and has been proposed already some time ago [2]. The first evidence for the detection of cosmic rays in resistance thermometers was found in 1975 [3], but more serious development work concentrating on single-crystal Si and Ge detectors has been recent [4-7]. McCammon et al. [8] have reached a spectacular 35 eV resolution in their Si detector using 6 keV X-rays.

2. NEUTRAL-CURRENT SCATTERING

2.1 Differential cross-section

The coherent scattering of neutrinos on heavy nuclei has several appealing features which may enable the study of the gauge field theories underlying the electroweak interactions. Let us consider a nucleus with \( Z \) protons and \( N \) neutrons, and apply the WS model in Eq. (1) ignoring the small spin-dependent terms. The differential cross-section [9] in the forward elastic peak due to neutral current is then

\[ \frac{d\sigma}{dq^2} = (G^2/8\pi) [Z(1 - 4 \sin^2 \theta_w) - N \sin^2 \theta_w] e^{-2\alpha q^2} [1 - q^2 (2ME_\nu + M^2)/(4M^2E_\nu^2)] \]  

and is independent of the neutrino type. Here \( \theta_w \) is the Weinberg angle, \( G \) the Fermi constant, \( M \) the nuclear mass, \( E_\nu \) the neutrino energy, and \( b \equiv r^2/6 \) is related to the r.m.s. nuclear radius \( r \) in analogy with electron scattering [9]. The cross-section has an enhancement roughly proportional to \( N^2 \) compared with charged current cross-sections. This is strictly true for spin-zero nuclei; other nuclei have additional small contributions from axial vector currents. These contributions depend more on the nuclear form factors but they are well below 10% of Eq. (2) [10] for medium-heavy nuclei such as Fe.
The coherent enhancement of the cross-section (2) occurs in the kinematic range \( q^2 < (2b)^{-1} = 3/r^2 = (100 \text{ MeV}/c)^2 \). At larger momentum transfers the situation is complicated by the quasi-elastic scattering, where the nucleus is left in an excited or broken state. There are, however, cases where simple analysis might be possible; some of these will be briefly discussed below. In the kinematic region where the coherent scattering dominates, we have \( M^2 \gg q^2 \) and the equality \( q^2 = 2MT \) holds, where \( T \) is the laboratory kinetic energy of the recoil nucleus. For the purpose of rate estimates, we approximate \( \sin^2 \theta_w = 0.25 \) and rewrite Eq. (2)

\[
\frac{d\sigma}{dT} = (G^2 MN^2/4\pi) [1 - (T/T_{\text{max}})] \exp \left( -T/T_{\text{coh}} \right),
\]

where \( T_{\text{max}} = 2E^2/(M + 2E_r) \). We wish to emphasize that Eq. (3) is supposed to be valid only up to \( T_{\text{coh}} = 3/(2Mr^2) \) (= 240 keV for Si; see Table 1), whereas for \( E_r = 40 \text{ GeV} \) in the SPS neutrino beam and for \( M(\text{Si}) = 26 \text{ GeV} \), we have the hypothetical \( T_{\text{max}} \approx 30 \text{ GeV} \).

Figure 1 shows the qualitative behaviour of the recoil spectrum for a Si target-detector. The upper line is the coherent cross-section for a pointlike nucleus (at \( E_r > 1 \text{ GeV} \)); the exponentially dropping line shows the cross-section of Eq. (2) using the r.m.s. nuclear radius from electron-scattering data [12]. The shaded area indicates the range of energy deposits in the detector where contributions from excited nucleons could add features both in the recoil spectrum and in the signal shapes.

2.2 Total coherent cross-section

In estimating the total coherent cross-section \( \sigma_{\text{coh}} \) we integrate Eq. (3) to get

\[
\sigma_{\text{coh}} = (G^2/4\pi) MN^2 T_{\text{coh}} f(\xi),
\]

where \( f(\xi) = 1 - (1 - e^{-\xi})/\xi \), and \( \xi = T_{\text{max}}/T_{\text{coh}} = (2/3)E^2_r r^2/(1 + 2E_r/M) \). In the high-energy limit we have \( f(\xi) = 1 \), and the cross-section is constant and a few orders of magnitude higher than the usual neutrino cross-sections. In the low-energy limit \( T_{\text{coh}} > T_{\text{max}} = 2E^2_r/M \), which implies \( E_r < 50 \text{ MeV} \), and the total coherent cross-section decreases strongly with energy [13]:

\[
\sigma_{\text{coh}} = (G^2/4\pi) N^2 E^2_r.
\]

Figure 2 shows the behaviour of the coherent cross-section for O, Si, Ge, and Bi targets, as a function of neutrino energy \( E_r \).

2.3 Quasi-elastic scattering

Above \( q^2 \approx 3/r^2 \) the recoil-energy spectrum registered by the calorimeter would reflect the sum of many possible processes, one of which is the elastic coherent process

\[
\nu + A \rightarrow \nu' + A,
\]

which goes down approximately as \( \exp \left( -2b/q^2 \right) \), and others are

2
$\nu + A \rightarrow \nu' + A'$; \quad $A' \rightarrow A + \gamma$

$\nu + A \rightarrow \nu' + B + X$ \quad plus subsequent decays of $B$ and/or $X$,

where the excitation energy of the quasi-elastic reaction products may show up delayed depending upon the lifetime of the particular state selected. The delayed calorimetric signal might provide a sensitive trigger for the selective study of some of these reactions and allow good discrimination among the various gauge models [11].

3. THE DETECTOR

The development work at CERN has concentrated on the understanding of the thermal behaviour of the calorimeter, in order to be able to optimize the construction and to be able to extrapolate the detector size to the region of interest for neutrino experiments and other applications where large masses might be desirable. Our results on small integrated phosphorus-implanted Si detectors and melt-doped Ge detectors are encouraging; these are discussed elsewhere in these Proceedings [14] in the light of the recent analysis of our previous data.

3.1 Calorimeter elements

For the purpose of the experiments discussed here, we need the total detector masses in the range 1 to $10^3$ kg, consisting of 0.1 to 1 kg lumps of pure Si and/or Ge. The single-crystal rods would be cut into slices and mounted in a frame cooled by a $\text{^3He/\text{^4He}}$ dilution refrigerator. The thermistors are attached to each detector by laser welding or sintering techniques, and are cut, etched, and wired after attachment. Crystals of B and Bi, and also compounds such as BeO, Al$_2$O$_3$, TiO$_2$, GeO$_2$, SiC, and TiB$_2$, could be included in the detector, depending on the availability of pure single-crystal materials and on the scope of the experiments.

Table 1 gives the energy resolution of 0.1 kg calorimeter units at 30 mK temperature, based on the uncertainty principle of quantum statistics,

$$\Delta E_{\text{rms}} = \xi \sqrt{kT_0 C_0},$$  \hspace{1cm} (6)

where $T_0$ is the detector temperature, $C_0$ the heat capacity, and $\xi \approx 2.5$ depends slightly on thermistor parameters; the table is based on the Debye heat capacity only.

3.2 Amplifiers

The preamplifiers must have their input stages near the detectors, in order to reduce the parasitic lead capacitance, and to protect against interference, cross coupling, and noise. This allows one to obtain a frequency response matching the counting rate, which is dominated by cosmic-ray muons (about 1.5 s$^{-1}$ in 1 kg units).

The input stages of the preamplifiers can use either Si or GaAs JFETs cooled to 100 K or 10 K, respectively. The subsequent stages of amplification may use commercial integrated circuits; the amplifiers can be located at room temperature.
3.3 EMI control

The extremely small signals corresponding to temperature increments below 1 $\mu$K in the calorimeters require the ultimate in the control of the electromagnetic interference (EMI) in the difficult range below 1 MHz. The main sources of interferences are related to the operation of heavy electrical equipment and also to acoustic microphonics. Our experience shows that by enclosing the equipment in a double-walled Faraday cage and heavily filtering the main power feed, these interferences can be reduced to an acceptable level. This technique is also efficient in removing interferences in the higher frequency spectrum, which cause direct heating of the thermistors and thermometers in the level $10^{-10} - 10^{-12}$ W; this heating fluctuates and adds to the noise of each detector in a correlated way. The severity of this heating may be visualized by recalling that the heat conductance is around $10^{-10}$ W/K from a calorimeter at 30 mK to the heat sink.

The data-acquisition electronics must provide signal triggering, vetoing, digitization, and transmission via fibre-optic links to a computer located outside the Faraday cage. Apart from the power feed into the cage, no other galvanic transmission line is allowed to penetrate the shield. It is also necessary to soften the equipment operated in the shielded area with respect to its electromagnetic emission.

4. RATE ESTIMATES

Our primary physics aim in the experiments discussed here is to reach an excellent statistical accuracy in the measurement of the large cross-section for neutral-current neutrino–nucleus scattering predicted by Eq. (2). Table 1 summarizes the cross-sections for some elements of interest. The rate estimates of Table 2 are made for the neutrino beams at the CERN Super Proton Synchrotron (SPS) and Antiproton Collector (ACOL), and for the RAL ISIS spallation neutron source and the Gösgen reactor.

For SPS we have assumed $1.5 \times 10^{13}$ protons on target (p.o.t.) at 10 s intervals and a neutrino yield of $2 \times 10^6 \, \nu \cdot \text{cm}^{-2}/(10^{13} \, \text{p.o.t.})$, which roughly corresponds to an effective distance of 500 m from the decay channel. The ACOL beam flux is calculated at a distance of 15 m from the decay straight section, using the predicted machine parameters [15]. The ISIS flux is based on a beam current of 100 $\mu$A and 15 m distance from the production target. The reactor numbers refer to operation at 3 GW thermal power and 40 m effective distance from the core; such conditions can be met at Gösgen, for example, but larger fluxes may be available elsewhere (closer to the core).

The required target mass is calculated for Ge calorimeters, asking for an event rate of 1/h which would allow the collection of about $10^4$ events in a year. Such an amount of events might enable the weak interaction models to be studied in detail.

5. BACKGROUND

The background rate may be $10^4$ times higher than the coherent event rate, and must therefore be measured very accurately. This is not a major problem in pulsed beams; continuous sources may require extra care and the use of calorimeter elements of various sizes and shapes. We shall discuss below some of the sources for background, which may turn out to be of prime interest in their own right.
5.1 Quasi-elastic scattering

As the energy resolution of our projected detector may be rather good, it would be tempting to look for anomalous behaviour in the predicted spectrum of recoil energies. At the upper end of the coherent recoil spectrum it is expected that the nucleus might be left in an excited state; this may slightly increase the cross-section [11] and, in particular, may deform the detector signal because of the delayed release of the de-excitation $\gamma$'s from the nucleus. These reactions depend much on the target nucleus and may provide a sensitive test of the models of electroweak interactions [11]. The deformed signals might offer a clear signature and high background rejection in these studies. The normalization with the coherent forward peak could allow another unique determination of the parameters of the electroweak interaction.

5.2 Exotica

Because our method of detection is not based on ionization and charge collection but on the measurement of the heat resulting from the collisional energy loss of the beam particle, the detector could be sensitive to new 'exotic' particles escaping all other detectors because of the particle's inability to ionize. Among the candidates there are slow heavy monopoles, slow heavy supersymmetric particles, and other candidates for dark matter, for example.

Another interesting kinematic region is the low $q^2$ part of the recoil spectrum. It has been proposed that a new light neutral gauge boson $U$ could increase the neutrino cross-sections at very low $q^2$ [16]. This gauge boson is necessary if one wants spontaneous breaking of the supersymmetry to generate large masses for spin-0 leptons and quarks at the one approximation [16].

5.3 Astrophysics and nuclear explosions

The detector with somewhat smaller grains could have interesting applications in astrophysics, for example in the studies of the solar neutrino spectrum or observation of neutrino bursts from supernova events. Also, the detector could be useful in the studies or observations of man-made nuclear explosions.

5.4 Cosmic-ray muons

The sea-level rate of 200 s$^{-1}$ cm$^{-2}$ of muons will cause about 1.5 s$^{-1}$ counting rate in 1 kg detector units of about 80 cm$^2$ area horizontally. The muon will deposit about 10–50 MeV in the detectors, which is a clear signature in comparison with the coherent recoils below 1 MeV. The thermal and electric rise-time of the detector modules is about 10 $\mu$s; this allows the use of a rather narrow window for the vetoing of the coincident events in the detector.

5.5 Residual radioactivity

The $\alpha$-emitters usually leave narrow lines which may serve for calibration purposes. The $\beta$- and $\gamma$-emitters are more problematic and must be reduced to a minimum. However, the background is measured to a high accuracy in pulsed beams.

The radioactivity background rate must not exceed $10^3/(d\cdot kg)$ in the coherent recoil energy region below 1 MeV. On the basis of experience in low-counting laboratories and of measurements performed on our constructional materials, this background rate seems possible to achieve.

A large calorimetric detector could allow the determination of interesting new limits for rare radioactive decays, such as the electron decay and neutrinoless double-beta decay [5].
5.6 Beam-related particles

The charged particles are easily vetoed because they deposit about 100 MeV in the detector modules in coincidence. Fast neutrons deposit about 30 times less and also cause coincidences. Slower neutrons may be very problematic and their rate may have to be measured separately.

6. CONCLUSIONS

To summarize, relatively small (∼ 100 kg) detectors in medium- and low-energy neutrino beams could reach event rates around 1/h in the coherent forward elastic peak due to neutral currents. This could allow a unique measurement of the parameters \( a_0 - a_1/2 \) (= 1 in the WS model) and \( a_0 + a_1/2 \) (= \( 1 - 4 \sin^2 \theta_w \) in the WS model) if the cross-section ratios on different nuclei could be accurately determined.

Comparison with other types of events in the same detector and/or other detectors could allow discrimination between the various gauge field models for electroweak interaction theories.

Any anomalous behaviour in the recoil spectrum could give hints of the existence of exotic phenomena; conversely, the absence of anomalous features could be interpreted as setting limits to these phenomena. The selective excitation to nuclear levels could offer another sensitive determination of the weak interaction parameters, if the statistics would allow substantially lower cross-sections to be determined.

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   Proceedings.
Table 1
Calorimeter material properties

<table>
<thead>
<tr>
<th>Element</th>
<th>Z</th>
<th>M  (g/mol)</th>
<th>T_{coh} (keV)</th>
<th>θ_D (K)</th>
<th>ΔE^a) (eV)</th>
<th>α_{coh} (10^{-38} cm^2)</th>
</tr>
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<tbody>
<tr>
<td>C</td>
<td>6</td>
<td>12.000</td>
<td>892</td>
<td>2240</td>
<td>11</td>
<td>0.151</td>
</tr>
<tr>
<td>Si</td>
<td>14</td>
<td>28.086</td>
<td>242</td>
<td>647</td>
<td>46</td>
<td>0.527</td>
</tr>
<tr>
<td>Ge</td>
<td>32</td>
<td>72.590</td>
<td>54</td>
<td>378</td>
<td>64</td>
<td>2.526</td>
</tr>
<tr>
<td>Bi</td>
<td>83</td>
<td>208.980</td>
<td>10</td>
<td>119</td>
<td>212</td>
<td>12.777</td>
</tr>
</tbody>
</table>

a) ΔE is given for 0.1 kg mass at 30 mK temperature

Table 2
Neutrino fluxes, event rates, and required Ge target masses

<table>
<thead>
<tr>
<th>Machine</th>
<th>E_{ν} (GeV)</th>
<th>Flux (cm^{-2} s^{-1})</th>
<th>Rate (day^{-1} t^{-1})</th>
<th>Required target mass^a) (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPS</td>
<td>&lt; 40</td>
<td>(2 \times 10^5)</td>
<td>5</td>
<td>5000</td>
</tr>
<tr>
<td>ACOL</td>
<td>3</td>
<td>(10^7)</td>
<td>250</td>
<td>100</td>
</tr>
<tr>
<td>ISIS</td>
<td>0.3</td>
<td>(10^5)</td>
<td>200</td>
<td>120</td>
</tr>
<tr>
<td>Reactor</td>
<td>&lt; 0.01</td>
<td>(3 \times 10^{12})</td>
<td>60000</td>
<td>0.4</td>
</tr>
</tbody>
</table>

a) For a Ge detector with rate 1/h
Fig. 1  Differential cross-section for coherent elastic neutrino-nucleus scattering

Fig. 2  Total cross-section for coherent neutrino scattering