2 Measurement of the Neutrino Magnetic Moment at the Bugey Nuclear Reactor

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2.1 Introduction

In the standard model the magnetic moment vanishes for massless neutrinos. Even for massive ν_e with masses in the range observed recently, the standard model predicts magnetic moments much below 10^{-20} μ_B, which are not accessible experimentally. The experimental evidence for a large magnetic moment would mean new physics beyond the standard model. With a finite magnetic moment the spin of a lefthanded neutrino may flip due to the electromagnetic interaction, and the neutrino becomes a "sterile" righthanded state which does not interact, and hence is experimentally invisible. The precession of a magnetic moment in the range $\mu_\nu \sim 10^{-10} - 10^{-12}$ μ_B in the solar magnetic field offers an alternative explanation to the MSW effect for the observed deficit of solar neutrinos.

We measure the magnetic moment of antineutrinos $\overline{\nu}_e$ from a nuclear reactor, using the elastic scattering reaction $\overline{\nu}_e e^- \rightarrow \overline{\nu}_e e^-$. This process is very sensitive to the magnetic moment of the $\overline{\nu}_e$ (especially at low neutrino and low electron recoil energies) because it is a purely leptonic and theoretically well understood weak process. A finite neutrino magnetic moment leads to an excess of forward scattered low energy electrons.

A detailed description of the apparatus can be found in Ref. [1, 2] and in previous annual reports. MUNU uses a 1 m^3 time projection chamber (TPC, gaseous CF_4 at 3 bar) surrounded by a tank filled with liquid scintillator to guard against cosmic muons and Compton scattering of low energy γ's. We measure both the angle and the energy of the recoil electron and hence can calculate the neutrino energy. The energy threshold for detecting electrons is typically 300 keV. We also measure simultaneously the signal and the background, since electrons cannot be scattered in the backward hemisphere.

2.2 Data analysis

The experiment works well since the beginning of 2001. We collected neutrino data during 111 days, corresponding to 68 days after deadtime subtraction. We also collected reactor off data during 37 days (24 days after deadtime subtraction). In addition, calibration data were recorded periodically for various triggers. A typical event is shown in Fig.2.1.

The data are being analysed following two different routes. In the first procedure ("visual" tracking, applied by the Neuchâtel group) every potential neutrino event is examined by eye and the scattering angle and recoil energy is determined. We briefly discuss the results from 30 days of neutrino runs with a high offline electron threshold of 700 keV. The lefthand side of Fig.2.2 shows the energy distribution of the recoil electrons for forward emission, i.e. for electrons emitted in the direction opposite to the reactor core. The distribution for backward electrons is also shown. Backward electrons do not stem from neutrino-electron scattering. Assuming that they are isotropically distributed we can subtract the two spectra to obtain the contribution from the signal events (Fig.2.2, right). The spectrum shows the expected

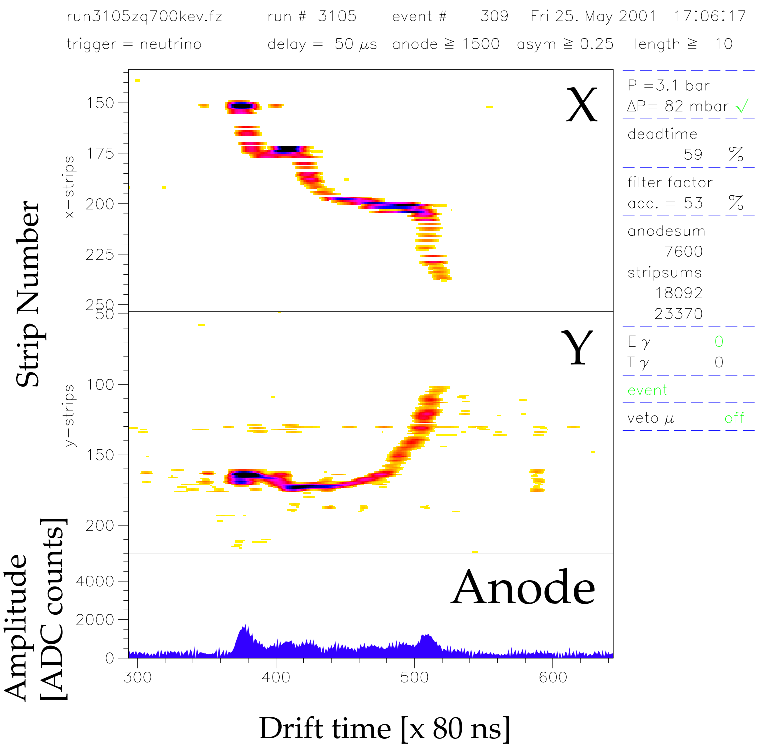

Figure 2.1: *Typical neutrino-electron scattering event visualised in the MUNU TPC. Shown are the x-z and y-z projections and the pulse height measured on the anode (bottom). Note the high ionisation rate of the electron at the end of its track (dark blob).*

shape, rising towards low electron energies. We obtain 95 ± 20 neutrino events for 30 days, while expecting 51 for a vanishing neutrino magnetic moment. We thus observe roughly twice as many events as predicted.

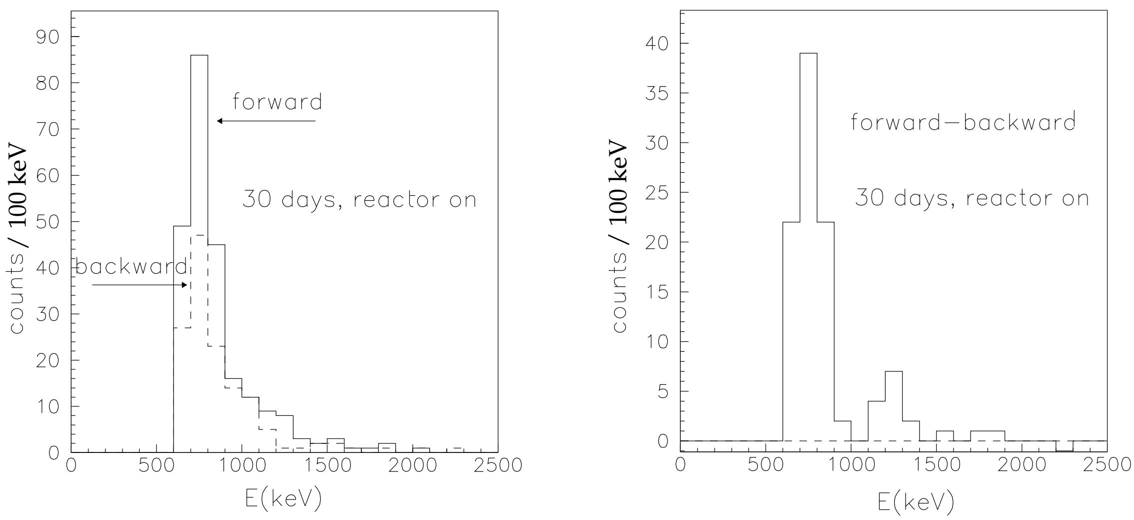

Figure 2.2: *Left: recoil energy distribution of electrons in the TPC for a 30 days run (visual tracking). Right: subtracted plot. The low energy cut is due to the offline threshold cut of 700 keV (the event drop below 700 keV is not sharp because a precise re-calibration of the anode pulse height was performed after the cut).*

In the alternative analysis (followed by the University of Zürich group) events are processed using a pattern recognition program ("automatic tracking"). With the automatic reconstruction program we should be able to analyse larger datasets, e.g. neutrino data with lower electron recoil energies. However, the software needs to be carefully tested and compared to Monte Carlo simulation. In fact, some of the early reconstruction algorithms were inappropriate and we had to rewrite part of the reconstruction software. We now describe in more details the analysis of about 24% of the data using the new automatic reconstruction software[3].

The typical TPC trigger rate of 100 Hz was reduced by the anti-Compton shield (which mostly removed the cosmic muons) to about 0.15 Hz. The size of an event was 600 kB and we collected 1.4 million raw data events on exabyte tapes with reactor ON. The data were first filtered to remove noise on the anode signal and to set a preliminary electron recoil energy threshold of 250 keV. Events with tracks crossing the anode led to fast photomultiplier signals and were removed. The anti-Compton veto was applied with a threshold of 100 keV and a first fiducial volume cut was applied to remove events with signals close to the edge of the TPC, i.e. those with a signal on the first or last $x-y$-strips (which are perpendicular to the axis z of the TPC).

These cuts led to $2.8{\times}10^5$ reactor ON events (and to $8.1{\times}10^4$ reactor OFF events) to be further processed by the pattern recognition programme. The point with the largest energy deposit (see Fig.2.1) determines the coordinates of the track endpoint (stopping electron). The track is then reconstructed and the vertex (neutrino-electron scattering point) determined independently in the $x-z$ and $y-z$ projections. The vertex position along z has to agree in either projection within a resolution of 1.4 cm determined by Monte Carlo simulation using GEANT. A new fitting procedure was developed to determine the azimuthal angle ϕ of the electron as the previous approach led to computational instabilities. The electron recoil angle (polar angle Θ) is finally determined knowing the position of the reactor core. The $\cos\Theta$ (Fig.2.3) distribution is now in much better agreement with the results from the visual tracking. The events are then written to data summary tapes.

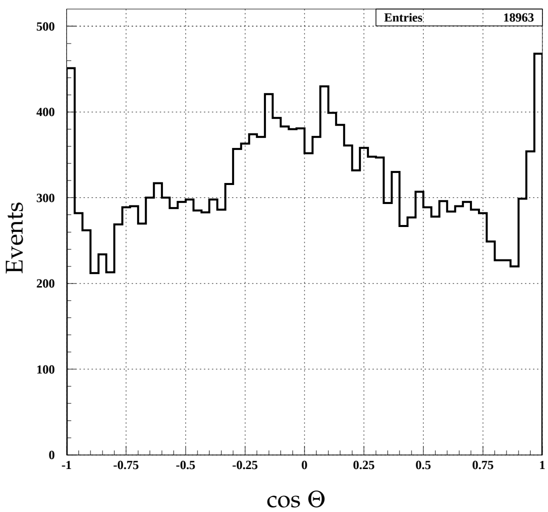

Figure 2.3: *Distribution of* $\cos\Theta$ *of recoil electrons for reactor ON events (not corrected for acceptance). The value* $\cos\Theta$ *= 1 corresponds to the direction opposite to the reactor core.*

This reconstruction procedure was applied so far to 30% of the available $2.8\ {\times}10^5$ reactor ON events (and to 56 % of the reactor OFF events). Further cuts were then applied: (i) an electron threshold cut of 500 keV, (ii) a fiducial volume cut of 42 cm around the TPC axis and (iii) a drift time cut ensuring that the track is confined within 40 μs (the maximum drift time of the TPC), (iv) a positive neutrino energy, reconstructed from the recoil angle and recoil energy. We obtained 160.4 ± 2.8 events/day in the forward hemisphere (hence opposite to the reactor core) and 155.1 ± 2.8 events/day in the backward hemisphere. This leads to a forward/backward asymmetry A_{FB} of 5.3 ± 4.0 events/day (the corresponding asymmetry for reactor OFF events is -4.1 ± 5.0). Figure 2.4 shows A_{FB} as a function of electron energy. The electroweak prediction without contribution from the neutrino magnetic moment is shown as well.

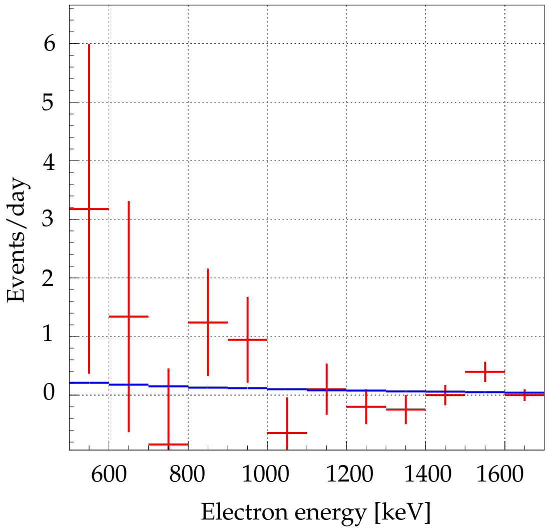

Figure 2.4: *Forward/backward asymmetry A_{FB} as a function of electron energy (crosses). The solid histogram shows the expected electroweak signal assuming a vanishing magnetic moment.*

As for the visual tracking at 700 keV threshold, we find about twice as many events as expected. Of course the statistical significance is not yet sufficient to claim a non-vanishing magnetic moment, but another 75% of the data remain to be processed. We find from these results a preliminary 90% confidence level upper limit of 3 $\times 10^{-10}$ μ_B. Previous laboratory experiments led to upper limits of $\mu_\nu < 1.9\times\ 10^{-10}$ μ_B [4] and 1.5 $\times$ 10^{-10} μ_B [5]. The astrophysical upper limits, e.g. from SN1987A, are lower by two orders of magnitude but make assumptions, in particular that the neutrino is a Dirac particle. On the other hand, it is interesting to note that a reanalysis of Reines' Savannah data[6] led to a magnetic moment of the size of our upper limit, when taking into account today's improved knowledge of reactor spectra[7].

Data taking for this experiment was completed in autumn 2001. The detector is currently running at 1 bar, and various calibrations are being performed before de-commissioning in 2002.

References

[1] C. Amsler *et al.*, Nucl. Instr. Methods **A 396** (1997) 115.

[2] M. Avenier *et al.*, Nucl. Instr. Methods in Phys. Research (in print).

[3] O. Link, PhD thesis, Universität Zürich, in preparation.

[4] A. I. Derbin *et al.*, JETP Lett. **57** (1993) 768.

[5] J.F. Beacom and P. Vogel, Phys. Rev. Lett. **83** (1999) 5222.

[6] F. Reines, H.S. Gurr and H.W. Sobel, Phys. Rev. Lett. **37** (1976) 315.

[7] P. Vogel and J. Engel, Phys. Rev. **D39** (1989) 3378.