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

C. Amsler, O. Link and H. Pruys

in collaboration with:
Institut des Sciences Nucléaires (Grenoble), Université de Neuchâtel, Università di Padova

(MUNU Collaboration)

The MUNU experiment measures 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 pure leptonic and theoretically well understood weak process.

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 become 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.

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) to measure the scattering angle and the kinetic energy of the recoil electron. The energy threshold for detecting electrons is typically 300 keV. Since the cross section for neutrino reactions is very low, background measurements are important. To reject background events due to cosmic muons and Compton scattering of low energy γ's, the TPC is surrounded by a tank filled with liquid scintillator. The electrons are scattered into the forward hemisphere. To subtract the background, electrons are also measured in the backward hemisphere. Measurements during reactor shutdown were done to check that equal amounts of background electrons are emitted in the forward and backward hemispheres.

Data taking was completed in 2002. We collected neutrino data during 111 days, corresponding to a livetime of 66.3 days after deadtime subtraction. We also collected reactor off data during 37 days (19.3 days after deadtime subtraction). In addition, calibration data were recorded periodically for various triggers.

A first quick analysis was done by "visual" tracking: every potential neutrino event was examined by eye and the scattering angle and recoil energy were determined. This method, applied by the Neuchâtel group, was restricted to the analysis of recoil electrons with an energy above 700 keV.

A systematic data analysis was performed by the University of Zürich group using a pattern recognition program ("automatic tracking"). With the automatic reconstruction program we were able to analyze larger datasets, e.g. neutrino data with lower electron recoil energies. The software was carefully tested and compared to Monte Carlo simulation [3]. The angular resolution and acceptance were determined from Monte Carlo generated events (see fig. 2.1). The resolution and acceptance become worse at lower energies, mainly due to multiple scattering and electronic noise.

The final analysis is done by comparing the electron rates in the forward hemisphere (neutrino scattering events and background events) with those in the backward hemisphere (background events

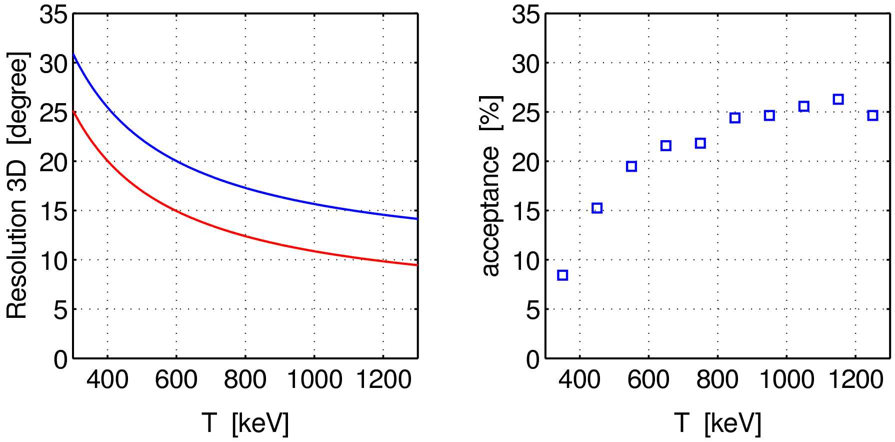

Figure 2.1: *Left: Angular resolution on the direction of the recoil electron as a function of electron energy. Red curve: 3d angular fit with true vertex; blue curve: fit with reconstructed vertex. Right: Acceptance as function of electron energy.*

only).

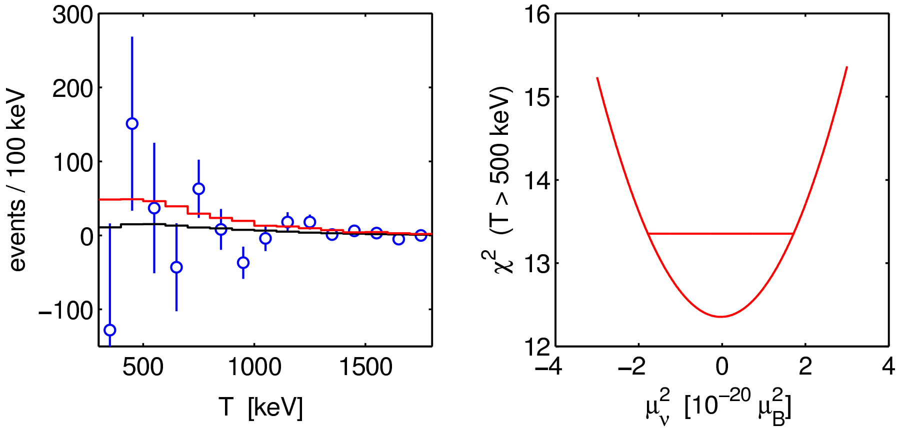

Figure 2.2: *Left: Energy spectrum of forward minus backward events. The data points are compared with Monte Carlo spectra without magnetic moment (black curve) and with a magnetic moment of* $1.7 \times 10^{-10}\mu_B$ *(red curve). Right:* χ^2 *as function of* μ_ν^2 *(fit parameter).*

Figure 2.2 (left) shows the measured forward minus backward intensity as a function of electron energy. The curves show Monte Carlo simulations based on the electroweak theory with no contribution from the neutrino magnetic moment (black) and with a magnetic moment of $1.7 \times 10^{-10}\mu_B$ (red). The Monte Carlo simulation gives the expected number of events per 100 keV as a function of recoil electron energy T

$$MC(T) = W(T) + \mu_\nu^2\, M(T),$$

where the part $W(T)$ is independent of the magnetic moment and the part involving $M(T)$ depends on the square of the magnetic moment. Fitting this expression to the data and using μ_ν^2 as free parameter gives $\mu_\nu^2 = (-0.04 \pm 1.74) \times 10^{-20}\mu_B^2$ (fig. 2.2, right). Thus there is no indication of a finite magnetic moment. A 90% confidence level upper limit of

$$\mu_\nu < 1.7 \times 10^{-10}\,\mu_B \qquad (2.1)$$

is obtained using the unified approach of ref. [4] to obtain an upper limit from gaussian data close to a physical boundary. This upper limit is somewhat smaller than the preliminary limit $2.3 \times 10^{-10}\mu_B$ published by the MUNU collaboration [5] and somewhat larger than the limit $1.4 \times 10^{-10}\mu_B$ obtained by a visual scan above 700 keV. However, our upper limit, eqn. (2.1), is independent of the applied energy threshold (see fig. 2.3). The larger background compensates for the increased sensitivity to μ_ν at lower recoil energies.

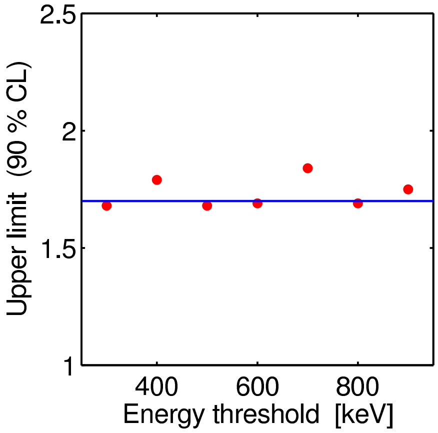

Figure 2.3: *Upper limits on μ_ν (in units of $10^{-10}\mu_B$) as a function of recoil energy threshold.*

Previous laboratory experiments led to upper limits of $\mu_\nu < 1.9 \times 10^{-10}$ μ_B [6] and 1.5×10^{-10} μ_B [7]. 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 [8] led to a magnetic moment of the size of our upper limit, when taking into account today's improved knowledge of reactor spectra [9].

The present work is part of a PhD thesis [3]. The apparatus is being dismantled in 2003. This report is therefore the last one on our contribution to the MUNU experiment.

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