Electron Scattering for Neutrino Physics at MAMI and MESA

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Abstract. The groundbreaking discovery of neutrino oscillations represents a concrete indication of new physics and the measurement of the oscillation parameters has the potential to unlock new knowledge on the fundamental building blocks of matter. For measuring the neutrino properties to percent-level precision, an ambitious accelerator-based experimental program was started by two international collaborations: HyperK and DUNE. However, these experiments will only be able to achieve their unprecedented precision goal if our current knowledge of neutrino-nucleus interactions in the detectors is dramatically improved. In this contribution, we describe how experiments based on electron beams can provide key information to neutrino experiments, benchmarking theoretical models, improving simulations needed for a reliable extraction of the neutrino oscillation parameters, and decisively contribute to the success of next-generation neutrino experiments.

1. Introduction

Neutrinos stand out among the other elementary particles for their peculiar properties. Although they are copiously produced within many physics processes ranging from radioactive decays to supernova explosions, their ultimate properties remain elusive.

According to the Standard Model of particle physics (SM), neutrinos are described as massless, electrically neutral particles interacting only through the weak interaction. The groundbreaking discovery of neutrino oscillations implies that neutrinos have a tiny mass and this represents a striking evidence of physics beyond the SM. The mystery about neutrinos thickens since they do not have charge: this opens the possibility for neutrinos to be their own antiparticles. Particles with this property are described by Majorana spinors instead of Dirac spinors like all the other SM fermions.

In the SM, there are three neutrino flavour eigenstates: ν_e, ν_μ, ν_τ associated to the corresponding SM leptons (electron, muon, and τ), while the mass eigenstates ν_1, ν_2, ν_3 are different. Flavour and mass eigenstates are connected by a mixing matrix, the Pontecorvo-Maki-Nakagawa-Sakata matrix [2, 1] which can be conveniently parameterized by three angles $\theta_{12}, \theta_{23}, \theta_{13}$ and one CP-violating phase δ. If neutrinos are Majorana fermions, two additional phases have to be considered:

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{Solar Neutrinos}}\underbrace{\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{-i\delta} & 0 & c_{13}\end{pmatrix}}_{\text{Reactor Neutrinos}}\underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\text{Atmospheric/Accelerator}}\underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & e^{i\alpha_1/2} & 0\\ 0 & 0 & e^{i\alpha_2/2}\end{pmatrix}}_{\text{Majorana Phases}}\cdot\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix},$$

where $c_{ij}=\cos\theta_{ij}$ and $s_{ij}=\sin\theta_{ij}$. In the previous equation, the mixing matrix is decomposed in three matrices which refer to the corresponding most sensitive experiments, plus a matrix containing the Majorana phases.
The precise knowledge of these parameters represents a fundamental step forward towards a full understanding of the SM and a promising path for going beyond it. The current and future experimental activity is focused on the measurement of the mixing angles and the CP-violating phase, which is often regarded as one of the main future goals of this research. Measuring the neutrino oscillation parameters is the subject of a world-wide intense experimental activity which is taking a significant step forward with the gearing up of two major international initiatives: the HyperK [4] and DUNE experiments [3]. These experiments plan at reaching O(1%) precision in the measurement if the neutrino oscillation parameters and at measuring the CP-violating phase δ: this will be possible only reducing the present limiting systematic uncertainties on the interaction cross section of neutrinos with nuclei in the detectors.
In accelerator-based neutrino experiments, neutrinos are produced impinging a proton beam on a thick target. Neutrinos are then detected by a near-detector (ND) close to the target and by a far-detector (FD) placed at a distance optimized for detecting neutrino oscillations. The oscillation parameters are extracted with a fit to the ND and FD data. Since the oscillation probability depends crucially on the neutrino energy E_ν, this quantity must be precisely reconstructed and this requires a detailed understanding of the neutrino-nucleus cross section (νA) in the detectors. For example, considering for simplicity only two neutrino flavours, the probability of a neutrino ν_α to oscillate into ν_β $(\alpha,\beta=e,\mu,\tau)$ is

$$P(\nu_\alpha\to\nu_\beta)=\sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2(\mathrm{eV})L(\mathrm{km})}{E_\nu(\mathrm{GeV})}\right),$$

where L is the baseline oscillation distance and in parentheses the correct units are specified. The extraction of the difference of the squared masses Δm^2 and of the oscillation angle θ depend on the reconstruction of E_ν and $P(\nu_\alpha\to\nu_\beta)$ from the number of events detected at the ND (N_{ND}) and at the FD (N_{FD}):

$$N_{FD}(\nu_\alpha\to\nu_\beta,E_R)=\int dE_\nu\Phi_{\nu_\alpha}(E_\nu)\times\sigma(E_\nu)\times R_{\nu_\alpha}(E_\nu,E_R)\times P(\nu_\alpha\to\nu_\beta,E_\nu),$$

$$N_{ND}(\nu_\alpha,E_R)=\int dE_\nu\Phi_{\nu_\alpha}(E_\nu)\times\sigma(E_\nu)\times R_{\nu_\alpha}(E_\nu,E_R)\quad. \tag{1}$$

Φ_{ν_α} is the neutrino flux coming from the target, and E_R is the energy ultimately reconstructed by the detector. Only the FD formula contains the energy-dependent oscillation probability. A common feature of Eqs. 1 is the presence of the neutrino interaction cross section $\sigma(E_\nu)$ and of the detector response $R_{\nu_\alpha}(E_\nu,E_R)$ (the "migration matrix") which encodes detection efficiency and resolution effects and connects the reconstructed neutrino energy E_R to the true neutrino energy E_ν. These quantities depend from the neutrino interaction with nuclei, which is still affected by a significant lack of precision. The modeling of the cross section is complicated by the array of different mechanisms entering the process: elastic scattering, quasi-elastic scattering, excitation spectrum of the nucleon in the nucleus, meson production, and deep inelastic scattering. The possible presence of multi-particle final states adds further complications.

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2. Neutrino generators and the role of electron scattering

Currently, the complex modeling required from long-baseline neutrino experiments is done with simulation packages (commonly known as "generators") containing theoretical and data-driven models [5, 6, 7]. Neutrino experiments use mainly two methods for reconstructing the initial neutrino energy E_ν:

- **Kinematic Method.** This reconstruction technique is exploited for example by T2K [10] and in the future by HyperK [4] using water-based Cherenkov detectors. Cherenkov light is generated only if particles exceed an energy threshold which for protons is about 1 GeV. Particles produced below threshold in a neutrino-nucleus interaction remain undetected, biasing the neutrino energy reconstruction. The presence of an additional neutron or pion is particularly challenging: as chargeless particles, neutrons are difficult to detect, and pions require low energy thresholds. The method also assumes a charged current quasi-elastic reaction (CCQE) and it is thus fundamental to know the details of this process.
- **Calorimetric Method.** This method is used in current experiments like MINOS [8], NOνA [9], and in the future by DUNE [3]. The idea is to have an energy measurement of all the produced particles and in the case of DUNE this will be realized with a liquid argon time projection chamber detector. An advantage of the method resides in its not relying on a specific process like CCQE. Challenges for the calorimetric method are again neutron and pion detection.

The reconstruction methods are limited by the limited knowledge of neutrino-nucleus (νA) cross sections. For example, in [11] the extraction of the oscillation parameters was studied in the case of kinematic reconstruction and potential biases as large as 3σ were demonstrated if nuclear models were not accurately known. Similar results were obtained for the calorimetric method [12].
Within current experiments, νA interactions contribute to the systematic uncertainty at the O(10%) level while the new experiments require O(1%).
Electron-nucleus scattering (eA) can provide decisive information for understanding these processes, since the vector part of the interaction current is the same as in the νA case.
In recent years, theoretical nuclear physics made substantial progress in calculating νA cross sections with *ab-initio* methods like quantum Monte Carlo [17] and Coupled Cluster Theory [16].
Despite these successful efforts, exclusive channels are not yet within reach, and the large number of nucleons to treat represents a formidable computational challenge for *ab-initio* theory. More phenomenological methods are currently used by the experimental collaborations for describing the available νA data [13, 14, 15].
The neutrino community is engaged in an effort aimed at improving the knowledge of νA interactions also employing electron scattering [18, 19].

3. The MAMI Accelerator and the A1 Experimental Setup

The Mainz Microtron (MAMI) is an electron accelerator operated by the Institute for Nuclear Physics of the University of Mainz and it is employed for nuclear and hadron physics experiments. MAMI is a multi-stage racetrack microtron with normal conducting acceleration cavities. The accelerator is available for experiments since 1991 and the last added stage, MAMI-C, became operational in 2007 rising the beam energy up to 1.6 GeV with a maximum current of 100 μA. The beam diameter is $\sim$0.1 mm with an energy resolution of 13 keV. A beam stabilization system maintains the beam position constant within $200 \mu m$. The beam has a continuous-wave structure (100% duty cycle) and the possibility to be polarized at the $\sim 80\%$ level. The beam can be delivered to different experiments. Here we will focus on the A1 Collaboration (see Fig. 1)

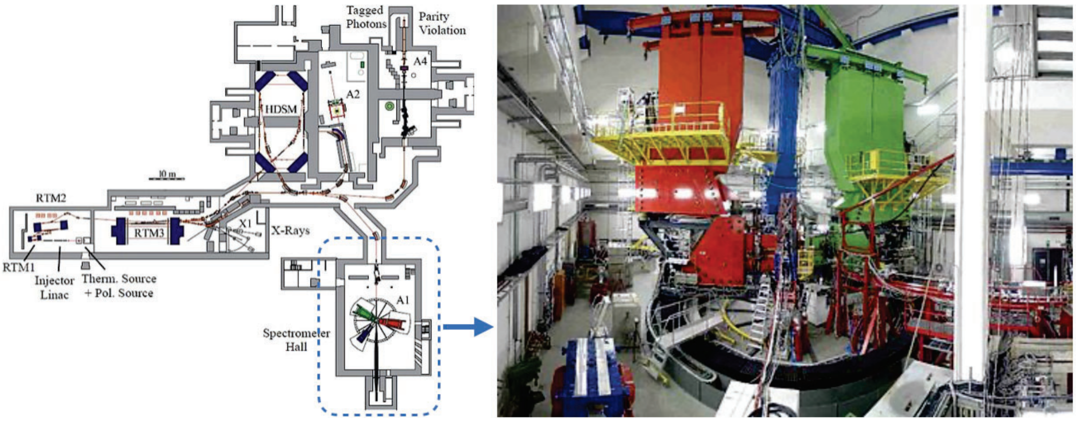

Figure 1. The MAMI accelerator floor plan and a picture of the A1 three-spectrometer setup

which operates a three-spectrometer setup for fixed-target electron scattering experiments.
The A1 spectrometers have a momentum resolution of 10^{-4} and have the same detector package composed of two vertical drift chambers, two planes of scintillator bars, and a Cherenkov detector. The scintillator planes serve as trigger detectors and for particle identification, together with the Cherenkov detector. The spectrometers can be employed in coincidence (double or triple) for exclusive measurements. This experimental setup is very well suited for the precision measurement of inclusive and exclusive nuclear cross sections.

4. Preliminary Results and Prospects

In 2021, a pilot experiment was performed by the A1 collaboration, measuring the inclusive electron scattering cross section on ^{40}Ar. The purpose of the measurement was twofold: estimating the potential for a datataking campaign aimed at neutrino physics, and testing the newly developed supersonic jet-target designed for the MAGIX experiment (see next section).
The jet-target was developed by the University of Münster (Germany) [20] and its main advantage is the absence of walls containing the target gas leading to a minimization of backgrounds. In precedence, the target was tested with hydrogen [21], and this was the first time it was operated with a heavier gas. Three kinematics were measured

(i) $E_0 = 705 MeV$, $\theta_e = 20°$
(ii) $E_0 = 705 MeV$, $\theta_e = 32°$
(iii) $E_0 = 240 MeV$, $\theta_e = 20°$

where E_0 is the electron beam energy and θ_e the electron scattering angle. Small scattering angles are more interesting for neutrino physics, since they are closer to the experimental conditions of neutrino experiments. In the future, higher angles will be investigated for addressing nuclear physics questions like the effects of meson exchange currents and the nuclear transverse response function.
The third kinematic setting (iii) had lower beam energy and constituted a test for future experimental facilities exploiting neutrinos produced from kaon decays at rest [22].
Preliminary results and calculations using two neutrino generators (Genie [6] and NuWro [7]) are shown in Fig. 2 for the kinematics (i).
The A1 collaboration is planning future measurements on argon and oxygen, which are the planned targets for the future long-baseline neutrino experiments DUNE and HyperK, respectively.

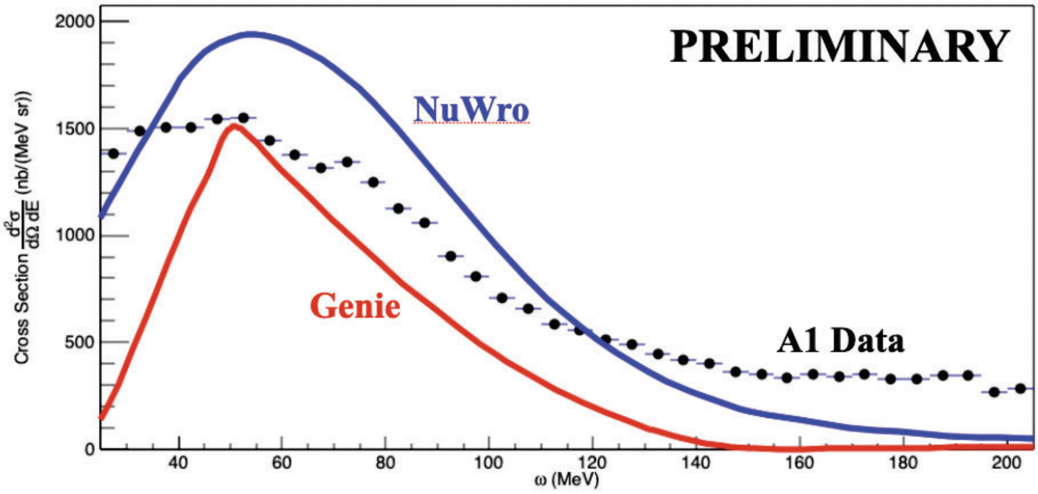

Figure 2. Preliminary data from inclusive electron scattering on argon with a gas-jet target. The data is confronted with preliminary calculations using the neutrino generators NuWro [7] and Genie [6] in electron mode. The energy of the beam was 705 MeV with scattering angle 20°. Statistical error bars are smaller than the black markers.

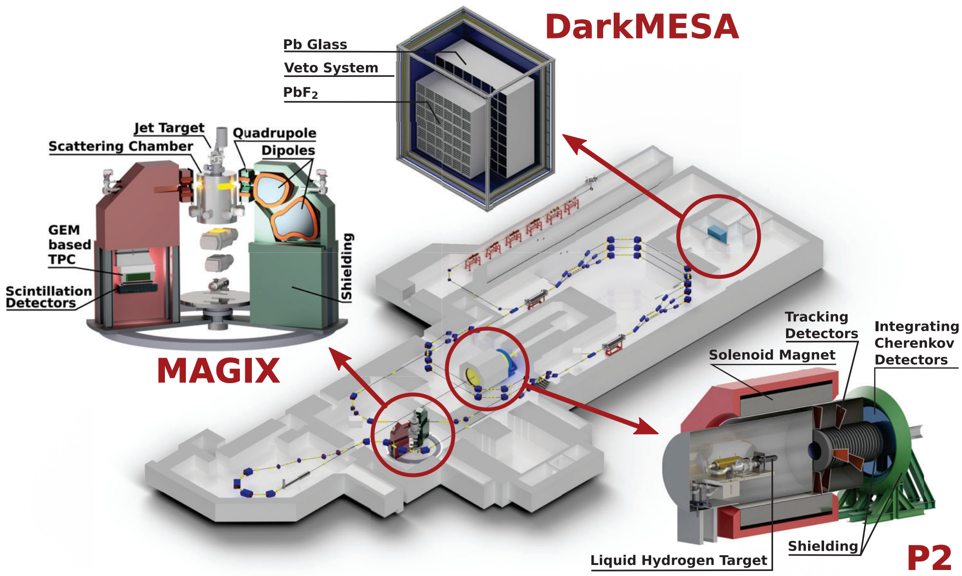

Figure 3. The MESA accelerator floor plan with the three experiments: DarkMESA, MAGIX, and P2.

5. Future opportunities: MESA

The Institute for Nuclear Physics at the Mainz University is building a new multi-turn, 100% duty-cycle, energy recovery linac for precision experiments with a beam energy of 100-200 MeV [23] (see Fig. 3). MESA (Mainz Energy-Recovering Superconducting Accelerator) will operate in two modes: energy recovery mode (ERM) and external beam mode (XBM).
In ERM, the accelerator will provide a beam current of up to 1 mA at 105 MeV for the MAGIX internal target experiment with multi-turn energy recovery capability. In XBM, a polarised beam of 150 μA will be provided to the P2 experiment [24]. An additional experiment, DarkMESA [25],

will be placed after the P2 beam dump, running in parallel to P2 and searching for dark sector particles [26].
The MESA accelerator will consist of a polarised source followed by a low energy beam transport system containing a spin manipulation system and a chopper-buncher section. Normal conducting cavities will accelerate the beam up to 5 MeV before injection into the main linac equipped with a total of four ELBE-like 9-cell superconducting cavities [27] installed in two cryomodules. The linac will provide an energy gain of 50 MeV/pass.
This new accelerator, coupled with the MAGIX experimental setup can provide in future valuable data for neutrino physics at low energies. MAGIX is a two-spectrometer setup similar in its principle to the A1 apparatus. Two high-resolution spectrometers can rotate around a jet-target which allows the MESA beam recirculation and energy recovery. The MESA beam energy will be well suited for electron scattering in a region (50-100 MeV) which is interesting for experiments aiming at detecting neutrinos from supernovae (SN). For example, SN neutrinos are a key component of the DUNE physics program and neutrino generators focused on this energy region are already actively developed [28]. The low energy region where SN neutrinos are expected is particularly challenging, since nuclear excited states play a relevant role: in this context, a direct and controlled experiment performed with electrons can provide important information for testing and tuning neutrino generator codes.

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