Exp.-Nr.: A1/??–17
Eingang:

Mainz Microtron MAMI

Collaboration: A1

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Letter of intent

Quasielastic experiments with ^{40}Ar

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Abstract

We propose a series of electron-induced nuclear experiments on argon that will provide new vital input to deficient models of nuclear structure and dynamics that are presently used to interpret signals detected in the accelerator-based neutrino experiments. Extensive, worldwide, experimental and theoretical efforts gathered around existing and upcoming neutrino facilities clearly show that the precise measurements of the neutrino masses, mixing angles and CP-violating phase represent the highest priority of today's particle as well as nuclear physics. With the planned project we have an opportunity to contribute an important part to this effort and pave the way to a better understanding of key properties of neutrinos.

Contents

1 Introduction

According to the Standard model neutrinos should be massless particles. However, detection of neutrino flavour oscillations provided an unambiguous evidence that neutrinos have non-vanishing masses. These oscillations were observed by various experiments and the confirmation of the phenomenon eventually led Art McDonald and Raymond Davis, Jr. to win a Nobel prize. The neutrino oscillations describe mixing between the flavour eigenstates and mass eigenstates and is presently described within the framework of a 3×3 mixing matrix, defined by three mixing angles and a CP-violating phase. Within this model the probability for neutrino changing its flavour depends on the energy of the particle and the distance of the detector from the neutrino source and is non-zero only if the masses of the three neutrino mass states are different. The parameters describing mixing are presently known to the level of a few percent except for the CP-violating phase, which is known only to about 25%. Hence, in order to achieve a qualitative improvement in the understanding of the neutrino properties, new oscillation experiments are required that will offer thorough exploration of the CP-invariance violation and conclusive tests of the three-massive-neutrinos paradigm [1]. Such experiments require percent-level control of the systematic uncertainties, which translates into novel challenges for our understanding of neutrino scattering off complex nuclei, especially off argon.

There are several new neutrino oscillation experiments scheduled or planned for the near future. The leading experiment among them is the Deep Underground Neutrino Experiment (DUNE) in the USA [2]. The experiment will connect the 1.2 MW neutrino beam-line at Fermilab and Sanford Underground Research Facility (SURF) in South Dakota, 1300 km from Fermilab, which will facilitate the detector, see Fig. 1. The DUNE detector will be a very large 40 t liquid argon time-projection chamber, which will combine tracking and a calorimetric detector. The detector is designed to measure the muonic- to electronic-neutrino oscillation channel. At Fermilab the incident muonic neutrinos are produced in a two step procedure: Monoenergetic protons first hit heavy nuclear targets and produce pions. In the second step pions then decay into a lepton and the interesting (anti)neutrino. As a result of this sequence, the energies of the initial neutrinos from the accelerator are not well defined but range from a few hundred MeV up to 3 GeV. This consequently means that the DUNE detector will be able to detect the first three oscillation maxima at 2.2, 0.8 and 0.5 GeV, see Fig. 2

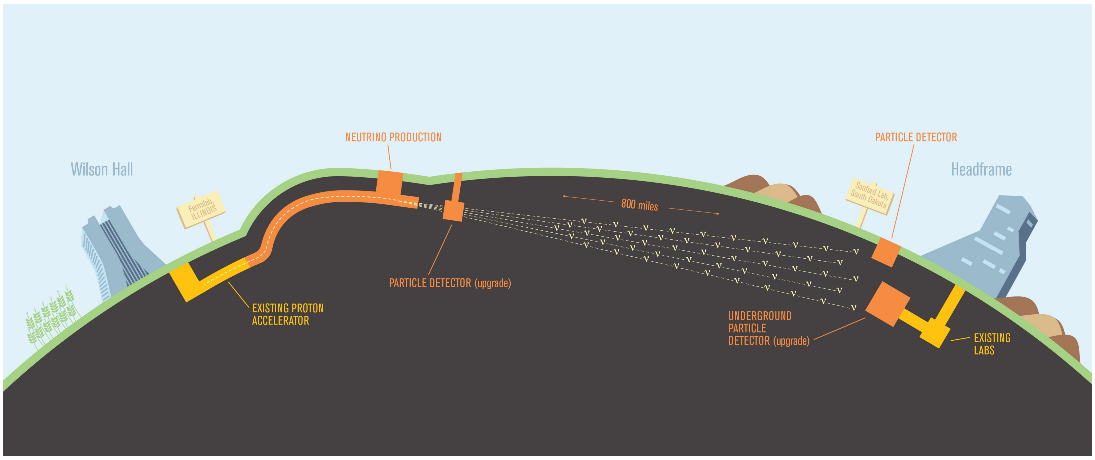

Figure 1 — The DUNE experiment. LBNF will provide facilities that are geographically separated into the near site facilities, those to be constructed at Fermilab, and the far site facilities, those to be constructed at SURF. [2].

Not knowing the energy of the incoming neutrino, which defines the kinematics of reaction, nor its flavour, represents the principal challenge of the neutrino experiments [1]. Consequently the data can not be analysed on the event-by-event basis. Instead one needs to work with ensembles of events and rely on the Monte-Carlo simulation to produce probability-weighted maps that connect detected signals to distributions of possible true kinematics. Inaccuracies in the construction of these maps can lead to problems in neutrino energy reconstruction that distort the spectrum to an unacceptable degree.

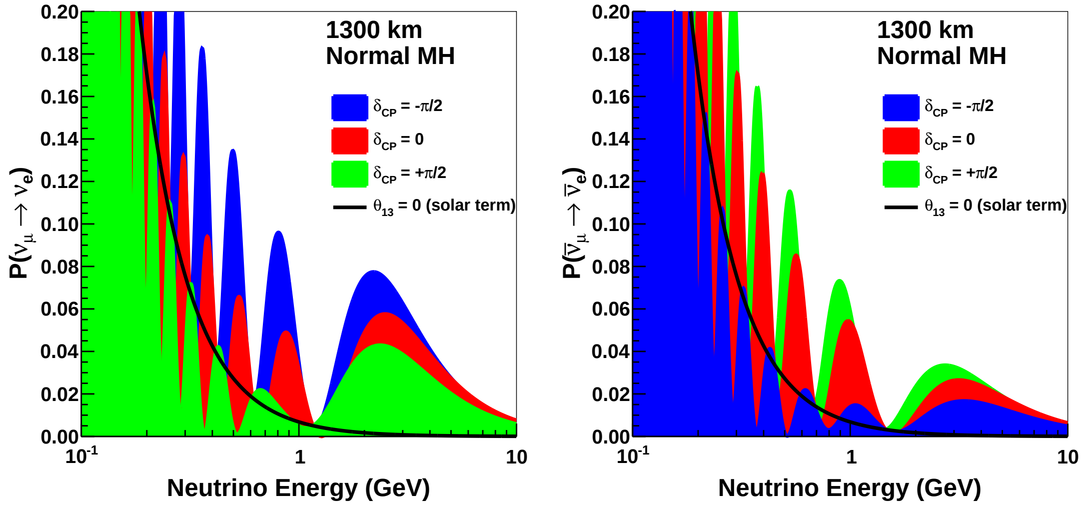

Figure 2 — The appearance probability at a baseline of 1300 km, as a function of neutrino energy, for $\delta_{CP} = -\pi/2$ (blue), 0 (red), and $\pi/2$ (green), for neutrinos (left) and antineutrinos (right), for normal hierarchy. The black line indicates the oscillation probability if θ_{13} were equal to zero [3].

Therefore, measurements of neutrino oscillation probabilities, as a function of the incoming neutrino energy, are highly dependent on accurate models of neutrino-nucleus interactions. That is, one must precisely know the energy-dependent cross section for any type of interaction that could contribute to an observed final state in the detector. Hence, in order to be able to exploit the full physics capability of the upcoming neutrino facilities, the description of the neutrino-nucleus scattering, which is presently unreliable, needs to be improved. A tremendous effort is currently being made to develop theoretical models and corresponding MC event generators that are capable of providing a full description of the neutrino-nucleus cross-section in the energy range from a few hundred MeV to a few GeV. In this energy range, relevant for DUNE, the interaction of neutrinos with the nucleus can be described as the scattering of neutrinos from the nucleons that are bound inside the nucleus. These charged (neutral) current quasi-elastic processes, where the interaction is mediated by the charged (neutral) weak boson W^+ (Z^0), are similar to the quasi-elastic reactions in the electron-nucleus scattering, where the virtual photon is the mediator of the interaction. Since the vector part of the weak response is related to the electro-magnetic response through the charged vector current, the models, developed to describe neutrino-nucleus scattering, should first be validated using data from the nuclear $(e, e'p)$ reactions.

2 Quasi-elastic scattering

In the quasi-elastic neutrino scattering a neutrino interacts with a bound nucleon and ejects it from the nucleus. The cross-section for such reaction depends on the binding energy and the Fermi momentum of the nucleon before the interaction. It can also happen that an interaction boson does not hit a single nucleon, but a correlated pair, and emits two nucleons from the nucleon. The probability for such short-range-correlation (SRC) processes is small, but not negligible. Furthermore, if neutrino brings enough energy, additional hadrons, can be produced inside the nucleus, most probably pions. Finally, after the primary interaction, the hit nucleon does not escape the nucleus instantly but needs to transverse through the dense nuclear medium and undergoes the final state interactions (FSI) with other nucleons before exiting the nucleus. This effect depends strongly on the kinematic conditions and can contribute up to 20% of the cross-section in the energy range of the interest. See Fig. 3. All these effect are present also in the electron-scattering experiments and have been extensively studied for various nuclei in many different experiments. In the approaches based on the many-body theories is the complete response of the nucleus commonly combined into an object known as a spectral function $S(E_m, p_m)$, which yields the probability of removing a nucleon with a Fermi momentum p_m from the nuclear ground state leaving the residual system at an excitation energy E_m, see Fig 4. The differential cross section for quasi-elastic scattering of a lepton from the nuclear target can be written as a product of the spectral function and a simplistic nucleon cross-section [4] that depends only on the kinematic parameters and nucleon form-factors, and thus allows for a direct comparison of the theory with the measured data.

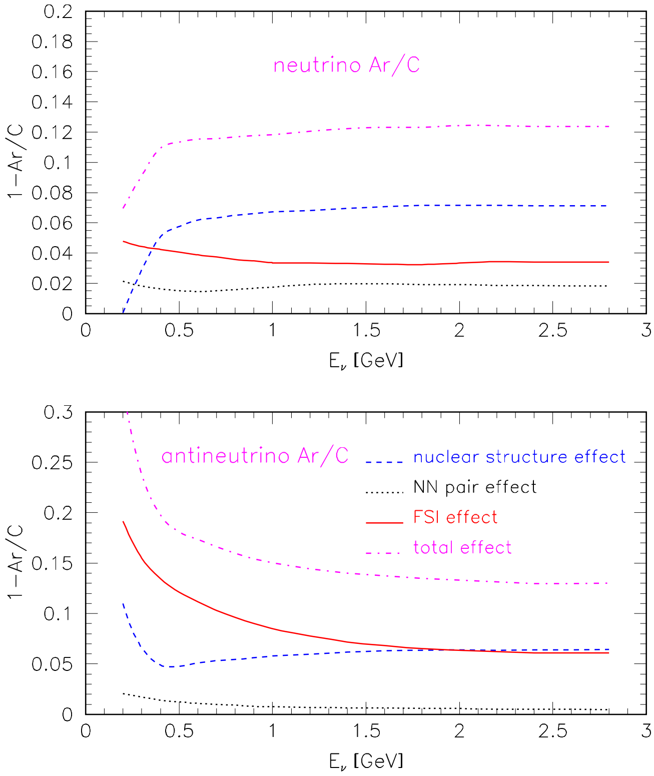

Figure 3 — Nuclear structure (dashed line), NN correlation (dotted line), FSI (solid line), and total nuclear effects (dashed-dotted) for CCQE scattering of muon neutrino (upper panel) and antineutrino (lower panel) on ^{12}C and ^{40}Ar vs incoming (anti)neutrino energy [5].

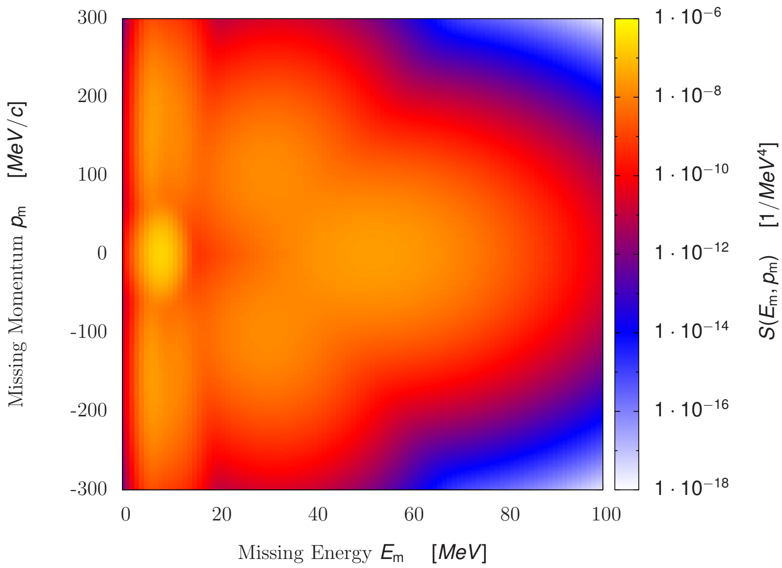

Figure 4 — A very basic model of the ^{40}Ar spectral function $S(p_{miss}, E_{miss})$, which tells the probability of removing a nucleon with a Fermi momentum p_m from the nuclear ground state leaving the residual system at an excitation energy E_m. The most interesting part of the spectral function is at $E_{miss} < 30\,MeV$, where S changes quickly with E_{miss} and p_{miss}. Note, $S(p_{miss}, E_{miss})$ is not equal to $S(-p_{miss}, E_{miss})$.

The calculations of the spectral function for electromagnetic electron scattering have been performed for various light and heavier nuclei, and are able to describe the measured data reasonably well. Especially detailed has been the study of the carbon data, which is also interesting in relation with the MiniBooNE neutrino experiment that uses mineral oil as the detector medium. There is a plethora of (e,e'p) scattering data available that can be used to construct and validate the models for carbon. However, it turns out that in spite of all the efforts, the response of this nucleus is still not understood well enough, especially for the case of the transverse kinematics, where the theory significantly underestimates the measured cross-section [6]. The handicaps of the present models were demonstrated also by the MiniBooNE collaboration [7, 8], who showed that their CCQE neutrino data can not be completely described with the available Monte-Carlo generators.

The theoretical description of the quasielastic response of carbon is presently not satisfactory, but our understanding of the interaction between lepton and Argon is significantly poorer. For Argon only one twenty year old data set from Frascati exists [9]. See Fig. 5. In that experiment, they measured the inclusive cross-section for $^{40}\mathrm{Ar}(e,e')$ reaction, but only in the longitudinal kinematics. Hence, since the future experiments (most notably DUNE, but also MicroBooNE [10] and others) will use liquid argon as a detector medium it is of paramount importance to provide new electron-scattering data in the correct energy range, that will ensure a better description of neutrino-nucleus scattering which matters at the level of $10-20\%$ for the determination of the oscillation parameters. This effort started with an experiment at the Hall-A collaboration of the Jefferson Lab [11]. There a 2.2 GeV electron beam in combination with an extended gaseous argon target and high resolution spectrometers were used to determine the spectral function at Q^2 between $0.2\,\mathrm{GeV}^2/c^2$ and $0.9\,\mathrm{GeV}^2/c^2$. During this beam-time QE data for the antiparallel kinematics (Fermi momentum of the initial nucleon and the momentum transfer vector are antiparallel) were collected. Unfortunately in the time given, no data for parallel kinematics could be collected. Consequently, the collected sample can be used to test the theoretical model, but does not offer a complete picture of the nuclear response, especially no insight is offered into the sub-leading effects like FSI, which depend strongly on the relative directions of a virtual photon and the bound initial proton.

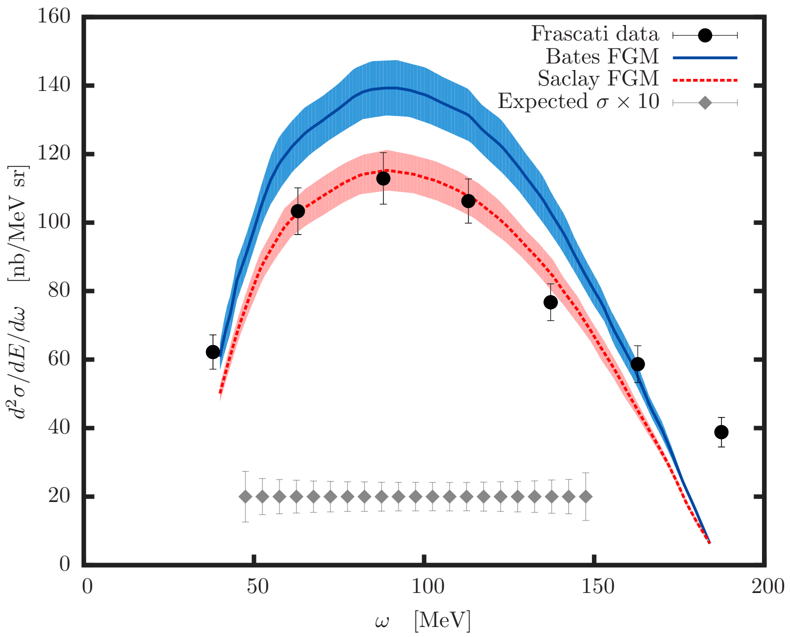

Figure 5 — The inclusive cross-section for reaction $^{40}\mathrm{Ar}(e,e')$ at the incident electron energy of 700 MeV and $\theta = 32°$ (black points); the full and dotted curves are the Fermi-Gas-Model results based on the analysis of Saclay and Bates data, respectively [9]. Grey points show the expected number of data points together with the corresponding uncertainties for the first kinematic setting of the proposed Mainz experiment. See Table 1. The shown uncertainties are multiplied by factor 10 for clarity.

3 Experiments

To overcome the present impasse and to provide data that are desperately needed, we propose a series of new measurements at the Johannes Gutenberg University in Mainz. We will use the MAMI accelerator [12, 13] which produces a 1.5 GeV continuous-wave polarised electron beam and offers a possibility to provide data in the energy range of most interest, i.e., in the region of second and third oscillation maxima. The experiment will be performed at the three-spectrometer hall optimised for precision analysis of charged particles [14]. Its three spectrometers with outstanding momentum and angular resolution allow detection of charged particles with high resolution and sample purity. The ability to position the spectrometers at any scattering angle between 15° and 160° and their large momentum acceptances give us a unique kinematic opportunity to precisely measure the cross-section for quasi-elastic scattering of electrons off argon in the region of Q^2 up to $1\,\mathrm{GeV}^2/c^2$.

Table 1 — Proposed settings for inclusive measurements with estimated DAQ rates ν_{DAQ} and needed time.

Setting	E_0 [GeV]	θ_e [°]	E' [GeV]	ω [GeV]	Q^2 [GeV$^2/c^2$]	ν_{DAQ} [Hz]	Events [10^3]	Time [h]
1	500	30	436.68	63.32	0.0585	2556.5	1000	0.11
2	500	40	414.57	85.43	0.0970	666.2	1000	0.42
3	500	50	390.04	109.96	0.1393	225.0	1000	1.23
4	500	60	364.81	135.19	0.1824	91.8	1000	3.03
5	500	70	340.20	159.80	0.2238	43.7	1000	6.36
6	500	80	317.14	182.86	0.2621	23.4	1000	11.88
7	500	90	296.18	203.82	0.2962	13.9	1000	20.05
8	500	100	277.61	222.39	0.3258	9.01	1000	30.82

As first we propose an inclusive cross-section measurement of $^{40}\mathrm{Ar}(e,e')$. We want to start with the measurement sensitive to the longitudinal part of the cross-section and reproduce the Frascatti results, see Fig. 5. Then we will sequentially change the kinematics and collect data that are more sensitive to the transverse response functions, see Fig. 6. Such measurement has not been done before and will give us the possibility to investigate not only the part of the nuclear response that is sensitive to the magnetic density, but also the part that depends on the magnetic currents - which is even more important! In the experiment an electron beam with an energy of 500 MeV will be used in combination with a clustered jet argon target. This newly developed point-like target will offer a background-free cross-section measurement while still ensuring enough luminosity ($10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$) for a high-statistics measurement. For the measurement of cross-section a large-acceptance spectrometer A will be employed. Its position will be changed over seven equidistant stops from 30° to 100°, while its momentum will be changed such that data would always be collected at the top of the quasi-elastic peak. For a sub-percent precise monitoring of beam luminosity spectrometer B will be employed, anchored at a fixed elastic setting. Alltogether 7 days of beam-time (assuming $\approx 50\,\%$ efficiency) are needed in order to determine the cross-section to a 0.2% relative uncertainty - which is a 20 times smaller uncertainty than the one of the Frascati measurement.

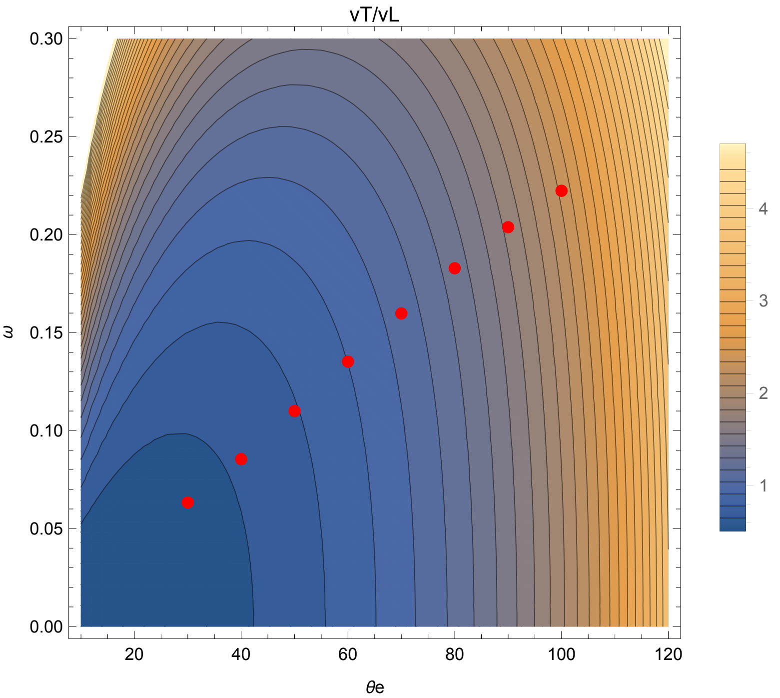

Figure 6 — The ratio v_T/v_L as a function of ω and θ_e demonstrates the sensitivity of the measured cross-section to the longitudinal and transverse response functions R_L and R_T. The red points mark the kinematics we selected for the proposed inclusive experiment, see Table 1.

In the second step we want to perform an exclusive measurement of $^{40}\mathrm{Ar}(e,e'p)$ cross-section in order to determine the spectral function for the parallel kinematics (see Fig. 8). Protons will be detected with spectrometer A in coincidence with electrons detected in spectrometer C. Since the cross-section for exclusive reactions is much smaller than the one for the inclusive processes, we need an at least two orders of magnitude increase in the luminosity. Hence, for this experiment the jet target will be replaced with a cooled 4 cm high-pressure gaseous target. The target, which has been typically used for the measurements with ^{3}He is a part of the standard A1 apparatus and will ensure luminosities of $4.0 \cdot 10^{35}\,\mathrm{cm^{-2}s^{-1}}$. The ultimate luminosity could be reached with the liquid Argon target. However, such target is not appropriate for our measurements, due to the pronounced external nuclear interactions of the ejected protons with the target liquid, which could significantly distort the measured spectra (see Fig. 7). The measurements are foreseen for six different electron-kinematic points with spectrometer C being positioned at angles between 50° and 100°, covering the Fermi momenta from $0\,\mathrm{MeV}/c$ to $300\,\mathrm{MeV}/c$. See Table 2 and Fig. 8. To gather one million coincidence events for each kinematic setting 14 days of beam-time will be needed. Since in the coincidence modus the DAQ is not limited by the rate, we can add spectrometer B to the experiment and in-parallel detect also coincidences between spectrometer A (protons) and spectrometer B (electrons). If we position the spectrometer B carefully between 50° and 15°, we can simultaneously measure the spectral function also for the anti-parallel kinematics. This way we can, independently of the Jefferson Lab's experiment, provide a complete set of measurements in the Q^2 range between $0.02\,\mathrm{GeV}^2/c^2$ and $0.6\,\mathrm{GeV}^2/c^2$, required to determine the spectral function.

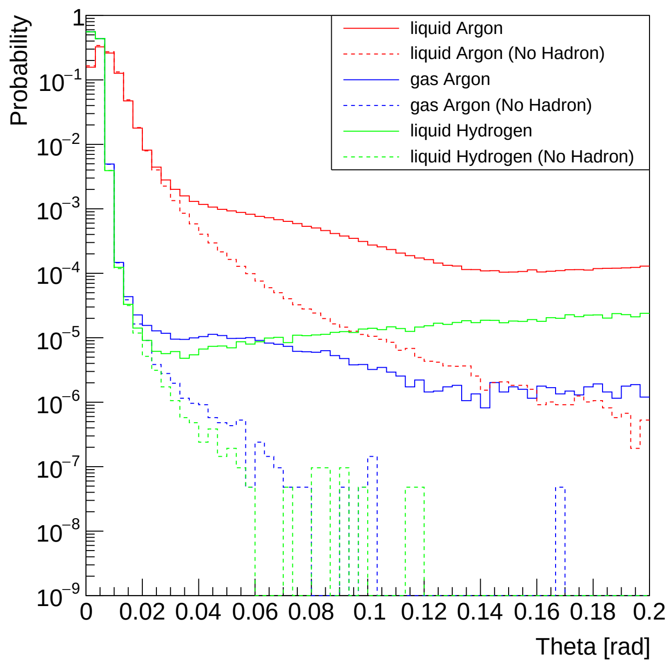

Figure 7 — The Geant simulation shows the comparison of the angular deviations of a proton transversing through different types of targets. The effect is the largest in the liquid Argon target, mostly due to nuclear interactions between the outgoing proton and the Argon nuclei. Sizeable change in the proton's direction hints a substantial influence of the nuclear medium on its spin orientation, thus makes liquid Argon target unsuitable for the double polarisation measurement.

In the last step we want to analyse double polarisation data of $^{40}\mathrm{Ar}(\vec{e}, e'\vec{p})$ and extract the components of the polarisation, transferred from the virtual photon to the ejected proton. It turns out that the polarisation components P_z (along the momentum transfer vector) and P_x (perpendicular to the momentum transfer and inside the reaction plane) do not depend on the nuclear density but are rather sensitive to the contributions of the final state interactions [15]. Hence, double polarisation analysis gives us a unique opportunity to precisely investigate FSI, which is impossible to do with the cross-section measurements, where FSI is camouflaged by other effects. The theoretical calculations provided by C. Giusti et al. (see Figs. 9 and 10) predict a $15-20\%$ decrease of the P_x/P_z ratio at Fermi momenta between $100\,\mathrm{MeV}/c$-$200\,\mathrm{MeV}/c$, which should be clearly visible in our data. In order to do this kind of analysis no new data and no extra beam time is needed. If spectrometer A is equipped with a focal-plane polarimeter and a polarised beam is used in the exclusive cross-section measurement from the previous paragraph, such data are obtained for free. With the collected statistics of 1 million events per kinematic setting, we expect to determine the polarisation components with a 2% uncertainty, which is enough to validate the theoretical predictions.

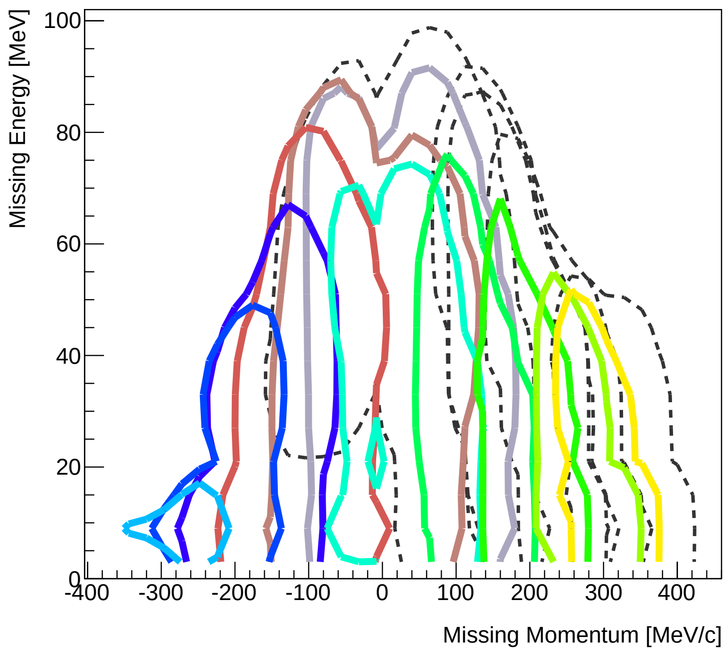

Figure 8 — The coloured lines demonstrate the regions in $(E_{\mathrm{miss}}, p_{\mathrm{miss}})$ plane covered by the proposed 11 kinematic settings. The black dashed lines show the sections covered by the JLab experiment [11]. The most interesting part of the plane is at small E_{miss} and $p_{\mathrm{miss}} \leq 0$ where spectral function changes most rapidly (see Fig. 4) and where no data exist yet.

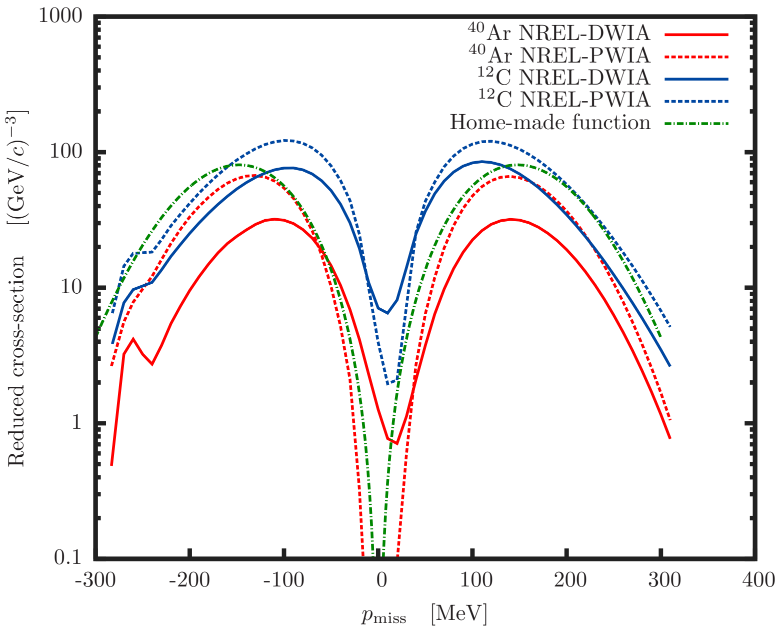

Figure 9 — Theoretically predicted $^{40}\mathrm{Ar}(e, e'p)$ cross-section for kinematic setting No. 1 from Table 2. The full and dashed red lines represent DWIA and PWIA calculations made by C. Giusti [6], respectively. The calculations for $^{12}\mathrm{C}(e, e'p)$ are shown with blue lines for comparison. The dashed-dotted line shows the results obtained with PWIA and model spectral function from Fig. 4.

4 Conclusions and beam-time requests

In conclusion, the most interesting and most important questions of today's particle physics are related to neutrinos: What are the neutrino masses and what is their mass order? Do neutrinos violate CP symmetry? There is a series of upcoming experiments that aim to answer these questions by performing high precision measurements of the neutrino oscillations. Among them, the most notable is the accelerator-based neutrino experiment DUNE that uses liquid argon as a detector medium. The main problem of the experiment is the undefined energy of incident neutrinos from the accelerator. Consequently, the measured neutrino spectra need to be studied in conjunction with a Monte-Carlo simulation in order to extract the correct shape of the neutrino oscillation. This procedure depends strongly on the nuclear structure models used in the simulation. Therefore, it can not be stressed enough that the precision study of neutrino properties can be performed only if the nuclear structure of the Argon is understood to a few percent level. Unfortunately, at this time the available models can not be really tested, because except for the unanalysed and incomplete

Table 2 — Proposed settings for exclusive measurement with estimated DAQ rates ν_{DAQ} and needed time.

N	El. Spec.	E_0 [GeV]	θ_e [°]	E' [GeV]	ω [GeV]	Q^2 [GeV$^2/c^2$]	P_p [GeV$/c$]	θ_p [°]	ν_{DAQ} [Hz]	Events [10^3]	Time [h]
1	C	600	50	450	150	0.193	512	49	1224	1000	0.56
2	C	600	60	450	150	0.270	512	47	608	1000	0.56
3	C	600	70	450	150	0.355	512	44	205	1000	1.36
4	C	600	80	450	150	0.446	512	41	65	1000	4.25
5	C	600	90	450	150	0.540	512	37	15	1000	18.83
6	C	600	100	450	150	0.634	512	33	2	1000	118.31
1	B	600	50	450	150	0.193	512	49	87	1000	3.19
2	B	600	40	450	150	0.126	512	50	150	1000	1.86
3	B	600	30	450	150	0.072	512	49	216	1000	1.28
4	B	600	20	450	150	0.033	512	43	138	1000	2.01
5	B	600	15.5	450	150	0.020	512	38	117	1000	2.37

data from Jefferson Lab, no precision measurements exist. This desperate need for new, high precision data is the main motivation for the proposed experiments in Mainz that will provide a complete spectral function for Argon, give insight into the transverse part of the nuclear response function and allow for a precise study of final state interactions. To successfully execute the proposed experiments, we ask for 21 days of beam time, one week for the inclusive measurement and five weeks to collect data for the exclusive channel.

Support of the neutrino experiments is of course not the only motivation for doing such measurements. They are interesting also within the scope of fundamental nuclear physics. Comparing new ^{40}Ar data to the available data on the double magic nucleus ^{40}Ca will offer a valuable new insight into the details of nuclear forces and dynamics between protons and neutrons. Moreover, the double polarisation data could be used in combination with ^{2}H, ^{4}He and ^{12}C data to study the recently observed and unexpected local behaviour of final state interaction, whose influence changes much slower with the atomic number than expected [15]. The Mainz facility has a long tradition of doing high precision unpolarised and polarised experiments on different nuclear targets. Collaboration produced an extensive series of publications describing high precision (even sub-percent) studies of cross-sections and polarisation transfer ratios. This clearly proves that the A1 collaboration offers a unique setup where the proposed measurements on argon can be successfully performed. The obtained results will provide new and valuable input to the theory and will help improving the description of the response of light and medium-weight nuclei to electromagnetic and weak probes.

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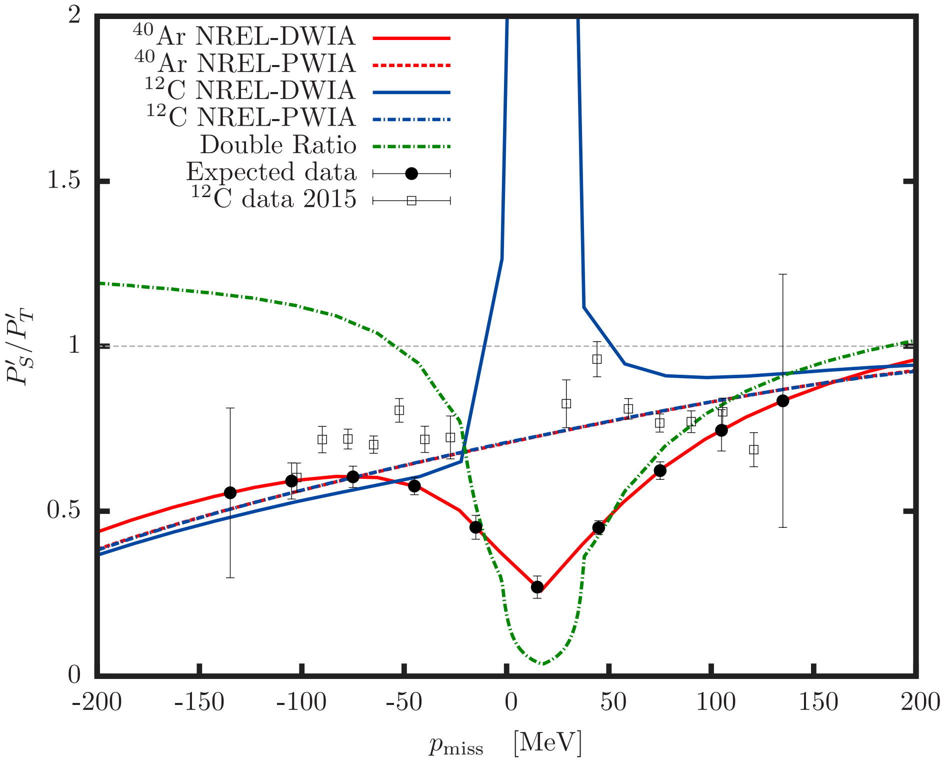

Figure 10 — Ratio of the polarization transfer components P_x/P_z as a function of the missing momentum p_{miss}. The full and dashed red lines show the DWIA and PWIA predictions of C. Giusti, respectively. The green dashed-dotted line shows the ratio of DWIA and PWIA calculations and exhibits the size of the FSI contribution at different values of p_{miss}. The full points show the expected data points obtained with the proposed experiment, together with the estimated uncertainties. The data will provide enough resolving power to be able to distinguish between different calculations and validate the present description of the FSI. Blue lines show the corresponding calculations for $^{12}\mathrm{C}(\vec{e}, e'\vec{p})$. The empty squares show the preliminary results for carbon obtained during the two week experimental campaign at A1 in 2015.

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