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Proposal

Quasielastic experiments with ^{12}C and ^{16}O

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Abstract

We propose high precision electron-induced nuclear experiments on oxygen and carbon that will allow a complete study of the electromagnetic properties of light nuclei. The cross-sections measured at carefully chosen kinematic points at various energy and momentum transfers in both quasi-elastic and delta resonance regimes, will shed light on all the key components of the electron-nucleus interaction. In the nuclear physics community such data are much-awaited and are crucially needed to answer fundamental questions about the nuclear structure, like quenching of the Coulomb sum rule, and to improve the available theoretical models. Furthermore, the experimental results will provide a vital new input to deficient existing models of nuclear structure and dynamics, currently employed to interpret signals detected in accelerator-based neutrino experiments.

Contents

1 Scientific background

Electrons represent a very precise probe for the atomic nucleus. In the past decades, experiments with electrons have provided increasingly accurate information on the structure of nuclei and their constituents. At the heart of this effort are the inelastic experiments on nuclear targets at energies below 1 GeV, which give insight into the properties and dynamics of nucleons embedded in a nuclear medium. Various such experiments were performed, most of them before the year 2000, but, due to the experimental constraints, the acquired data were sensitive only to the longitudinal (charge) part of nuclear response. The more complex transverse (magnetic) response was never thoroughly investigated. The urgent need for new precise measurements was evidenced by recent state-of-the-art *ab-initio* calculations which could not be validated, given the present lack of experimental data. An important motivation for new studies of inclusive quasi-elastic cross-sections comes also from the neutrino physics community. The precise measurement of neutrino masses, mixing angles and CP-violating phase represent one of the highest priorities of contemporary fundamental physics. It has been demonstrated that the interpretation of the measured oscillations requires extensive theoretical and experimental support from the nuclear physics community. The proposed project will directly contribute to a key part of this effort and pave the way to a better understanding of fundamental properties of neutrinos.

According to the Standard Model neutrinos should be massless particles. However, detection of neutrino flavour oscillations provided unambiguous evidence that neutrinos have non-vanishing masses. These oscillations were observed by various experiments and confirmation of the phenomenon led Raymond Davis, Jr., Arthur B. McDonald, and Takaaki Kajita to win the Nobel prize. Neutrino oscillations describe mixing between flavour eigenstates and mass eigenstates, and is presently described within the framework of a 3×3 mixing matrix (Pontecorvo–Maki–Nakagawa–Sakata matrix, or PMNS matrix), parameterized by three mixing angles and a CP-violating phase[1]. Within this model, the probability for a neutrino of 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 states are different. The parameters describing this mixing are presently known to the level of a few percent, while the CP-violating phase 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, allowing for a thorough exploration of the CP-invariance violation and conclusive tests of the three-massive-neutrinos paradigm. Such precision experiments require percent-level control on the systematic uncertainties, which translates into novel challenges to our understanding of neutrino scattering off complex nuclei, especially oxygen, carbon, and argon.

The most important running accelerator-based neutrino oscillation experiment is T2K in Japan. T2K (Tokai to Kamioka) is a long-baseline neutrino experiment in which an intense beam of muon neutrinos from the accelerator at J-PARC in Tokai is sent to a Super Kamiokande detector, located in mine Kamioka, 295 km away. The energy of the neutrino beam is centered around 600 MeV since muon neutrinos with this energy have the maximal oscillation probability after travelling the distance between the two sites. The flux of the neutrino beam before any oscillations occur is measured by the near detector ND280. The detector is positioned in the vicinity of the neutrino source and employs plastic scintillator (carbon) and water as a detection medium. The main detector, Super Kamiokande, consists of a stainless steel tank filled with 50,000 tons of ultra-pure water, surrounded by 13,000 photomultipliers (PMTs) for light detection. When a neutrino interacts with water, a charged particle (electron or muon) is produced: travelling faster than light in water, it creates Cherenkov radiation, which is recorded by the PMTs. Using the information recorded by each PMT, the direction and "flavor" (type) of the incoming neutrino can be determined. T2K began its experimental program in 2010 and so far delivered more than $3 \cdot 10^{21}$ protons on the neutrino target.

Next to the neutrino experiments that are already underway, there are also important new experiments scheduled to run in the near future. The leading international efforts are the Deep Underground Neutrino Experiment (DUNE) in the USA and HyperK in Japan. The DUNE experiment will connect the 1.2 MW

[1] If neutrinos are Majorana fermions, two additional phases must be considered.

neutrino beam-line at Fermilab and the Sanford Underground Research Facility (SURF) in South Dakota, 1300 km away from Fermilab. The main detector will be a very large 40 t liquid argon time-projection chamber, combining tracking with 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: mono-energetic protons first hit heavy nuclear targets and produce pions. In a second step, pions 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 means that DUNE will have the opportunity to measure the first three oscillation maxima at 2.2, 0.8 and 0.5 GeV. Similarly to the T2K, the luminosity of the neutrino beam is determined with a near detector, which uses plastic scintillators (carbon) as a detection medium. The future HyperK experiment will employ the same principle of T2K, replacing Super Kamiokande with a five-fold larger water Cherenkov detector.

Not knowing the energy of the incoming neutrino represents the principal challenge of neutrino experiments. In the detector, neutrinos could be identified only indirectly, predominantly through inclusive charged current quasi elastic scattering (CCQE) by detecting a lepton emerging from the reaction. However, using only kinematic properties of this charged particle, the energy of the incoming neutrino can not be uniquely determined. Thus, the measured data cannot be analysed on an event-by-event basis: one needs to work with ensembles of events and rely on Monte-Carlo simulation to produce probability-weighted maps connecting detected signals to distributions of possible true kinematics. Inaccuracies in the construction of these maps leads to inaccuracies in reconstructing the neutrino energy and induce a significant bias in the determination of the oscillation parameters. Measurements of neutrino oscillation probabilities as a function of the incoming neutrino energy rely heavily on accurate models of neutrino-nucleus interactions: one must know precisely the energy-dependent cross section for any type of interaction that could contribute to an observed final state in the detector. As a result, to be able to exploit the full capability of upcoming neutrino facilities, the description of neutrino-nucleus scattering needs to be strongly improved. A tremendous effort is currently being invested to develop theoretical models and corresponding MC event generators 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 the charged (neutral) current quasi-elastic processes, the incident neutrinos interact with the single nucleons that are bound inside the nucleus through the exchange of a charged (neutral) weak boson W^+ (Z^0). These reactions are closely related to 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 electromagnetic response through the charged vector current, the models developed for neutrino-nucleus scattering should first be validated using data from the electron induced nuclear reactions.

Within phenomenological models, the cross-section of the quasi-elastic interaction of a lepton (electron or neutrino) with a nucleus is governed by two key components: the bound state wave-function of the initial nucleon inside the nucleus, and the optical potential describing the reaction between the lepton and the nucleon. The characteristics of the bound state wave function are important for the results of exclusive $(l,l'p)$ quasi elastic processes with a well defined final state. On the other hand the cross-section for inclusive reactions (l,l') which represents the sum of all possible single particle bound state wave functions, is not particularly sensitive to the details of the choice of the bound state wave function. With the interaction potential, the story is exactly the opposite. The complex optical potential, which in addition to the quasi-elastic (QE) exchange of the primary boson includes also the interaction of the nucleon with nuclear medium in the final state (FSI), exchange of mesons between the nucleons (meson-exchange current, MEC) and even production of a delta resonance (DR), has a strong energy dependence. In the exclusive reactions with a well-defined kinematics this dependency is not visible. However, in the inclusive (e,e') and neutrino reactions, were the final state in not uniquely defined, and the cross-section represents a sum over all possible end-states and energies, the complex optical potential represents the key ingredient for a correct interpretation of the measured neutrino spectra. The theory has determined [1] that nuclear effects (FSI, MEC and DR) play an important role in the reconstruction of the initial neutrino energy. Simulations have shown that in the measured spectra of DUNE, these effects will cause a migration of

50 % of events to neighboring bins. If ignored, these wrongly reconstructed QE events will cause 1σ bias in the determination of the square mass difference (Δm^2_{13}) and 3σ bias in the determination of the mixing angle θ_{23} (see Fig. 1). Therefore, it is imperative that nuclear effects are modeled properly.

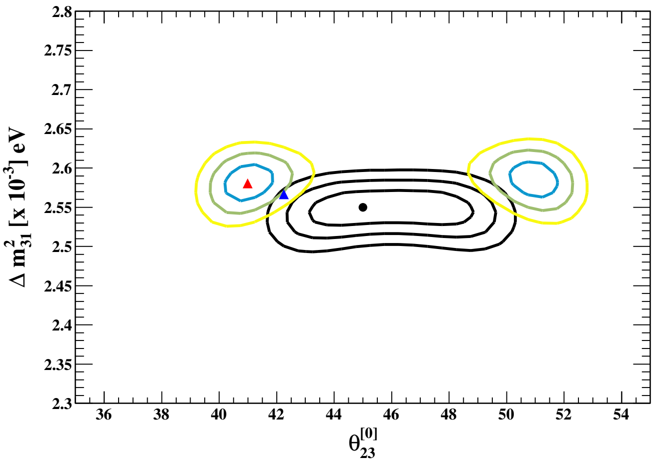

Figure 1 — Confidence region in the $\theta_{23} - \Delta m^2_{31}$ plane for different scenarios. Black point shows the true value of the oscillation parameters and the lines depict the 1, 2 and 3 σ regions around it. Blue triangle shows equivalent result, assuming that 50 % of the QE event have migrated from their original bins due to the presence of the nuclear effects. The red triangle with the corresponding 1, 2 and 3 σ error bands (coloured lines) shows the oscillation parameters, when presence of the nuclear effects is completely neglected [1].

In the last years, comprehensive theoretical studies of the interaction potential has been done for the carbon nucleus, for which the richest sample of nuclear measurements is available (gathered and maintained by D. Day and I. Sick [2]), with 2900 different data points from 11 experiments. The studies have been strongly motivated by the MiniBooNE (MINERvA) neutrino experiment that uses mineral oil (carbon) as the detector medium. While FSI and MEC traditionally have a $10-20\,\%$ effect in the (e,e') cross-section, for this experiment the calculations have demonstrated [3], that the nuclear effects contribute approximately 50 % to the total cross section at energies $0.6-1\,\mathrm{GeV}$, thus playing a decisive role in the interpretation of the data. However, it has turned out that in spite of all the efforts, the response of this nucleus is still not understood well enough. There is a 10 % difference between theory and (e,e') data at the top of the quasi-elastic peak and 10 % difference between theoretical cross-sections using different optical potentials, which directly translates into 15 % difference in the neutrino CCQE cross section [4]. The comparison with the data also demonstrates that the discrepancy increases rapidly at higher energy transfer when moving closer to the delta resonance, which is not comprehensively considered in present models. To improve the situation, further theoretical efforts are aimed at matching all available (e,e') data over the full kinematic range of the experiment.

Unfortunately, for ^{16}O, equivalent theoretical studies cannot presently be performed, given the severe lack of experimental data. Except for two old experiments [5, 6] that provided limited data for five kinematic settings at forward angles, no other published data is available yet. Consequently, only circumstantial tests of available theories are possible [7] relying on data collected from neighbouring nuclei. The models employed for describing the interaction of neutrinos with the detector medium thus rely on the uncorrected and most probably faulty parameterization of the nuclear response, meaning that the absence of electron scattering data on ^{16}O, ^{12}C (and also on ^{40}Ar) at the moment directly limits the precision of neutrino experiments like T2K (and its future successor HyperK) and DUNE.

2 Problem identification

The main concerns regarding the interpretation of the upcoming neutrino data are the uncertainty and bias caused by the potentially incomplete description of the lepton-nucleus interaction, predominantly due to the lack of available electron scattering data, needed to test the theoretical models. The cross-section for the interaction of the lepton with the nucleus depends on two nuclear response functions: the longitudinal response, R_L, depends on the transition charge density and is sensitive to the nucleon-nucleon correlations; the transverse response, R_T, depends on the magnetic currents and describes the dynamics of the nucleons inside the nucleus. The event generators considered in the Monte-Carlo simulations of neutrino experiments employ phenomenological a parameterization of the nuclear cross-section, relying on the scaling of the nuclear responses, implemented using the superscaling functions. The appearance of superscaling allows to conclude that different nuclei have a universal spectral function once the dependence on the Fermi momentum is removed. Superscaling turns out to be particularly useful when dealing with the separated longitudinal and transverse responses. In quasi-elastic scattering one expects that both response functions scale to a universal curve and that the integral of the superscaled result satisfies the Coulomb sum rule. The analysis of the available data has shown (see Fig. 2), that while the longitudinal response indeed scales with the momentum and atomic mass, the transverse response clearly violates scaling. Moreover, the lack of available data at large momentum transfers prevents to test the Coulomb sum rule. Within the scope of simple nuclear models, the Coulomb sum rule states that the integral of the charge response of the nucleus over the full range of energy transfer should, at large momentum transfers, be equal to the total charge of the nucleus. A deviation from this prediction would indicate unaccounted nuclear effects inside the nucleus.

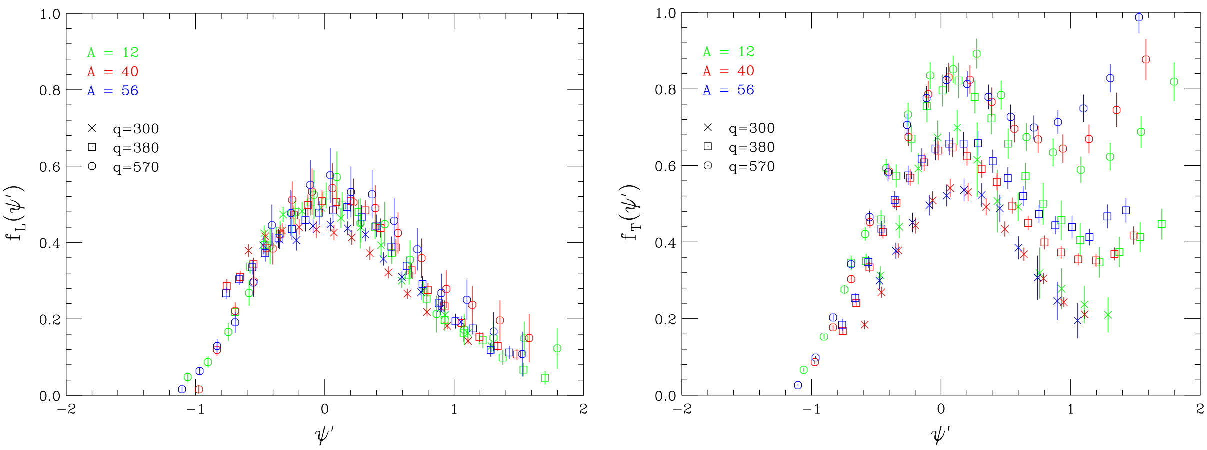

Figure 2 — Longitudinal and transverse scaling functions for the scattering of electrons from different nuclei at different momenta $|\vec{q}|$. Within error bars, the longitudinal response scales to a universal curve, while the transverse response does not [8].

Superscaling breaking of the transverse response points to a serious issue of neutrino event generators: with the absence of real data, the description of scattering under large angles is not under control, although such events represent an important part of the event sample. Hence, it is of paramount importance to provide new electron-scattering data in the energy range compatible with the T2K and DUNE experiments, that will ensure a better description of neutrino-nucleus scattering which weights at the level of 10 % (or 3 σ) for the determination of the oscillation parameters.

This effort started in 2017 with the experiment E12-14-012 of the Hall-A Collaboration at Jefferson Lab. The experiment collected inclusive electron-scattering data for *C*, *Al*, *Ar* and *Ti* at the kinematics corresponding to beam energy 2.222 GeV and scattering angle 15.54°. The data extend over a broad range of energy transfer ω covering both the QE peak and the DR, but only for very forward angles, thus offering only limited insight into nuclear effects and focusing on the longitudinal response. The angular dependence of inclusive cross-sections and the transverse response remain unexplored. Hence, to get a complete picture of the nuclear response, including sub-leading effects like FSI and MEC, the data should not only be collected as a function of ω, but also as a function $|\vec{q}|$. Such data for ^{12}C remain at the moment unavailable, while data for ^{16}O and ^{40}Ar is even more scarce. The study of the oxygen nucleus represents in particular a current priority for the neutrino community, since it impacts already running experiments.

3 Objective of the proposed project

With the proposed experiment we want to provide new and valuable input to nuclear theory that will help to improve the description of the response of light and medium-mass nuclei to electromagnetic

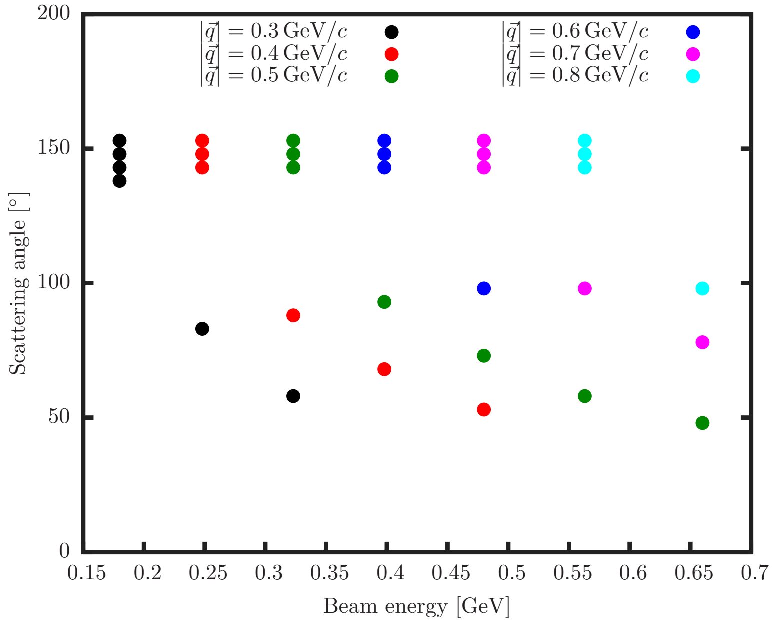

Figure 3 — The experiment will gather data at seven different beam energies and various scattering angles in order to collect data at six different values of 3-momentum transfers $|\vec{q}|$. The details of the proposed kinematic settings are gathered in Table 1.

and weak probes. The most interesting and most important questions of today's particle physics are related to neutrinos: What are the neutrino masses and what is the mass hierarchy? Do neutrinos violate CP symmetry? There are several experiments that aim to answer these questions by performing high precision measurements of the neutrino oscillations. Presently the most relevant among them is the accelerator-based neutrino experiment T2K employing water (oxygen) as detector medium. The main issue of the experiment is the undefined energy of the incident neutrinos produced by the accelerator. Consequently, the measured neutrino spectrum needs to be studied in conjunction with a Monte-Carlo simulation in order to extract the correct shape of the neutrino oscillation as a function of the neutrino energy. This procedure depends strongly on the nuclear structure models used in the simulation. It can not be emphasized enough that the precision study of neutrino properties can be performed only if the interaction of a lepton (neutrino and electron) with oxygen is understood to the level of a few percent. Unfortunately, at this time the available models can not be really tested, because except for the few kinematically restricted data set from 1990s, no precision measurements exist. This desperate need for new, high precision data is the main motivation for the proposed dedicated experiment, that will provide a comprehensive set of inclusive $^{16}\mathrm{O}(e,e')$ cross section measurements at several beam energies below 700 MeV, consistent with the T2K neutrino oscillation maximum. We will contribute high precision data for $10\,\mathrm{MeV} \leq \omega \leq 600\,\mathrm{MeV}$ and $38^\circ \leq \theta_e \leq 153^\circ$ covering both the QE and DR regions, see Fig. 3 and Fig. 4. With the acquired data the two response functions, R_L and R_T could be separated and individually studied: this is crucial for the development of robust neutrino generators, which need to work reliably over a wide kinematic range. Our hypothesis is that the new data will successfully validate present theoretical descriptions of nuclear dynamics in the regime of longitudinal kinematics or forward angle, but will exhibit significant deviations from models of the of transverse kinematics at large angles, where they generally underestimate the true cross-sections by $10-20\,\%$ in both QE and DR regions.

The data are not only relevant for the neutrino community, but also offer an unique chance for further advances in the theoretical description of $^{16}\mathrm{O}$. In particular, we will be able to determine the Coulomb sum rule for $0.2\,\mathrm{GeV} \leq |\vec{q}| \leq 0.8\,\mathrm{GeV}$ and search for a possible quenching effects at large momentum transfer. Within the context of quasi-elastic scattering, the sum rule is expected to saturate at momentum transfers between 0.5 and $1.0\,\mathrm{GeV/c}$. The failure of the sum rule to saturate would indicate an incomplete description of the interaction mechanism and would require either the introduction of other mechanisms,

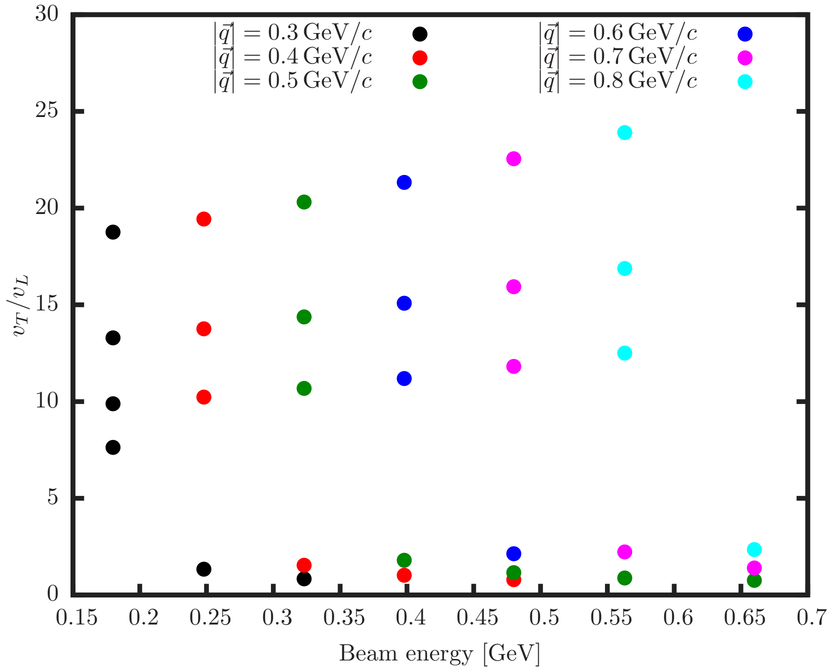

Figure 4 — The ratio v_T/v_L as a function of beam energy for different values of $\vec{q}$ demonstrates the sensitivity of the proposed experiment to investigate the longitudinal and transverse response functions R_L and R_T. The details of the proposed kinematic settings are gathered in Table 1.

like multi-nucleon correlations, or modifications of nucleon electromagnetic form-factors when bound inside the nuclear medium. The problem of the Coulomb sum rule has been an important open problem of nuclear physics for more than two decades, and it could not be addressed up to now due the lack of experimental data. With this experiment we are now having the unique chance to fill this gap and precisely validate the state-of-the art *ab-initio* models of oxygen's structure [7].

4 State-of-the-art in the proposed field of research and survey of the relevant literature

The key goal of the proposed project is to provide a comprehensive set of electron scattering data that will improve the present theoretical description of the electron-nucleus and neutrino-nucleus interactions and is crucial for a precise extraction of the neutrino properties from the long base neutrino experiments (T2K, HyperK, and DUNE) using carbon and oxygen as a detector medium.

The T2K experiment is a long-baseline neutrino oscillation experiment [9]. Its goal is to measure the mixing angle θ_{13} and perform a precision measurement of the oscillation parameters Δm^2_{23} and θ_{23}. Other goals of the experiment include the measurement of various neutrino cross sections, sterile neutrino searches, and progress in determining the CP-violating phase of the lepton sector. The experiment uses a muon-neutrino beam produced at the J-PARC facility. Neutrinos are detected at a Near Detector (ND280) and at the Far Detector (Super-Kamiokande). The most recent oscillation results of T2K [10] provided the world best measurement of the mixing angle θ_{23} and for the first time put constraints on the CP violating phase, excluding CP conserving values at 2-sigma. The capabilities of the J-PARC accelerator will be expanded even more with the construction of the HyperK experiment which will continue the experimental program started with T2K.

The Deep Underground Neutrino Experiment (DUNE) will be the largest experiment for neutrino science. It will consist of multiple neutrino detectors placed in the world's most intense neutrino beam. One (carbon) detector will record particle interactions near the source of the beam, at the Fermi National Accelerator Laboratory. A second, much larger, (liquid argon) detector will be installed at the

Sanford Underground Research Laboratory in South Dakota, 1300 kilometers away from the source. The construction of the facility at Sanford started on July 21, 2017. Tests of the detectors are also already underway at CERN. The description the project, its scientific objectives, the strategy of the experimental program as well as the details about the detectors is gathered in a four volume conceptual design published on-line [11, 12, 13, 14].

The status and prospects of theoretical studies of neutrino–nucleus interactions is reviewed by Omar Benhar et al. [15]. The authors discuss the influence of the nuclear effects on the determination of oscillation parameters. The models developed to describe the variety of reaction mechanisms contributing to the nuclear cross sections are analyzed, with emphasis placed on their capability to explain the large body of available electron scattering data. The impact of the uncertainties associated with the description of nuclear structure and dynamics on the determination of oscillation parameters is illustrated and possible avenues towards a better understanding of the signals detected by accelerator-based experiments are outlined. Detailed studies of the impact of nuclear effects on the extraction of neutrino oscillation parameters can be found also in the publications of P. Coloma and P. Huber [16], A. M. Ankowski and C. Mariani [17] and S. Naaz et al. [1].

In the energy range of T2K/HyperK and DUNE experiments, the dominant contribution to the neutrino-nucleus cross section comes from the charged-current quasielastic (CCQE) reaction and resonance production processes. To successfully accomplish the physics goals of the experiments, the reaction mechanisms of the neutrino-nucleus interaction need to be precisely understood. The theoretical model for neutrino-nucleus scattering in the 1 GeV region was developed by A. M. Ankowski and J. T. Sobczyk [18]. In particular, they constructed spectral functions for oxygen, calcium, and argon, that could be used to calculate the electron and neutrino cross sections. They tested their results on the existing data and observed a good agreement for oxygen and calcium, but only in the vicinity of the QE peak. The delta resonance is not included in their calculations.

Unfortunately, tests of the lepton-oxygen interaction with the (e,e') data are at the moment not possible, because there is not enough experimental data. Presently only two 25-years old publications are available from M. Anghinolfi et al. [5] and J S O'Connell et al. [6], which provide measurements for two scattering angles (32° and 37.1°) and with very limited statistics. There are no experiments foreseen in the near future that could improve this situation. Recently, the experiment E12-14-012 was performed at the Thomas Jefferson National Accelerator Facility, where we measured differential cross sections for $^{12}\mathrm{C}(e,e')$, $^{27}\mathrm{Al}(e,e')$, $^{40}\mathrm{Ar}(e,e')$ and $^{48}\mathrm{Ti}(e,e')$ at incident electron energy $E = 2.222\,\mathrm{GeV}$ and scattering angle $\theta = 15.541^\circ$. These data [19, 20, 21] cover a broad range of energy transfers, where quasi-elastic scattering and delta production are the dominant reaction mechanisms. The new data sets show the capability of modern scattering experiments but unfortunately offer only one "omega scan" constrained to a single forward angle scattering angle. Additionally, the experiment does not offer data for oxygen. The necessity to provide data also for oxygen is recognised in the concluding remarks of [19], where it is stated that measurements on oxygen would be of particular interest because water serves as both target and radiator in the large Cerenkov detector of T2K.

Following S. Boffi and C. Giusti describing electromagnetic interactions with complex nuclei [22], the cross-section for inclusive quasi-elastic scattering of electrons from nuclei depends on two response functions R_L and R_T, sensitive to charge density and magnetic current, respectively. The longitudinal response is accessible from the cross-section measurements at small scattering angles, while the transverse response function dominates the large angles (large $|\vec{q}|$). Since the R_T is a more complex theoretical object, it represents a more stringent test of the model. Additionally, for neutrino experiments, where the kinematics of the reactions can not be precisely selected and large angle scattering processes can play an important role in the analysis, the good control over the transverse response is needed. To achieve this, we should not just repeat the Jefferson Lab experiment with a different target: we need a new experiment that will go beyond that, providing data also at large scattering angles to access the transverse response function R_T.

A lot can be learned also from the comparison of oxygen measurements with the equivalent results for carbon [21, 23]. Carbon has been the most extensively studied nucleus. For this nucleus we have the richest sample of (e,e') data. It consists of 2883 data points from 11 experiments for the energies between 0.16 GeV and 5.8 GeV. However, all data are limited to scattering angles below 60°. These data, joined into a single database, maintained and managed by O. Benhar, D. Day, and I. Sick [2], has been used to study the structure of this nucleus and to develop models describing its response. For a long time these calculations were limited to the QE region and the most demanding part was the description of the transverse response, which has been for a long time incomplete [22]. Recent calculations of G.D. Megias et al. [24] based on the SuSAv2-MEC approach achieved better agreement and extend their reach also to the delta resonance region. However, the description of the cross-sections at large scattering angles remains incomplete, partially also due to the lack of data at these kinematic conditions.

The $^{12}C(e,e')$ reaction is of course interesting also in the context of neutrino physics and has played an important role in the development of models describing cross-sections in the experiments like MiniBooNE [25], MINERvA [26], and T2K [9], that use carbon-based materials (mineral oils, plastic scintillators) as detector medium. O. Benhar et al. [27] studied electron- and neutrino-nucleus scattering in the impulse approximation regime and calculated inclusive cross-sections in the kinematical region relevant for neutrino oscillation experiments like MiniBooNE. On the other hand, A. Meucci and C. Giusti [28, 29] used relativistic Green's function model to describe the charged-current inclusive differential neutrino-nucleus cross sections of the MiniBooNE, MINERvA, and T2K experiments. They put special emphasis on a consistent description of the final state interaction [30, 3, 31]. A comprehensive study was recently made also by M. V. Ivanov et al. [4], where they presented the global relativistic folding optical potential (GRFOP) fits to elastic proton scattering data from ^{12}C nucleus at energies between 20 and 1040 MeV. The new GRFOP potential was then employed within the relativistic Green's function model for inclusive quasi-elastic electron scattering and for (anti)neutrino-nucleus scattering at MiniBooNE kinematics. The results obtained are comparable with the results obtained in previous studies, done with the phenomenological optical potentials (A. Meucci and C. Giusti [28], but still incapable of reproducing the neutrino spectra measured by the MiniBooNE experiment. Hence, this clearly indicates that future high-precision neutrino experiments can succeed only if present theoretical models will be further evolved and improved. Within this effort, comprehensive electron scattering data in the region between 0.6 GeV and 0.9 GeV would be of extreme interest.

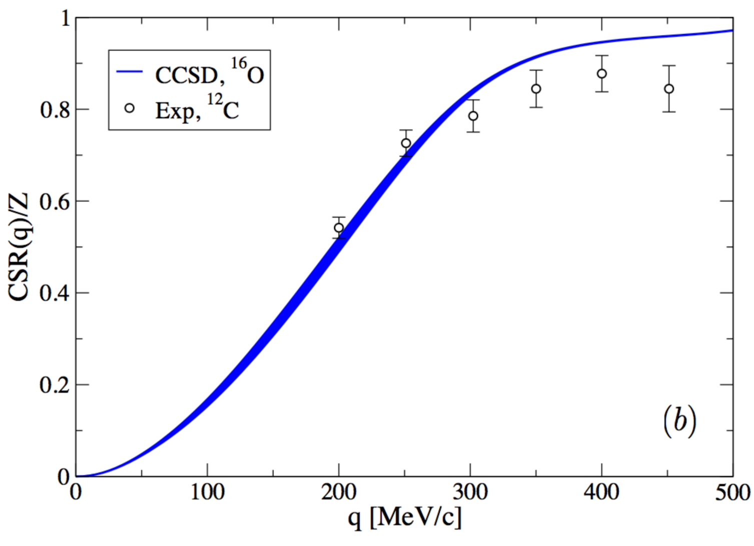

Figure 5 — Coulomb sum rule for ^{16}O from coupled-cluster theory using a chiral two-body force. In the absence of the ^{16}O data, the calculations could be compared only to experimental results for ^{12}C. See S. Bacca et al., J. Phys. Conf. Ser. 966, 012019, 2018

Beside the mean field calculations new experiments that perform measurements at large scattering angles, would be important also for the modern *ab-initio* theories. For instance, the group from Mainz studies electromagnetic reactions from coupled-cluster theory. In [7] they investigated electromagnetic reactions and the related Coulomb sum rule for oxygen using coupled cluster theory and the Lorentz integral transform (see plot 5). Their approach is relevant, because it can be directly extended to *ab* *initio* studies of the neutrino-nucleus cross section, but first needs to be precisely checked using electron scattering data.

5 Proposed work program

The project will start with a one-week introductory study. Although the experiment will use only the standard equipment of the A1 collaboration, the apparatus first needs to be prepared and optimised for running under the selected kinematic conditions. For that purpose we intend to collect data with a thin carbon-foil target and electron beam with energy of 600 MeV. For the spectrometer, 20 different momentum configurations between 520 MeV/c and 630 MeV/c are envisioned. Configurations are chosen such that the elastic events are always inside the detectors acceptance. Positions and widths of the elastic lines, reconstructed at different positions of the spectrometer's acceptance will be used to verify the available optics matrices (parameterizations describing magnetic optics of the spectrometer), and relate signals detected in the detectors with physically interesting particle coordinates at the vertex. Additionally, these data will be used also for the determination of the efficiency of the Vertical Drift Chambers (tracking detector), scintillation detectors (triggering detector) and Cherenkov detector (particle identification and cosmic background suppression).

The calibration measurement will be followed by the actual experiment using the same experimental setup. The study of inclusive cross-sections for the $^{16}\mathrm{O}(e,e')$ reaction will be done with a continuous-wave electron beam at 7 different energies between 180 MeV and 660 MeV. For the measurement of cross-section the large-acceptance spectrometer A will be employed. It will be positioned at 7 different angles between 38° and 153°, while its momentum will be changed from 100 MeV to 660, MeV in order to accumulate data over a large kinematic range, covering both the QE peak and the DR region. Altogether, measurements in 400 different kinematic settings are envisioned. Assuming a beam current between 10 μA and 20 μA the detection rates are expected to be between 20 Hz and 500 Hz, see Fig. 6 and Table 1. The measurement at each kinematic setting will be repeated with the $^{12}\mathrm{C}$ target by using 0.5 mm a thick carbon foil. This can be done with minimal additional effort but gives to our experiment an important advantage: it will allow systematic checks in combination with older measurements, and give new insight by providing new comprehensive data sets also for carbon in the presently unmeasured region of $|\vec{q}| > 600$ MeV. Altogether, 36 days of beam-time are needed in order to determine the cross-section for both $^{16}\mathrm{O}$ and $^{12}\mathrm{C}$ to a 0.3% relative uncertainty. The experiment will be divided into two, three weeks long segments. In the first part the data for $|\vec{q}| = 0.2, 0.4, 0.6$ GeV will be collected. In the second part the data for $|\vec{q}| = 0.7, 0.8$ GeV will be recorded.

For the measurement with oxygen, the experiment will employ a waterfall target, which generates a thin film of water perpendicular to the beam direction. Assuming a beam current of 20 μA, a luminosity of $4 \cdot 10^{35}\,/\mathrm{cm}^2\mathrm{s}$ can be achieved. Without an extensive metal frame in the vicinity of the vertex, this target will allow measurements of the cross-section without unwanted backgrounds originating from the target walls. This way we will minimize the target-related systematic uncertainty, typically a limiting effect in experiments with an extended cryogenic target. Furthermore, the use of an effective point-like target makes the experimental results less sensitive to shortcomings due to the track reconstruction in the spectrometer. The only disadvantage of the waterfall target is the contamination with scattering events on hydrogen. However, the cross-section for the $H(e,e')$ process can be simulated with very high accuracy and can be precisely subtracted from the measured spectra [32].

With a well understood experimental apparatus and a thin target, the success of the experiment depends predominantly on the precise determination of the beam luminosity. In general, the luminosity is measured by a non-invasive magnetic probe or by an invasive calorimeter detector. Unfortunately, these detectors are not accurate enough (2 %) for our purpose. For a sub-percent precise monitoring of beam luminosity spectrometer B will be employed, anchoring it at a fixed elastic scattering setting. By comparing the observed rates in spectrometer B with those simulated with the known elastic cross-section, we will establish a precise absolute calibration and gain a superior control over systematic uncertainty.

Table 1 — Proposed settings for inclusive measurements together with the expected rates for carbon and oxygen target and required time per setting, assuming beam current of 20 μA.

Kinematic settings				**carbon**		**oxygen**	
Setting	E_0 [GeV]	θ_e [°]	Number of ω settings	Rate [Hz]	Time [h]	Rate [Hz]	Time [h]
kin01	0.18	138	12	310	1.1	206	1.6
kin02	0.18	143	12	282	1.2	188	1.75
kin03	0.18	148	12	258	1.3	172	1.95
kin04	0.18	153	12	241	1.4	161	2.05
kin05	0.248	83	12	500	0.68	570	0.6
kin06	0.248	143	12	130	2.55	86	3.85
kin07	0.248	148	12	120	2.75	80	4.15
kin08	0.248	153	12	113	2.95	75	4.4
kin09	0.323	58	12	500	0.68	500	0.68
kin10	0.323	88	12	255	1.3	170	1.95
kin11	0.323	143	12	65	5.15	43	7.7
kin12	0.323	148	12	60	5.5	40	8.25
kin13	0.323	153	12	56	5.9	37	8.8
kin14	0.398	68	12	506	0.65	337	1
kin15	0.398	93	12	102	3.25	68	4.9
kin16	0.398	143	12	33	10	22	15
kin17	0.398	148	12	31	10.55	21	15.8
kin18	0.398	153	12	30	11.1	20	16.65
kin19	0.48	38	12	500	0.68	500	0.68
kin20	0.48	53	12	833	0.4	555	0.6
kin21	0.48	73	12	181	1.85	121	2.75
kin22	0.48	98	12	52	6.3	35	9.45
kin23	0.48	143	12	18	18.2	12	27.25
kin24	0.48	148	12	17	19.35	11	29.05
kin25	0.48	153	12	16	20.7	11	31.05
kin26	0.563	58	12	318	1.05	212	1.55
kin27	0.563	98	12	29	11.3	19	17
kin28	0.563	143	12	10	33.35	7	50
kin29	0.563	148	12	9	35.3	6	52.95
kin30	0.563	153	12	9	37.5	6	56.25
kin31	0.66	48	12	451	0.75	301	1.1
kin32	0.66	78	12	40	8.2	27	12.35
kin33	0.66	98	12	15	21.45	8	32.15

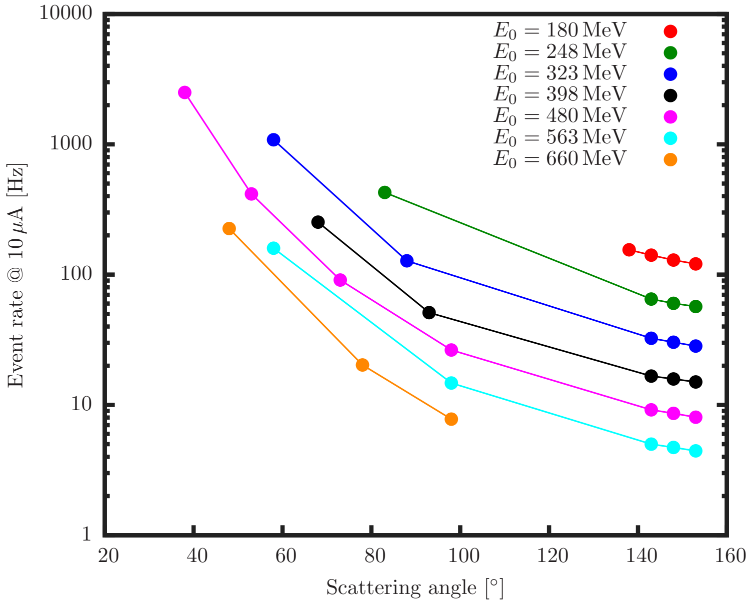

Figure 6 — Expected raw rates for the kinematic settings of the proposed experiment (see Table 1) assuming beam current of $10\,\mu$A. During the experiment we intend to use electron beam with $20\,\mu$A. The maximum DAQ rate is $\approx 500\,$Hz.

Each experimental agenda will be followed by data analysis, starting with the calibration of the apparatus. The first analysis phase consists in the determination of the best set of selection cuts. This includes cuts on the angular acceptance of the spectrometer, to remove any boundary distortions, cuts on the vertex position, cuts on the momentum acceptance and cuts on the Cerenkov signal to select electrons and remove other background particles (e.g. muons and pions). For each cut, a systematic study will be performed in order to assess the influence of the cuts on the data. This is needed in order to prevent any systematic offsets that could influence the final results.

Once the best samples of events will be determined, the data will be combined with the simulation of the experimental acceptance in order to extract cross-sections as functions of ω at different values of $|\vec{q}|$. For that we will use the simulation package `Simul++`, which was designed specifically to simulate the experiments of the A1 collaboration and considers the true acceptances of the magnetic spectrometers, particle energy-losses on their transport from the target to the detector systems through the spectrometers, and the detailed description of the radiative corrections [32].

The cross-sections resulting from the analysis will be used to challenge the available theoretical models. We have a strong collaboration with the local theory group from the Mainz University, led by Sonia Bacca, who performs the *ab-initio* calculations on oxygen. The comparison of the measured longitudinal response with the calculations at different values of $\vec{q}$ will challenge the theoretical predictions and directly expand the precision frontier of nuclear physics. We have also established collaborations with the theoretical groups from Pavia and Sevilla who are strongly involved in the development of nuclear models for neutrino experiments. While their calculations agree well with the results of the recent Jefferson Lab experiment at higher energies and small angles (sensitive to R_L), they are eagerly waiting to test their calculations in the kinematics regime sensitive to R_T, where large discrepancies are expected.

The proposed project presents no major inherent risks. Even though we are using a very complex system, which is susceptible to malfunctions, these types of experiments present no special risks. The replacement parts are available for all the components involved in the experiment, and experience has showed that with the technical support teams always available, even major malfunctions can be repaired in less than a month. The data will be collected with more statistics than needed for achieving the necessary precision of the cross-section measurements and the absolute systematic uncertainty will also be below $1\,\%$.

6 Feasibility study

The feasibility of the proposed experiment was assessed and demonstrated by a short experiment performed in 2019, using a carbon target, beam electrons with an energy of 855 MeV and spectrometer at 70°. The results of the experiment are presented in figures 7 and 8. They agree well with the available theoretical models and simultaneously demonstrate the enormous potential of the Mainz facility for performing such measurements. In 10 hours we collected data for 7 different kinematic settings around the quasi-elastic peak with a statistics superior to any previous experiment. Summarizing, the project represents a low risk

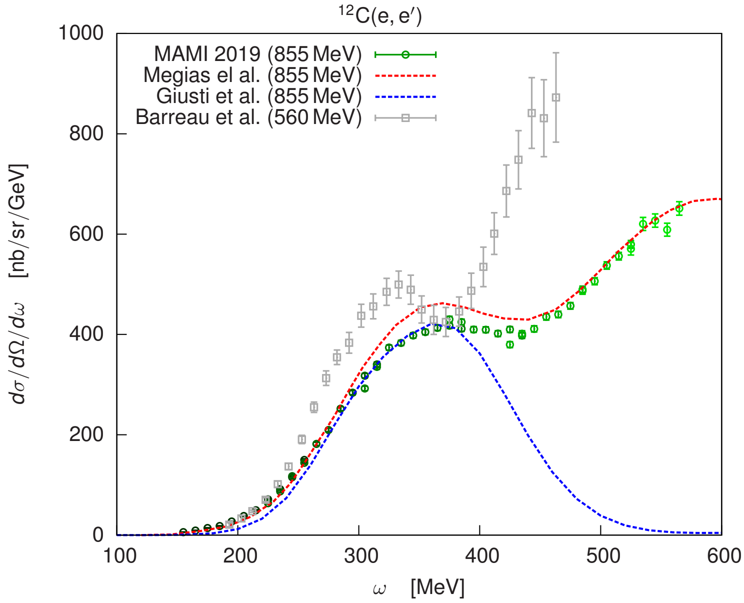

Figure 7 — Extracted cross-sections together with rescaled old measurements at similar kinematics and theoretical calculations of Giusti *et al.* and Megias *et al.* The data shows good agreement with the calculations.

of failure while offering a remarkably large scientific gain. We expect experimental results confirming the theoretical predictions for the Coulomb sum rule. An agreement would represent an important advancement for theoretical nuclear physics. It would establish the considered theoretical approaches and motivate similar calculations also for other nuclei. On the other hand, we expect the experiment to reveal significant discrepancies between data and theory in the transverse kinematics, since this kinematic region has not been measured before. Moreover, the behaviour of the transverse response is crucial for current and future neutrino experiments.

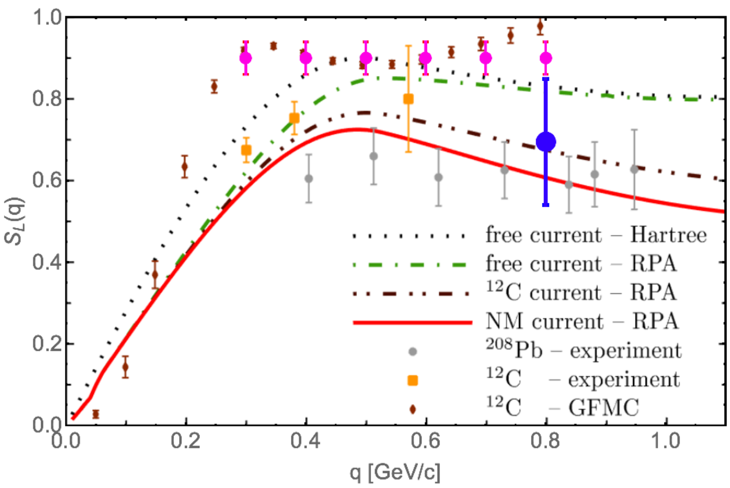

Figure 8 — The Coulomb sum rule as a function of the three-momentum transfer $|\vec{q}|$. The blue point shows the results of the test experiment, together with the existing data on carbon (orange squares) and corresponding theoretical calculations [33]. The purple points at the top show $|\vec{q}|$ values and expected precision of the data points acquired in the proposed experiment.

7 Conclusions and beam-time requests

In conclusion, the project's goal is to perform a high precision electron scattering experiments on oxygen and carbon that will for the first time allow a complete study of their electromagnetic properties and provide a vital new input to existing models of nuclear structure and dynamics, employed to interpret data from accelerator-based neutrino experiments. To successfully realize the proposed experimental agenda, we ask for 36 days of beam-time, including 5 extra days for accelerator maintenance and repairs of eventually faulty equipment broken during the experiment.

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