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Neutrino Scattering Physics at a Super Beam Facility

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This is a summary of Neutrino Scattering Session (WG2). We find that at the time of a Super Neutrino Beam Facility there will already exist a relatively precise set of experimental results for ν - nucleus scattering. What this new facility will provide is the opportunity to attain equally precise results for $\overline{\nu}$ - nucleus and ν $\overline{\nu}$ - nucleon scattering results. For the study of ν $\overline{\nu}$ - polarized target, the intensities and beam properties of a Neutrino Factory will be required.

1. Neutrino Scattering Physics at a Super Beam Facility

1.1. Introduction

A Super Neutrino Beam Facility (SNBF), with high-intensity neutrino and antineutrino beams, will offer a unique opportunity to explore neutrino scattering processes with unprecedented precision. While there will have been significant progress made in this area with current and currently planned experiments, existing beams will lack the intensity needed to make the precision measurements required for complete understanding of the physics.

The pre-SNBF experiments will provide measurements of neutrino charged-current (CC) and neutral-current (NC) (quasi)elastic scattering and CC and NC production of pions and strange particles on nuclear targets. It will remain for the SNBF to make high-precision measurements of these processes with antineutrino beams and with nucleon targets.

It is assumed in the following sections, that these current and near-future experiments will have completed relevant measurements by the time of start-up of the SNBF

- Auxiliary experiments to predict the neutrino flux such as HARP, BNL E910and MIPP;
- Jefferson lab high precision elastic scattering experiments for precisio determination of the vector form factors;
- The K2K suite of near detector experiments including the SCIBAR experiment;
- The MiniBooNe experiment;
- The MINERvA experiment running parasitically to MINOS; and
- T2K-I, although details of a neutrino scattering detector are not yet known.

A review of what we expect to be the state of knowledge of neutrino scattering physics and what will still be awaiting experimentation at SNBF is presented below.

1.1.1. Low-energy Neutrino Cross-sections: Quasi-elastic Scattering

As shown in Figure 1, MINERvA will have measured the cross-section up to E_ν = 20 GeV with statistical errors ranging from $\leq$ 1% at low E_ν up to 7% at E_ν = 20 GeV. The expected beam systematic error is 4–6% thanks to precision measurements of hadron production (the largest uncertainty in predicting neutrino flux) by the current MIPP experiment [1]. For the axial-vector form-factor, measurement of neutrino quasi-elastic scattering is the most direct way to improve our knowledge. MINERvA's ability to measure $d\sigma/dQ^2$ to high Q^2 will have allowed investigation of the non-dipole component of the axial-vector form factor to an unprecedented accuracy. Figure 1 shows the extraction of the axial-vector form factor from the quasi-elastic event sample accumulated over a 4-year MINERvA run. The data points are plotted as

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a ratio of F_A/F_A(Dipole) with the indicated assumptions. Also shown are the currently available values of F_A from early experiments. MINERvA will have measured the axial nucleon form-factor with precision comparable to vector form-factor measurements at JLab. Combining MINERvA's measurements with Jefferson Lab data that will be available by the time of the SNBF will permit precision extraction of all form factors needed to improve and test models of the nucleon [2]. Similar accuracy for $\overline{\nu}$ can only be achieved with SNBF.

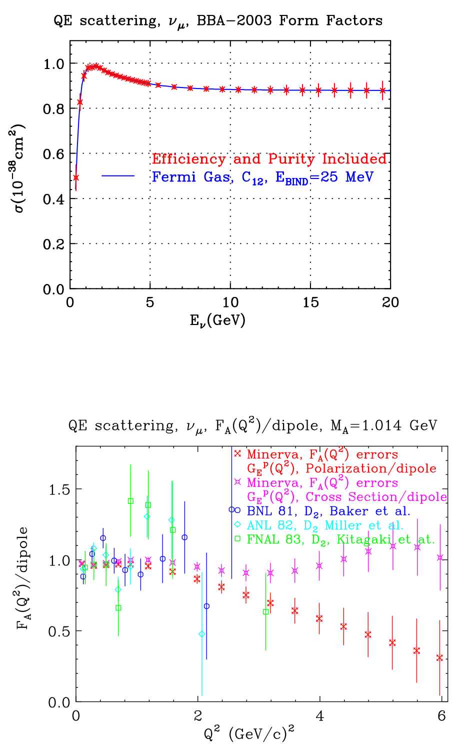

Figure 1. Above is the simulated cross-section measurement for MINERνA in a 4-year run (statistical errors only) assuming M_A=1.00 GeV and the Fermi gas model. Below are the projected axial form-factor results for MINERνA for two different assumptions: F_A/dipole=G_E^p/dipole from cross-section and F_A/dipole=G_E^p/dipole from polarization. Also shown are the extracted values of $F_A(q^2)$/dipole for deuterium bubble chamber experiments Baker *et al.* [3], Kitagaki *et al.* [4] and Miller *et al.* [5].

1.1.2. Low-energy Neutrino Cross-sections: Resonance Production

To simulate resonance-mediated reactions, Monte-Carlo programs still use early theoretical predictions by Rein & Sehgal [6] or results from electro-production experiments, since existing data on neutrino-induced resonance production is inadequate. The theoretical and experimental picture of the resonance and transition regions is far more obscure than the quasi-elastic and DIS regions which border it.

Analysis of resonance production in MINERvA [7] will have focused on several experimental channels, including inclusive scattering in the resonance region ($W < 2$ GeV) and exclusive charged and neutral pion production.

This channel may need additional investigation with an even-more fine-grained detector such as a LAr TPC. The investigation of this channel for ν is not limited by beam intensity but rather by detector techniques. Similar accuracy for $\overline{\nu}$ can only be achieved with SNBF.

1.1.3. Low-energy Neutrino Cross-sections: Coherent Pion Production

MINERvA, with its high statistics and variety of nuclear targets, will have greatly improved our experimental understanding of coherent processes. Figure 2 shows the estimated statistical precision of MINERvA's CC coherent scattering measurement, as a function of neutrino energy, after background subtraction. The model of Rein & Seghal [8] has been assumed. Also plotted are the only currently available measurements in this kinematic region showing their total errors.

MINERvA's CC coherent event sample will also have been used to study the differential cross-sections. Comparison of the overall rates of NC and CC production, as well as the pion energy and angular distributions will allow valuable tests of the various models. For several recent models, the predicted NC/CC ratios in coherent scattering differ by around 20% [8,9].

MINERvA will also have compared the reaction rates for lead, iron and carbon. The A dependence of the cross-section depends mainly on the assumed model of the hadron–nucleus interaction and serves as a crucial test for that component of the predictions [11]. Figure 3 illustrates the broad range in A

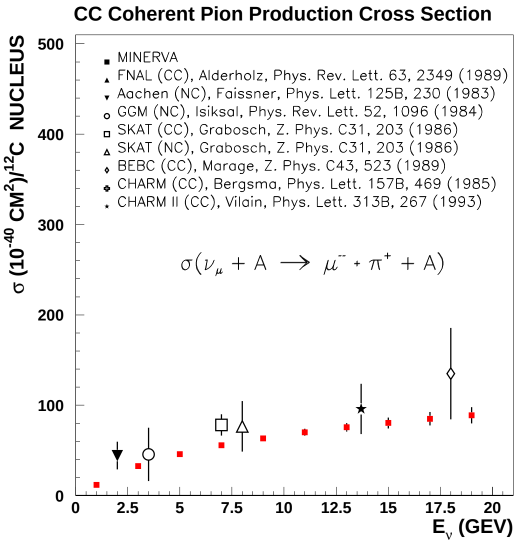

Figure 2. MINERνA's simulated CC coherent cross-section measurement, assuming a 4-year run, statistical errors only, compared with published data.

covered by MINERvA's measurement of the coherent pion cross-section. The shaded band is the range in A covered by existing experiments.

The MINERvA results [10] will have eliminated several models for coherent production by the time a SNBF comes on-line. Similar accuracy for $\overline{\nu}$ can only be achieved with SNBF.

1.1.4. Comment on a deficit at $q^2 < 0.2(GeV/c)^2$ region in the charged-current q^2 distribution

A deficit at $q^2 < 0.2(GeV/c)^2$ region in the charged-current q^2 distributions was first reported by the K2K experiment at NuInt01 Workshop [26] in 2001. MiniBOONE group reports the similar deficit in the quasi-elastic scattering [27] in 2003. K2K group confirmed the effect with a new fine-grain detector (SciBar) in 2004 [28–30]. The level of the discrepancy is of the order of 20-30%. Such difference is shown to have little effect on the neutrino oscillation analysis at present statistical errors [29]. However, this difference between data and the calculation should be solved before the future neutrino oscillation experiments which aim at the measurement of $\sin^2 2\theta_{13}$ at the level of 1% or better [**?**].

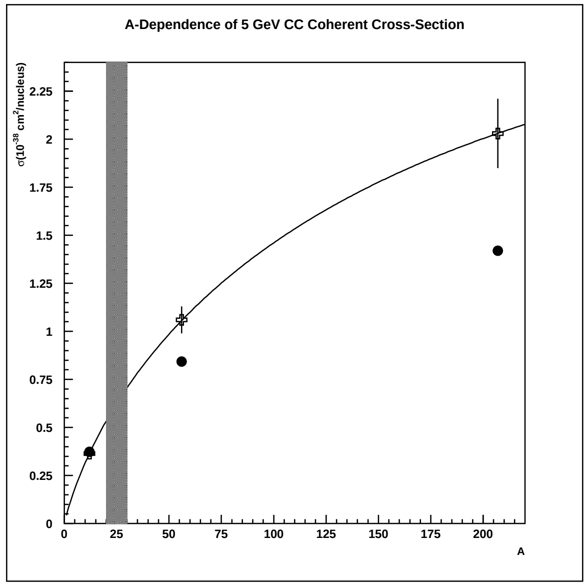

Figure 3. The range of A-dependence in coherent pion-production accessible to MINERνA is compared to the narrow range of existing data, shown by the shaded band. The curve is the prediction of the Rein-Seghal model [8] while the solid circles correspond to the prediction of Paschos and Kartavtsev [9]

Neutrino-nucleon cross section in the few GeV region is expressed in terms of the vector form factor and the axial form factor. We assume under CVC hypothesis that the vector form factor is the same as that measured in electron scattering. The vector form factor for electron-proton scattering is well measured, but that for electron-nucleus scattering is not measured well, but we assume that we can calculate the nuclear effect. The accuracy of the calculation is poor, say 10-30%. The axial form factor is assumed to take a dipole form factor with an additional parameter M_A. It was recently pointed out that the dipole form factor is good to 10-20% [31].

The new K2K data suggest that the deficit is due to the suppression of the inelastic events and most likely the suppression of the charged-current coherent pion production [30].

The origin of the difference between data and the calculation may be due to various effects such as the wrong form factors, unknown nuclear effects, uncertain coherent pion cross sections and so on [29,30]. Kopeliovich points out that while the coherent pion production is expected to be suppressed at low energy, the incoherent pion production takes over at low energies [33].

A new experiment E04-001 (JLAB) was performed to measure the electron-nucleon and electron-carbon quasi-elastic and N*(1232) production cross sections with high statistics in January, 2005 [32]. This will give important information on the cross sections in the low Q^2 region.

The consistency between MiniBOONE data and K2K data should be understood.

1.1.5. Nuclear Effects in Neutrino Scattering

Analysis of neutrino reactions with nuclear media requires understanding the nuclear environment's effect on the process [13]. There are two general categories of such nuclear effects:

- The neutrino interaction probability on nuclei is modified relative to free nucleons. Nuclear effects of this type have been extensively studied in DIS structure function measurements using muon and electron beams, but have not been explored with neutrinos. Depending on the kinematic region, these nuclear effects can be quite different for neutrinos, particularly the shadowing phenomenon [33].

- Hadrons produced in a nuclear target may undergo final-state interactions (FSI), including re-scattering and absorption. These effects may significantly alter the observed final-state configuration and measured energy [16,17], and are sizable at neutrino energies typical of current and planned oscillation experiments [14].

The hadron shower observed in neutrino experiments is actually the *convolution* of these two effects. FSI effects are dependent on the specific final states that, even for free protons, differ for neutrino and charged-lepton reactions. The suppression or enhancement of particular final states by nuclear effects also differ for neutrino and charged lepton reactions. For these reasons, measurements of nuclear

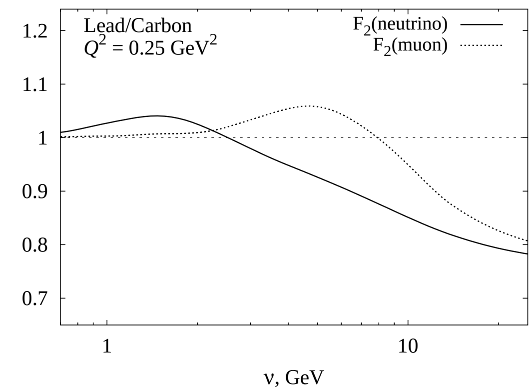

Figure 4. Predicted shadowing effects at Q^2 = 0.25 GeV^2 as a function of energy transfer (ν), for neutrinos (solid line) and muons (dotted line). Th plot on the left is for iron compared to deuterium while the right plot is leadcompared to carbon, what MINERνA will measure.

effects with charged leptons cannot be simply applied to neutrino-nucleus interactions.

It has recently been suggested that, for a given Q^2, shadowing can occ ur at much lower energy transfer (ν) for neutrinos than for charged leptons. This effect is unaccounted for in neutrino event generators. As explained in [15], for a given Q^2 the cross-section suppression due to sha dowing occurs for much lower energy transfer (ν) in neutrino interactions th an for charged leptons. Figure 4 shows the predicted difference between neutrino and charged lepton shadowing as a function of the energy transf er (ν). On the left is the ratio of iron to deuterium while on the right is shown the ratio of lead to carbon. The projected statistical error on the rati o of lead to carbon is order 2% at ν = 6 GeV. Clearly this is an important effect, and without MINERvA, there are no data available to measure it.

MINERvA will have carefully studied these effects with targets of carbon, iron and lead [15]. What will be missing is a comparison with deuterium which is essential for maximal understanding of these effects. Similar accuracy for $\overline{\nu}$ can only be achieved with SNBF.

1.1.6. The Perturbative - Non-Perturbative Interface and Deep-Inelastic Scattering

Despite the apparent dichotomy between the partonic and hadronic regimes, in nature there exist instances where the low-energy behavior of cross-sections (averaged over appropriate energy intervals) closely resembles that at asymptotically high energies, calculated in terms of quark-gluon degrees of freedom. This phenomenon is referred to as *quark-hadron duality* and is the focus of substantial recent interest in probing the structure of the nucleon [19–23]. For example, there are over 10 related experiments at JLab.

Understanding this transition requires reliable data in three kinematic regimes: in the scaling domain of high Q^2 DIS scattering; in the hadronic region of resonances and quasi-elastic scattering; and, perhaps most importantly, in the moderate Q^2 region between the two, where the transition is most dramatically manifest. MINERvA will have addressed this compelling topic for the first time with neutrinos with measurements spanning all three regimes, providing reliable data in the crucial transition region [24].

1.2. Goals of a Neutrino Scattering Physics Program in the SNBF Era

As shown, low-to-medium energy ν**- nucleus** scattering will be quite well covered. However $\overline{\nu}$**- nucleus** and ν / $\overline{\nu}$ **- nucleon**, in this same important energy range, will still not have been covered as needed. The simple reason why these topics will not have been covered is the meager event rate associated with them. The $\overline{\nu}$ event rate is down a factor of (3 - 5), depending on energy range, compared to a ν exposure. This comes from a combination of the cross-section ratio and the production rate ratio of π^+ to π^-. Combining this factor with the low absolute cross-section associated with low-energy neutrinos and what would take a 3 year run to accumulate with ν would take **9 - 15 years with** $\overline{\nu}$. Similarly a neutrino scattering physics program on the nucleon (Liquid H_2 and D_2 targets) has an event rate an order-of-magnitude lower than with a carbon target. To completely understand ν / $\overline{\nu}$ **- nucleon** as well as $\overline{\nu}$**- nucleus** scattering physics, the higher statistics available with a SNBF is essential.

1.2.1. Neutrino Beam Requirements

The standard 2-horn beam provides a very pure ν beam with only a small admixture of $\overline{\nu}$ background. Unfortunately, the converse is not true. As an example, the NuMI 2-horn $\overline{\nu}$ le-beam actually yields **more** ν events than $\overline{\nu}$ events. This is due to the forward going higher energy positive pions that go right through the neck of the horns and, thus experience no deflecting magnetic field. For a high-precision $\overline{\nu}$ beam in the SNBF era the logical choice of beam would be a sign-selected beam such as was used by Fermilab experiment E-815 (NuTeV) [25]. With this sign-selected beam, the ν contamination of the $\overline{\nu}$ beam is reduced to 4x10^{-3}, a dramatic improvement compared to the 2-horn beam.

1.2.2. Detector Requirements

An important goal of an SNBF neutrino scattering program will be a careful study of ν / $\overline{\nu}$ - nucleon scattering. This will require a large liquid hydrogen/deuterium target. The challenge will be to know what is happening to the events produced within the hydrogen/deuterium target before they leave the target and enter the tracking detectors surrounding the target. A way to record the tracks within the cryogenic liquid target itself is make the target active as in a Bubble Chamber. Contemporary large bubble chambers are being developed for WIMP searches by a University of Chicago/Fermilab collaboration and for Bubble Chamber spectroscopy by Los Alamos lab. These new chambers use CCD coupled readout to directly transfer the image to disk. Patern recognition and tracking software developed for emulsion experiments can then be directly employed to reproduce the three-dimensional images.

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