Soft Neutron Production in DIS: a Window to the Final State Interactions

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Abstract

Recently E-665 reported the first measurement of soft ($E_n \leq 10$MeV) neutron production in deep inelastic scattering (DIS) off nuclei. We report the first theoretical analysis of the data. We find that the observed cross section can be quantitatively explained as due to the final state interactions (FSI) of low energy nucleons ($E_N \sim 200 - 400$MeV) produced in the elementary $\mu N$ interactions. We argue that the data indicate strong a suppression of the FSI’s of fast partons (hadrons) in DIS at high energies, and that studies of the soft neutron production would provide a new sensitive probe of the dynamics of FSI’s in DIS both at fixed target energies and at the HERA $eA$ collider.

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The final state interactions (FSI) in deep-inelastic scattering (DIS) off nuclei are known to provide a unique way of probing the space-time evolution of strong interactions. However, observing these effects is challenging, especially if one wants to study their energy dependence. A number of experimental studies have focused on the production of leading hadrons in the current fragmentation region, see [1–3] and references therein. The data indicate that at high energies the absorption of the leading hadrons is very small and hence most of the FSI occur at smaller rapidities. Indications of such FSI were reported by E665 in [4]. This poses a serious problem for the planned studies of FSI’s at the HERA collider in its eA mode of operation (for review of the project see the report of the study group [5]) since the present detectors are not sensitive to hadrons produced in the proton (nucleus) fragmentation region. Hence we argued in [5] that a study of soft neutrons may provide one of very few windows at HERA for studies of FSI’s. Indeed such neutrons have energies \( \approx E_A/A \) (\( E_A \) is the energy of the nucleus) and very small transverse momenta. As a result the H1 and ZEUS neutron detectors have nearly 100% acceptance for these neutrons [6].

The production of soft neutrons with energies \( E_n \leq 10 \text{MeV} \) in DIS off nuclei appears to be one of the very few observables which can be studied both at fixed target energies using standard detectors of low energy neutrons and at a eA collider using a forward neutron calorimeter [6,7]. The key question which we address here is whether soft neutrons are sensitive enough to the FSI’s in DIS to be of use for such studies.

The mechanism of the soft neutron production at intermediate energies in pA scattering (kinetic energies, \( T_{inc} \leq 0.5 - 1 \text{GeV} \)) is reasonably well understood - such neutrons are produced in the preevaporation and evaporation of the residual nuclear system left after interaction of the projectile with the target, see e.g. Refs. [8]. For a recent review see [9]. In the case of heavy nuclei these neutrons provide the major channel of ”cooling” of the residual system.

In the first approximation the total neutron multiplicity is proportional to the number of nucleons knocked out from the nucleus in the initial (fast) stage of the interaction.
Recently the first measurement of the soft neutron yields in DIS was performed by the E-665 collaboration [11] at FERMILAB. Neutrons with energies $E_N \leq 10$ MeV were detected in high energy muon scattering off a number of nuclear targets: D, C, Ca, Pb. A relatively small average multiplicity of such neutrons, $\langle N_n(A) \rangle$ was observed. In particular, for the lead target where the data are most accurate

$$
\langle N_n(Pb)(E_n \leq 10 \text{ MeV}) \rangle = 5 \pm 1.
$$

As far as we know the only high energy data available in the high-energy data bases on the production of soft neutrons come from the ITEP (Moscow) experiment [15] for incident proton momenta of $1.4 \leq p_p^{\text{inc}} \leq 8.5$ GeV/c. We find that the shapes of the spectra for the overlapping energy range: $7.5 \text{ MeV} \leq E_n \leq 10 \text{ MeV}$ - are similar. However, the neutron multiplicity is much higher for the proton projectiles (about a factor of 5-6 larger for $p-Pb$ collisions at $E_p \sim 10$GeV) which reflects a much larger number of wounded nucleons in $pA$ interactions. In order to compare $pA$ and $\mu A$ data, we calculated the number of neutrons produced per wounded nucleon $\frac{1}{A \sigma_{\text{tot}}(aN)} \frac{d^3 \sigma(a+A\rightarrow n+X)}{d^3 p/E}$, since in Glauber type models without secondary interactions this quantity does not depend on the projectile [12]. This quantity is still about a factor of two larger for the proton case, indicating that secondary interactions are more important for the proton projectile.

Average $x$ for the trigger used in [11] is $\approx 0.015$. For such $x$ nuclear shadowing for $Pb$ is very small: $\sigma_{\text{tot}} = \sigma_{\text{imp.appr}} - \sigma_{\text{shad}}$ with $-\eta \equiv \sigma_{\text{shad}}/\sigma_{\text{imp.appr}} \approx 5\%$. Using the Gribov theory of nuclear shadowing which expresses the shadowing effect, $\sigma_{\text{shad}}$ through cross section of coherent diffraction in $\gamma^* N$ scattering, and the Abramovskii-Gribov-Kancheli cutting rules one finds that nuclear shadowing leads to an increase of the cross section of the diffractive events by $\sigma_{\text{shad}}$; the decrease of the cross section of single interactions from $\sigma_{\text{imp.appr.}}$ to $\sigma_{\text{imp.appr.}} - 4\sigma_{\text{shad}}$, and emergence of the cross section of simultaneous interactions with two nucleons equal to $2\sigma_{\text{shad}}$, see [14] for the recent discussion. Taking into account that the number of soft neutrons generated by the mechanism we discussed increases approximately by a factor of two for the events where two nucleons are knocked out, we find that the shadowing effects lead to a slight increase of average neutron
multiplicity by a factor \((1 - \eta)^{-1} \approx 1.05\) for the kinematics of [11]. Due to the shadowing effects, hence, we will neglect this small effect in the further analysis.

It is generally assumed that in DIS high-energy hadrons are formed at distances

\[
l_{\text{formation}} \sim \frac{p_h}{\mu^2}
\]  

from the interaction point (see e.g. [2]), in which \(p_h\) is the hadron momentum and the scale \(\mu^2\) is \(\leq 0.5\) GeV\(^2\). Hence at momenta above 10 GeV they are formed beyond the nucleus and only hadrons with energies \(\leq\) few GeV are involved in FSI’s with the residual nucleus. This picture is consistent with a very weak \(A\)-dependence of the leading particle spectra produced in DIS at high energies, see e.g. [3,1]. The most conservative assumption seems to be that only slow recoiling nucleons produced in the elementary lepton-nucleon DIS in the target fragmentation region reinteract with the nucleus. The spectrum of the recoil nucleons can be approximated at small \(x\) and not very large energies, where the triple Pomeron contribution is still small, as

\[
\frac{1}{\sigma_{\gamma^*p}} \frac{d\sigma_{\gamma^*p \to N + X}}{dz d^2p_t} \propto \exp(-a p_t^2) \sqrt{z}
\]  

with \(a^{-1/2} = \langle p_t^2 \rangle^{1/2} \sim 0.4\) GeV/c, see discussion in [12]. Eq.3 is consistent with the limited data of the BEBC neutrino experiment [10]. Here \(z\) is Feynman \(x\) for the nucleons. Typical kinetic energies of the nucleons produced in the nucleus rest frame are \(\sim 200-400\) MeV, and therefore by eq.2 they are formed within a modest nucleus radius. Soft neutrons should be produced both in the decay of the hole formed by the removal of a nucleon in the elementary lepton-nucleon DIS, and in the reinteractions of the secondary slow nucleons originating from the elementary DIS process.

Contribution of these two effects should be considered as a lower limit for the rate of the soft neutron production. This is because there exist other processes for which the standard time formation arguments do not hold as well. For example the slow pion absorption process is known to increase the excitation energy of a nucleus by 60 – 70 MeV and yield, on average, several additional soft neutrons per event, see e.g. [9].
Contributions of high-energy parton rescatterings, formation of hadrons inside the nuclei would further increase the neutron yield.

We focus on the case of the DIS scattering off lead, since the muon data are much more accurate in this case. To calculate the rate of the soft neutron production we considered the following model of the reaction: (i) a nucleon is removed from any point in the nucleus with a probability proportional to the nuclear density; (ii) an energy $W_n$ is assigned to the produced nucleon based on cross section of the process $\mu+N \rightarrow \mu'+N'+X$ as given by Eq.(3); the interactions of the nucleon produced in DIS are modeled with a Monte Carlo code for hadron-nucleus interaction which describes all stages of the process: the cascade, which includes knock-out of secondary nucleons, production and subsequent interaction of pions; preevaporation; and evaporation of neutrons and charged particles. This Monte Carlo code is very close to the codes are used over the years to describe cascades in $pA$ scattering at $E_N \leq 1GeV$, see e.g. [8,9]. Note that in the original experimental paper [11] only a qualitative analysis of the data was presented, assuming that neutrons originate from the decay of the hole formed by removal of a nucleon in the DIS $\mu N$ interaction. Production of the soft neutrons in the FSI’s of the nucleons produced in the primary DIS $\mu N$ scattering was not considered though in our calculation these FSI’s provide most of the soft neutrons.

The code was tested using available $pA$ data at intermediate energies [13-17]. We found that the code produces a good description of the neutron yields in the kinematics of interest, see Fig.1,2. The curves are about 20% above the data which is consistent with the typical 20% accuracy of such codes. This may also reflect uncertainties in the normalization of the data.

We find that the calculated spectrum of the soft neutrons is consistent with the E-665 data as reported in the erratum [11], see solid line in Fig.3.

We want to emphasize that the calculated yield of neutrons depends weakly on the model used for the spectrum of nucleons produced in the elementary reaction. In particular, assuming that all nucleons are produced with energy of 200 or 400 MeV (dashed
and dotted curves in Fig.3) practically do not change our result. To illustrate further our weak sensitivity to the model of the nucleon production we present in Fig.4 the multiplicity of the produced neutrons for different cutoffs in $E_n$. One can see that it weakly depends on the kinetic energy of the generated nucleon, $W_n$, for the kinetic energies of interest: $200 \text{ MeV} \leq W_n \leq 500 \text{ MeV}$. Note here that $\langle W_n \rangle$ for the model corresponding to Eq.[3] is $\approx 300 \text{ MeV}$.

We estimate

$$\langle N_n(Pb)(E_n \leq 10 \text{ MeV})\rangle_{\text{lower limit}} = 6 \pm 1.5,$$  \hspace{1cm} (4)

which is reasonably close to the experimental number of $5 \pm 1$.

It is worth noting that there is a trend in the E665-data for $\langle N_n(Pb)(E_n \leq 10 \text{ MeV}) \rangle$ to fall with increasing $q_0 \equiv \nu$ (see Fig.2 of [11]). This may be due to two causes: (i) the decrease of the probability for the leading hadrons to reinteract with nuclei with increasing $\nu$ as observed in [1], and (ii) a softening of the spectrum of the nucleons produced in the elementary process with decreasing $x$ (larger $\nu$ in the data sample of E665 correspond to smaller average $x$).

The multiplicity obtained in our “minimal” model of soft neutron production seems to leave very little room for the further processes of FSI of fast hadrons in the nuclei. The only alternative we could think of is that suppression of the FSI of produced nucleons starts at much lower energies than it is usually thought, say 1-2 GeV.

To illustrate the sensitivity of the E-665 to a model of the FSI let us estimate $\langle N_n(A) \rangle$ in a class of the models where it is assumed that the leading quark can interact with effective cross section $\sigma_{\text{eff}}$ of 10-20 mb, see e.g. discussion in [3],[8]. The number of extra interactions due to this mechanism can be estimated as

$$\delta(A) = \frac{1}{2} \frac{A - 1}{A^2} \sigma_{\text{eff}} \int d^2 b T^2(b),$$  \hspace{1cm} (5)

where $T(b)$ is the standard thickness function $T(b) = \int dz \rho_A(b, z)$. In the case of lead target this leads to $\approx 0.75\sigma_{\text{eff}}$ additional interactions per event where $\sigma_{\text{eff}}$ is measured in fm$^2$. Low energy nucleons produced in these interactions would have the energy
distribution close to the one in the elementary reaction and hence generate soft neutrons with the same efficiency as the “minimal” mechanism. Thus $\sigma_{\text{eff}} = 10(20)\text{mb}$ would lead to the estimated soft neutron multiplicity of $8.75 \pm 1.75$ $(12.5 \pm 2.5)$ (to produce a conservative estimate we include here the $pA$ data based adjustment factor of 0.8 for the theoretical value of eq.[4] which is well above the experimental value of $5 \pm 1$. We are planning to combine our MC code with a number of MC codes for production of high energy particles in $eA$ scattering to constrain parameters of these models using E665 data.

It would be really challenging to reconcile a low neutron multiplicity observed by E665 with the indications of a noticeable FSI’s in production of faster particles in the nuclear fragmentation region obtained in the same experiment, see discussion in [19]. This may require a more complicated dynamics of FSI’s than currently envisioned. It also calls for a systematic experimental study of the energy dependence of the neutron yield starting from the incident energies available in the HERMES experiment and in the forthcoming COMPASS experiment. One can expect a gradual decrease of the rate of soft neutron production with increasing of $\nu$ and $Q^2$. It would be interesting to study correlations between the neutron multiplicity and the spectrum of leading hadrons ($z$-distribution, $p_t$ broadening, etc). It is necessary also to repeat the E665 experiment at higher energies to check rather amazing finding of this experiment of the low rate of production of soft neutrons. If the decrease with $E_{\text{inc}}$ and low neutron multiplicity at $E_\mu \geq 200$ GeV are confirmed, the soft neutrons would provide a perfect tool to look for relatively rare final state interactions in DIS at the HERA collider at small $x$ by selecting events with much larger than average neutron multiplicity. For example it would be possible to investigate the $p_t$ broadening effects [20,21] via a study of the dependence of $\langle N_n \rangle$ on the transverse momentum of the leading hadron in the current fragmentation region.

At the same time there are a few questions which could be addressed at the intermediate energy lepton facility, like TJNAF. The first question concerns the estimate of the contribution to the soft neutron multiplicity from the decay of the hole state produced
by removing one nucleon in DIS. This problem is tightly connected with the study of the one-hole nuclear spectral function which is the subject of a number of \((e, e'p)\) experiments that are under way at TJNAF. It would be of interest to measure the spectrum of neutrons produced in the decay of the hole states, and its dependence on the missing energy. Hall C may provide possibilities for such study using a neutron detector in a combination with a high resolution \((e, e'p)\) experiment. Such measurements also may be performed as a part of the recently approved \((e, e'pn)\) experiment \cite{22}. The experiment of the same kind but measuring yield of soft neutrons as a function of the energy transferred by electron to nuclear proton (low energy resolution) can help to obtain the reliable estimate of the soft neutron multiplicity due to the FSI’s of the intermediate energy protons with medium and heavy mass nuclei in lepton-nucleus interaction.

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REFERENCES

[1] E665, M.R.Adams et al, Z.Phys. C61, 179 (1994).

[2] W.Busza, Nucl.Phys. A544, 49 (1992).

[3] T.G. O’Neill, G. van der Steenhoven, in Proceedings of Workshop on Future Physics at HERA, Hamburg, Germany, 25 Sep 1995 - 30 May 1996, 1033-1037.

[4] M.R. Adams et al., Z.Phys.C65, 225 (1995).

[5] M. Arneodo, A. Bialas, M.W. Krasny, T. Sloan, M. Strikman, in Proceedings of Workshop on Future Physics at HERA, Hamburg, Germany, 25 Sep 1995 - 30 May 1996, 887-926; e-Print Archive: hep-ph/9610423

[6] J.Chwastowski and M.W.Krasny, ibid, pp. 991-997.

[7] M.I. Strikman, M.G. Tverskoy, M.B. Zhalov, ibid, pp.1085-1088

[8] Y.Yariv, Z.Frankel, Phys. Rev. C20,2227 (1979); K.Gudima, H.Iwe, V.Toneev, J.Phys. G5,229 (1979);

[9] V.D.Toneev, In Proceedings of II TAPS Workshop "Gamma Ray and Particle Production in Heavy Ion Reactions”. Guardemar, Spain, May 31 - June 5, 1993, Eds. José Diaz, Giné Martinez, Yves Schutz. World Scientific Publishing Co., 1994, pp.350-417.

[10] P.Allen et al, Nucl. Phys. B214, 369 (1983).

[11] E665, M.R.Adams et al, Phys.Rev.Lett. 74, 5198 (1995), erratum ibid 80, 2020 (1998).

[12] L.Frankfurt and M.Strikman, Phys.Rep. 76,217(1981).

[13] M.R. Adams et al., Z.Phys. C67 403 (1995).

[14] L.Frankfurt and M.Strikman, Phys.Lett. B382, 6 (1996).

[15] Yu.D. Bayukov et al., ITEP-172, 1983.
[16] W.B. Amian et al., Nucl. Sci. Eng. 112, 78 (1992).

[17] S. Cierjacks, et al, Phys. Rev. C 36, 1976 (1987).

[18] A. Bialas, J. Czyzewski, Z. Phys. C 47, 133 (1990).

[19] D.J. Dean, et al Phys. Rev. C 46, 2066 (1992); K. Werner, Phys. Rep. C 232, 87-299 (1993).

[20] M. Luo, J.W. Qiu, G. Sterman, Phys. Rev. D 50, 1951 (1994).

[21] R. Baier, Yu.L. Dokshitzer, A.H. Mueller, S. Peigne, D. Schiff, Nucl. Phys. B 484, 265 (1997).

[22] J. Alster et al, TJNAF Experiment PR97-106.
FIG. 1. Comparison of the results of the Monte Carlo cascade-evaporation calculation of the neutron spectra in $p + Pb \rightarrow n + X$ process with the ITEP data [15] at $P_p = 1.4 GeV/c$ (lower curve) and $P_p = 2 GeV/c$ (upper curve) for $\theta_n = 120^\circ$. The overall experimental errors which are not shown in the figure are $\sim 20\%$
FIG. 2. Comparison of the results of the Monte Carlo cascade-evaporation calculation of the neutron spectra in $p + Pb \rightarrow n + X$ process at $E_{p}^{inc}=113$ MeV with the data [16].
FIG. 3. Comparison of the results of the Monte Carlo cascade-evaporation calculation of the neutron spectra in $\mu + Pb \rightarrow n + X$ process with E-665 data [11].
FIG. 4. Multiplicity of neutrons produced in the process where a nucleon with energy $W$ was produced in $Pb$ for different energy intervals of neutron energy. Dotted, solid, dashed curves are multiplicities of evaporated nucleons with kinetic energies $T_n$ for $0 \leq T_n \leq 6$ MeV, $0 \leq T_n \leq 10$ MeV, $0 \leq T_n \leq 50$ MeV; dashed-dotted curve is the total nucleon multiplicity.