Nuclear High-Momentum Components and y Scaling in Electron Scattering

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(Received 27 May 1980)

Inelastic electron scattering at large momentum transfer but small energy loss is used to investigate the high-momentum components in ^{3}He. The data also show a striking scaling dependence in the variable $y = \vec{k} \cdot \vec{q}/q$.

PACS numbers: 25.30.Cq, 21.40.+d, 21.90.+f, 27.10.+h

The subject of high-momentum components of nuclear wave functions has long been of particular interest. It deals with features of the wave function not dominated by the independent-particle aspects that account for most nuclear properties, and it is closely linked to the short-distance behavior of the nucleon-nucleon force and the pair correlation function.[1] In spite of this importance a convincing experimental determination of these elusive high-momentum components is not available.[2] To a great extent this is due to the small probability of finding in the nuclear wave function components with momenta $k > 300$ MeV/c. A number of direct reactions have been studied whose aim was to selectively pick out high-momentum components. In general, it has been found that two-step processes dominate the reaction, and these depend on the low-momentum components. This should not be surprising since for strongly interacting probes (projectiles or reaction products) the possibility to interact a second time is of the order of the probability of the high-momentum components.

In this Letter we propose a new way to investigate high-momentum components: inclusive electron scattering at large momentum transfer q and small energy loss ω. In the kinematic region of $q \gg k_F$ and $\omega \ll q^2/2m_N$ the low-momentum components do not contribute to the cross section, and because of the weak interaction of the electron we expect inclusive scattering to be much less subject to two-step processes. We show that a new scaling phenomenon, leading to a dependence of the cross section on a single dynamic scaling variable $y = \vec{k} \cdot \vec{q}/q$, provides striking evidence on the reaction mechanism and high-momentum components. The qualitative properties of the nuclear momentum distribution important for (e, e') reactions can be derived by assuming the nucleons to be weakly bound (separation energy $E \ll \omega$), to have no final-state interaction, and to be nonrelativistic. From momentum and energy conservation we obtain that the quasielastic cross section $\sigma(\omega, q)$ depends on values of k given by[3]

$$\left(\vec{k} - \frac{A-1}{A}\vec{q}\right)^2 - \frac{A-1}{A}(\omega - \omega_{\rm el} - E)2m = 0, \qquad (1)$$

where $\omega_{\rm el} = q^2/2mA$. At a given q and small $\omega - \omega_{\rm el}$, the momentum-space density at $k_0 = [(A-1)/A]q$ is sampled with a resolution $\delta k_0 \simeq \{[(A-1)/A]2m(\omega - \omega_{\rm el})\}^{1/2}$. By appropriate choice of q and ω, the high-k region can be investigated selectively and with reasonable momentum resolution.

Data for the kinematical region discussed have become available only recently[4]; these data, together with those of Ref. 5, cover a q range of 400–1600 MeV/c, appropriate for an investigation of the high-k components. These data are available for ^{3}He, a nucleus for which a particularly stringent comparison between experiment and theory is possible. By Faddeev or variational techniques the wave function can be calculated "exactly" by using realistic nucleon-nucleon interactions.

For the present calculations we will employ the Faddeev wave function of Brandenburg, Kim, and Tubis,[6] calculated with use of the Reid soft-core nucleon-nucleon interaction. The spectral function $S(k, E)$, the probability to find a nucleon of given momentum and separation energy, has been derived from this wave function by Dieperink *et al.*[7] From this spectral function the quasielastic cross section can be calculated[8] with use of plane waves for the electron, an energy-dependent optical potential for the recoil nucleon,[4] and the electron-nucleon cross section as parametrized by

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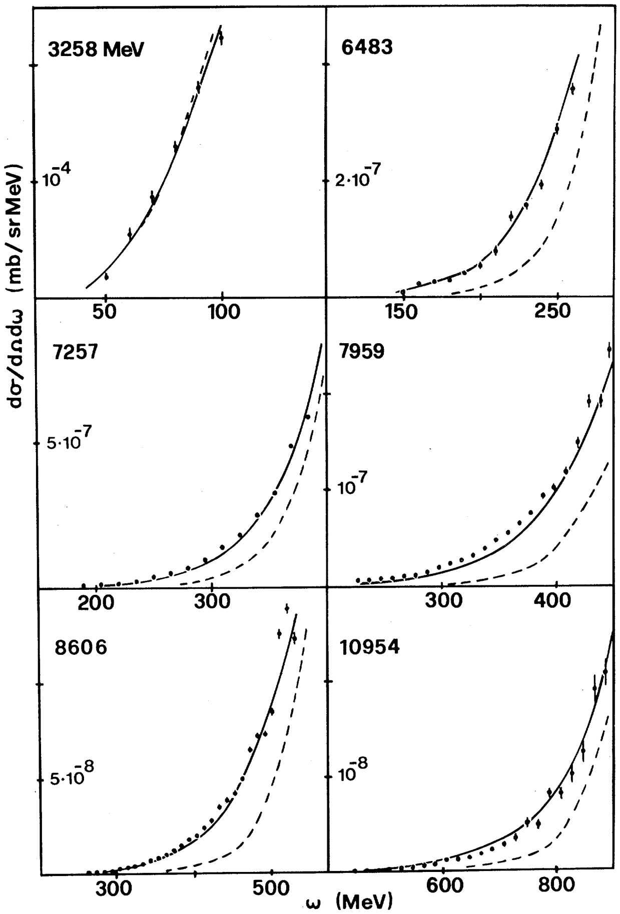

FIG. 1. Quasielastic cross sections as a function of electron energy loss. The solid (dashed) curves are calculated using the modified (unmodified) Faddeev spectral function.

Blatnik and Zovko.[9] Pronounced discrepancies between experiment and calculation occur for $q > 800$ MeV/c and "low" ω (see Fig. 1). These discrepancies cannot be accounted for by other reaction channels like π production[10] or Δ excitation.[11] The two-step processes of importance for electron scattering, meson-exchange currents (MEC), also yield contributions[12] to $\sigma(\omega, q)$ much smaller than the experimental cross sections. While processes involving two nucleons, mainly via intermediary Δ excitation, have important effects at large ω and large scattering angles, the calculations of Donnelly *et al.*[12] yield small contributions for the low-ω, small-angle (8°) regime studied here. We consequently assign the discrepancy to properties of the spectral function at large k.

In the above interpretation we have not considered the final-state interaction of the knocked-out nucleon with the correlated partner presumably responsible for the high-k component.[13] Because of the appreciable energy transfer (several 100 MeV) to the recoil nucleon, this interaction is not expected[13] to be very important; a quantitative calculation is still lacking, though.

In order to understand the disagreement at values of $k > 300$ MeV/c we have adopted the procedure of multiplying the Faddeev $S(k, E)$ with a phenomenological function $f(k)$, where

$$f(k) = 1 + (k/\bar{k})^n, \tag{2}$$

with $n = 2.5$ and $\bar{k} = 285$ MeV/c. This modification (including proper renormalization) increases the high-k components in the spectral function and gives an excellent fit to the data, both in the quasielastic peak (not shown) and the threshold region (Fig. 1). This modification permits a smooth transition between the region of low momenta, adequately explained by standard N-N forces, to a region where the short-range interaction dominates. This region is even more discernible when related to the scaling variable $y = \vec{k}\cdot\vec{q}/q$.

At large q ($q \gg k_F$) the quasielastic cross section $\sigma(\omega, q)$ is predicted[14] to scale, i.e., to become a function of a single variable y. For the one-nucleon–knockout mechanism the scaling variable y can be derived from relativistic momentum and energy conservation:

$$E - \omega + [(\vec{k} + \vec{q})^2 + m^2]^{1/2} + [\vec{k} + (A-1)^2 m^2]^{1/2} - Am = 0. \tag{3}$$

At large momentum transfer, $k_\perp^2$, the component of $\vec{k}$ orthogonal to q, is small against q^2 or $\vec{k}_\parallel \cdot \vec{q}$; the separation energy E and nucleon final-state interaction can be neglected. Then the component of $\vec{k}$ parallel to $\vec{q}$, $\vec{k}_\parallel$, becomes a function $y(q, \omega)$ determined by the measured quantities q and ω.

The dependence of the electron-nucleon cross section on the convection current linked to $k_\perp$ is weak and can be neglected. The cross section $\sigma(\omega, q)$, divided by the appropriate elementary cross section, then becomes a function $F(y)$ of the variable y only[14]:

$$\sigma(\omega, q) d\omega / (2\sigma_{ep} + \sigma_{en}) = F(y) dy, \tag{4}$$

where $F(y)$ measures the probability to find a nucleon with momentum $k_\parallel = y$ in ^{3}He.

Figure 2 shows the values $F(y)$ calculated from the data[4,5] at different energies, together with a list of symbols ordered according to increasing q. As q increases, the data sets converge towards a unique curve representing (for $q = \infty$) the

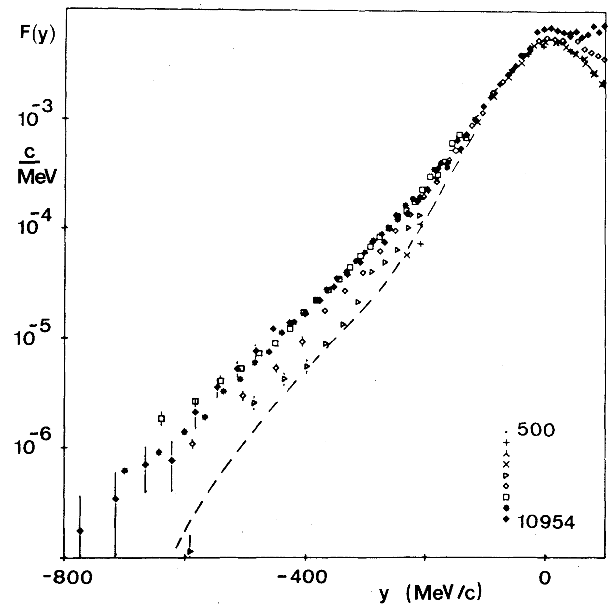

FIG. 2. Scaling function $F(y)$ obtained from the data of Day *et al.* (Ref. 4) and McCarthy *et al.* (Ref. 5). The different symbols refer to electron energies of 500, 2814, 3258, 3651, 6483, 7257, 7959, 8606, and 10 954 MeV. The dashed curve results from the cross section calculated with use of the Faddeev spectral function.

momentum distribution. The fact that scaling is so strikingly fulfilled demonstrates that the reaction mechanism is the one assumed—the interaction of the electron with a single nucleon. More complicated mechanisms like Δ excitation, MEC contributions, or scattering from quark constituents are not expected to scale in the variable y. Indeed, both experimental cross sections for Δ excitation ($\omega > q^2/2m, y > 0$) and the theoretical cross sections[12] for MEC do not show the remotest sign for scaling behavior.

The quantitative interpretation of $F(y)$, however, requires some care. While it is reasonable to ignore $k_\perp$, the same cannot be said for the separation energy E. Nucleons with high momentum are closely correlated and some treatment of the short range binding must be introduced before $F(y)$ can be quantitatively interpreted as a momentum distribution. In the absence of a final solution for treatment of highly correlated nucleons, we can compare the scaling results to $F(y)$ obtained from the theoretical cross section for the Faddeev spectral function $S(k, E)$. The dashed curve in Fig. 2 falls well below the experimental $F(y)$ and confirms that a substantial increase in the high-momentum components of the nuclear wave function is required to explain inclusive electron scattering from ^{3}He. Qualitatively, this corresponds to the long-standing problem of the ^{3}He charge form factor[15] which is too low for $q \simeq 600$ MeV/c.

We conclude that inclusive electron scattering at large q and small ω promises to become a most valuable new tool. Nuclear scaling indicates that the reaction mechanism is understood and is hardly subject to multistep processes that have obscured the interpretation of reactions involving strongly interacting probes. Gaining access to the high-momentum components of (two-body) wave functions is a topic meriting further, more detailed study.

The authors would like to thank T. DeForest, P. Fishbane, W. Hermans, J. Noble, and G. West for useful conversations and calculations. This research was supported in part by the U. S. Department of Energy and the Swiss National Science foundation.

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Energy Dependence of Multi-Pion Production in High-Energy Nucleus-Nucleus Collisions

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Exclusive π^- and charged-particle production in collisions of Ar+KCl is studied at incident energies from 0.4 to 1.8 GeV/u. Complete disintegration of both nuclei is observed. The correlation between π^- and total charge multiplicity shows no islands of anomalous pion production. For constant numbers of proton participants the π^- multiplicity distributions are Poissons. For central collisions $\langle n_{\pi^-}\rangle$ increases smoothly and to first order linearly with the c.m. energy. Disagreement with the firestreak model is found.

PACS numbers: 25.70.Hi, 24.10.Dp

There is considerable interest in studying pion production and its energy dependence in heavy-ion central collisions.[1-7] Pion multiplicity distributions at various energies are needed to test and constrain thermal- and cascade-model calculations as well as the hydrodynamical-model prediction of an increase in the pion yield at the onset of a phase transition.[4] Although exclusive π^- and charged-particle production data have been reported for projectiles from p to Ar incident on various targets,[8-10] no comprehensive study of their energy dependence in central collisions has been undertaken.

In this Letter we present the results of a systematic study of π^- production and accompanying nuclear disintegration in the interaction of ^{40}Ar +KCl for bombarding energies from 0.4 to 1.8 GeV/u. The experiment was performed at the Bevalac using the streamer-chamber facility. A 3-mm-thick KCl target was placed inside the sensitive volume of the chamber permiting 4π exclusive charged-particle detection and charge sign and rigidity determination in a 1.32-T magnetic field.

The streamer-chamber trigger technique as developed by Fung *et al.*[8] consists of an upstream beam-defining counter, a target, and a downstream scintillator which, covering 74 msr, detected the projectile spectator fragments. Data were taken at each energy in two trigger modes: an inelastic mode which rejected the noninteracting beam particles, and a central mode which selected events with small total charge in leading fragments compared to that of the beam. For each trigger mode 2000 to 5000 events were accumulated at bombarding energies at the target center of 360, 566, 772, 977, 1180, 1385, 1609, and 1808 MeV/u. Each event was classified according to its negative-pion multiplicity, total charged-particle multiplicity, and number of leading tracks.

Total charged-particle ($n_{\rm tot}$) and negative-pion (n_{π^-}) multiplicity distributions are shown in Fig. 1 for both trigger configurations at 1.8 GeV/u. For the inelastic trigger, $\sigma(n_{\rm tot})$ decreases exponentially for low multiplicities, and reaches a plateau for $25 < n_{\rm tot} < 40$ which is followed by a sharp cutoff at higher multiplicities. The observed shoulder at high multiplicities, which appears at all bombarding energies, is not reproduced by the fireball[7] or cascade[5,6] models. In the fireball model this may be ascribed to the clean-cut geometry which neglects dissipation of momentum and energy along the transverse direction, underestimating the number of participants. The total cross section observed for the