STUDY OF DEUTERON STRUCTURE IN EXCLUSIVE BREAKUP REACTIONS

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Introduction

Study of high-momentum components of the deuteron wave function is an important task of the hadron and nuclear physics. The deuteron, as the simplest nuclear system, provides a unique opportunity to observe the short-range nucleon-nucleon correlations without complications coming from influence of the nuclear environment.

A quasielastic deuteron breakup reaction with intermediate energy electrons or protons as projectiles is a good way to investigate the deuteron structure. A version of the method is an experiment with the deuteron beam scattered on the proton or nuclear target with subsequent measuring the spectator or the scattered/recoiled nucleon (deuteron fragmentation reactions).

In the impulse approximation (IA) the unpolarized differential cross section of the quasielastic deuteron breakup reaction is proportional to the momentum distribution of the nucleons in the deuteron:

$$\rho(q) = U^2(q) + W^2(q), \tag{1}$$

where $U(q)$ and $W(q)$ are the deuteron S- and D-state wave functions and q is the internal momentum. The polarization observables are expressed as functions of $U(q)$ to $W(q)$ ratios.Then in the frame of IA non-relativistic deuteron structure defined by the functions U and W can be directly derived from the experimental data.

The small-q behaviour of the U and W functions has been theoretically investigated using non-relativistic deuteron models with realistic potentials (Bonn, Paris etc). An important feature of all the potential model predictions is that the D-wave dominates at $q \sim 0.3-0.7$ GeV/c, whereas the S-wave has a node in the region around $q = 0.4$ GeV/c. On the other hand, the validity of the simple non-relativistic approach at q higher than 0.2–0.3 GeV/c is questionable. Double-scattering effects start to be important at relatively low q depending on the reaction kinematics. As a result, the IA contribution vanishes among the contribution of other processes, which are rather difficult to estimate in a correct, self-consistent way. In addition, the relativistic corrections and possible effects of the deuteron internal structure (like 6-quark bag) can effectively modify the behaviour of the functions U and W, in particular, the node position of the function U is shifted towards higher momentum.

An effective study of the deuteron structure is still possible within a certain range of q at such kinematic conditions that the IA dominates or, at least, the corrections are theoretically reproduced and of the same order of magnitude as the main IA term.

The quasielastic deuteron breakup and fragmentation reactions are investigated both in inclusive and exclusive experiments. In the inclusive experiments one detects either the scattered particle: electron (as Bosted in 1982) or proton (as Azhgirei in 1987), or in case of the fragmentation reaction the forward going proton .The latter is considered as the spectator proton (as Perdrisat in 1982 or Ableev in 1983). In the exclusive experiments one detects the two scattered particles in coincidence: ep, pp or pn. The event kinematics is completely reconstructed for this class of the experiments.

A review of the exclusive and inclusive experiments has been presented by V.Punjabi and C.Perdrisat at the conference "Deuteron 1991" (Dubna 1991).

The exclusive experiments make it possible to select and to study the predefined kinematic configurations. This provides certain advantages in calculations of the corrections to the IA and, finally, improves our understanding of the reaction mechanism.

It should be noted, that in most of the cases the experimental data with the proton projectiles at $q > 0.2$ GeV/c are 2–10 times higher than IA predictions depending on the geometry of the setup and other experimental conditions. For the case of the electro-disintegration (Saclay) the deviation from the IA is considerably smaller (the factor of 0.5–1.1). Taking into account the traditional corrections to the IA due to the final state interaction and the Δ-excitation enable to achieve a very good description of the reaction of the electro-disintegration up to $q \simeq 0.5$ GeV/c using the regular Paris potential, i.e. there is no need to include such exotics as $6q$-bag.

In the following sections we describe two experiments performed by the PNPI group at the PNPI synchrocyclotron [1,2] and at the accelerator Saturn-2 of the Nuclear Research Centre in Saclay, France, in collaboration with LNS (Saturn National Laboratory) and SPhN (France) William and Mary College (USA), Seoul University (Korea) and KFKI (Hungary) [3–5].

Gatchina experiment

Actually, two experiments were performed. In the first one [1], the reaction $pd \rightarrow pp(n)$ has been studied by means of a two-arm magnetic spectrometer up to $q = 0.3$ GeV/c at the angles $\theta_1 = 20°$ and $\theta_2 = 60°$. The recoil arm ($\theta_2 = 60°$) was instrumented by a polarimeter. The goal of the recoil proton polarization measurement was to compare the measured polarization with that in free pp scattering at appropriate kinematics and to use the result of the comparison as an independent indication of the IA applicability. In the second experiment [2], the reactions $pd \rightarrow pp(n)$ and $pd \rightarrow pn(p)$ were studied at the same angles ($\theta_1 = 20°$ and $\theta_2 = 60°$) which correspond to the quasielastic geometry. The recoil nucleon was detected by large-angle scintillation counter array, and no recoil polarization has been measured. The cross sections for the processes $pd \rightarrow pp(n)$ and $pd \rightarrow pn(p)$ were measured up to $q = 0.48$ GeV/c and $q = 0.35$ GeV/c, correspondingly. The non-quasielastic geometries with $\theta_1 = 30°$ and $\theta_2 = 60°$ and $\theta_1 = 15°$, $\theta_2 = 78°$ and $\theta_2 = 115°$ were also studied. In the latter case (measurements at $\theta_1 = 15°$, $\theta_2 = 78°$ and $\theta_2 = 115°$) we were searching for the dibaryon resonances in the pn effective mass spectrum. The differential cross sections measured in those geometries have been used as an additional evidence that the reaction mechanism is well understood even at the kinematics which is far not quasielastic one. No indication of the dibaryons was found [6].

The three-momentum of the forward proton (θ_1) has been measured with the magnetic spectrometer. The measurement of the recoil nucleon angles θ_2, ϕ_2 provides the complete kinematics study of the reaction . The missing mass spectrum of the undetected nucleon is expected to display a sharp peak positioned at the nucleon mass and a continuum at higher effective mass corresponding to reactions with mesons in the final state. The latter contribution and random coincidence background was effectively suppressed by the time-of-flight cut. A solid polyethylene target has been also used in the first runs of the experiment at small q, where the quasielastic peak can be easily distinguished from the background. The results of the both experiments are discussed in the section devoted to the analysis of the experimental data.

Polarized deuteron

In the previous section, we have described the experiment on quasielastic breakup of unpolarized deuteron. The unpolarized experiments are sensitive to the momentum distribution of nucleons in the deuteron which is given by the sum (1). The polarization observables related to the deuteron polarization are sensitive to the ratio of the U and W functions. Thus, combining the results of polarized and unpolarized experiments one can reconstruct the both functions.

Let us assume that quantization axis is directed along Y of the coordinate system. The deuteron polarization state is characterized by the relative occupancies $n_{0,\pm}$ which are the normalized probabilities ($n_+ + n_0 + n_- = 1$) to find the deuteron with spin projection 0 ± 1 on the quantum axis, respectively. It is convenient to combine the occupancies in two independent polarization observables, i.e. the vector polarization $p_y \equiv n_+ - n_-$ and the tensor polarization $p_{yy} \equiv n_+ + n_- - 2n_0$.

Due to the tensor polarization, the momentum distribution of the nucleons in the deuteron is no more sphere-symmetrical, and depends on the angle ϕ between the vector $\vec{q}$ and the quantization axis Y ($\cos\phi \equiv \frac{q_y}{q}$):

$$\rho(\vec{q}) = \rho_0 \left[1 + p_{yy} \frac{3\cos^2\phi - 1}{2} \, \frac{\sqrt{8}\kappa - 1}{2(1+\kappa^2)} \right] , \tag{2}$$

where $\rho_0 = U^2 + W^2$ and $\kappa = U/W$. Therefore the deviation from spherical symmetry is defined by the tensor polarization p_{yy} and relative contribution of the D-wave.

The vector polarization p_y leads to polarization of the nucleons in the deuteron:

$$\mathcal{P}_y = \frac{\kappa^2 - \frac{1}{2} + (1+\sqrt{2}\kappa)\frac{1}{2}(3\cos^2\phi - 1)}{1 + \kappa^2 + \frac{1}{2}p_{yy}(\sqrt{8}\kappa - 1)\frac{1}{2}(3\cos^2\phi - 1)} \, p_y \, . \tag{3}$$

One can see from the above expressions that the polarization observables in the experiments with polarized deuterons are sensitive to the ratio of S- and D-wave functions at a given internal momentum q.

Let us consider the quasielastic breakup reaction of the polarized deuterons by protons $\vec{d} + p \to p_1 + p_2 + n$. According to Madison convention, the differential cross section of the reactions with the polarized deuterons is written in the following way:

$$\frac{d^5\sigma}{dp_1 d\Omega_1 d\Omega_2}(p_y, p_{yy}) = \frac{d^5\sigma}{dp_1 d\Omega_1 d\Omega_2}(0,0) \left[1 + \frac{3}{2}A_y p_y + \frac{1}{2}A_{yy}p_{yy} \right] . \tag{4}$$

Then the vector and tensor analyzing powers are defined as

$$A_y = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_0 + \sigma_-} \, , \quad A_{yy} = \frac{\sigma_+ + \sigma_- - 2\sigma_0}{\sigma_+ + \sigma_0 + \sigma_-} \, , \tag{5}$$

where $\sigma_{0,\pm}$ are the cross sections at different spin states of the beam. In the framework of the IA the analyzing powers are equal to

$$A_y = \left[\frac{U^2 - W^2 - \frac{1}{\sqrt{2}}UW}{U^2 + W^2} n_y + \frac{3}{2} \frac{W(\sqrt{2}U + W)}{U^2 + W^2} k_y(\vec{k}, \vec{n}) \right] P_{pp} \, ,$$

$$A_{yy} = \frac{1}{2}\left(1 - 3k_y^2\right)\frac{W(W - 2\sqrt{2}U)}{U^2 + W^2}\,. \tag{6}$$

Vector polarization of the fast proton can be expressed through the polarization P_0 for the unpolarized deuteron case and the depolarization parameter D_v. In the framework of the IA the polarization P_0 is equal to the free pp scattering polarization P_{pp} and is not influenced by the specific deuteron wave function.This parameter can be used as an additional test of the reaction mechanism.The depolarization parameter D_v is expressed through the depolarization parameter in the nucleon-nucleon scattering D_{nn} and the $U(q)/W(q)$ ratio , thus being sensitive to the deuteron structure.

The analyzing powers A_y and A_{yy}, as well as the polarization parameters P_0 and D_v, have been measured in a wide kinematics range in the Saclay LNS-145 experiment [3–5].

Experiment LNS-145

The accelerator Saturn in Saclay accelerated the polarized deuteron beam up to the energy of 2.3 GeV (1.15 GeV/nucleon) and with the intensity up to 10^{12} 1/s. Both tensor and vector polarizations of the beam used were close to 100%.

The beam with such high parameters allowed to perform an exclusive deuteron fragmentation polarization experiment with complete reconstruction of the reaction kinematics. The goal of the experiment was to study the deuteron structure provided a redundant information about the reaction mechanism is obtained by measuring three polarization observables: tensor A_{yy} and vector A_y asymmetries and polarization transfer to the forward going proton.

The energy of the incident deuteron was chosen to be equal to 2 GeV that exactly corresponds to the Gatchina experiment done in the inverse (relative to the LNS-145 experiment) kinematics. This facilitated joint analysis of the unpolarized (Gatchina) and polarized (Saclay) experiments.

The polarized deuteron beam with the energy of 2 GeV and working intensity of $3 \cdot 10^9$ deuterons/impulse was focused on a liquid-hydrogen target of the magnetic spectrometer SPES-4. Liquid hydrogen in amount of 0.282 g/cm^2 was put into a cell made of mylar. The SPES-4 spectrometer consisted of dipoles, quadrupoles and sextupoles, which produced the double focusing at the intermediate and final focal planes of the spectrometer. The spectrometer had momentum acceptance of 7% and momentum resolution $\Delta P/P\,(\mathrm{FWHM}) = 0.2\%$. The solid angle of the spectrometer was defined by the collimator with different opening, being under remote control, and was typically $3 \cdot 10^{-4}$ sr. In the range of the spectrometer angular acceptance, the resolution on θ_1 and φ_1 was 0.1° and 0.3°, respectively.

The scattering angle θ_1, at which SPES-4 selected the scattered fast protons, was chosen to be equal to $\theta_1 = 18.2°$. The recoil spectrometer (RS) to detect the recoil protons was installed at the angle $\theta_2 = 57°$ and covered the angular ranges $53° < \theta_2 < 61°$ and $-5.8° < \varphi_2 < +5.8°$ in the horizontal and vertical planes, respectively. The RS consisted of two proportional chambers MWPC1 and MWPC2 and a scintillation wall. MWPC1 and MWPC2 were placed at 1.2 and 2.7 m distance from the target, respectively. The scintillation wall located behind the MWPC2 consisted of 7 plates of the ΔE-counters with the thickness of 1 cm placed in front of the 4×7 matrix of the scintillation E-counters with the scintillators of $12 \times 12 \times 20$ cm^3 each.The time-of-flight together with pulse-height data from the E- and ΔE-counters were readout in coincidence with the SPES-4 signal confirming that the proton from the deuteron fragmentation had been detected.

To measure the fast proton polarization, the polarimeter POMME (Bonin, 1990) has been used with the carbon analyzer located in the final focal plane of the spectrometer. The efficiency of the polarimeter was about 10% with the typical analyzing power equal to 0.2.

The measurements were made at six momentum settings of SPES-4: 1.6, 1.7, 1.8, 1.9, 2.0 and 2.05 GeV/c. The range of the internal deuteron momenta from 30 to 440 MeV/c was covered by the above kinematics. For a given momentum p_1 of the proton detected with the SPES-4 spectrometer, there is a limitation in the angle of the outgoing recoil proton. Respectively, there are two kinematics branches (two solutions for every angle θ_1) corresponding to two values of the recoil proton energy. As follows from the reaction kinematics, a substantial part of the recoil protons turns out to be emitted in the range of the RS angular acceptance and thus being detected in coincidence with the forward scattered protons.

Analysis of experimental data

The analysis of the described experiments was done in the framework of the theoretical model in which, besides of the IA diagrams, the triangular diagrams of nucleon rescatterings and the diagrams with Δ-isobar excitation have been taken into account. The nucleon-nucleon spin-isospin dependent amplitudes were calculated on the base of the Arndt's phase shift analysis. The final amplitude was built to satisfy to the Pauli's exclusion principal.

Results of the unpolarized Gatchina experiment are presented in Fig. 1. Theoretical curves correspond to the IA (dash-dotted lines), to the calculation with the rescatterings (dashed lines) and to the complete calculation in which in addition to the rescatterings, diagrams with the Δ-isobar have been included (solid lines). The dotted lines were calculated without the off-mass-shell intermediate state correction (unlike that in the case of dashed lines) in order to see explicitly the off-mass-shell effect. The calculations have been performed for two variants based on the Bonn and Paris deuteron wave functions, respectively.

In all cases, a good description of the $\rho(q)$ and the coincidence cross sections have been obtained in the framework of the model under consideration with the rescatterings and the Δ-isobar included. The Bonn wave function gives somewhat better description than the Paris one for the $(p, 2p)$-reaction at the geometrical conditions $\theta_1 = 20°$, $\theta_2 = 60°$ and $\theta_1 = 15°$, $\theta_2 = 115°$. The scale of differences, however, is insufficient to come to serious conclusions. A good description is kept also for out of quasielastic geometry at $\theta_1 = 30°$, despite the contribution of the above corrections to the IA at $q > 0.3$ MeV/c is noticeably bigger than that for $\theta_1 = 20°$.

For the (p, pn)-reaction some exceeding of the experimental cross sections over the theory has been observed at $q > 0.25$ GeV/c. This little discord could come from the experimental procedure, since background contribution in the case of pn coincidence detection was less reliably determined than that in the pp coincidence case.

In most cases it is sufficient to take into consideration the rescattering corrections only, the Δ-isobar having just a little effect on the cross sections and extracted $\rho(q)$. It should be noted however that for the backward scattering geometry ($\theta_2 = 115°$) the Δ-isobar contribution was found to be essential.

To conclude, one can see that the deuteron structure is well described in the framework of the non-relativistic potential approach with the Bonn (or Paris) potential up to rather high internal deuteron momenta $q \simeq 0.5$ GeV/c. The latter figure corresponds to internucleon distances in the deuteron of $r \simeq 0.4$ fm, at which noticeable influence of the nucleon structure would be naturally expected. Nevertheless, the simple non-relativistic approach based on the point-like nucleon structure proves to be still adequate for the unpolarized data description.

It is important to emphasize that the fact of good description of the experimental data is not a sufficient condition of validity of the reaction mechanism used. In order to describe the unpolarized measurement results at $q > 0.25$ GeV/c, one can try an alternative approach based on the pure IA with a modified nucleon momentum distributions in the deuteron. An important control criteria of the adequacy for a theoretical model are provided by the polarization observables which have been measured in the Saclay LNS-145 experiment.

Results of this experiment are presented in Figs. 2,3. The notations of the curves are the same as in Fig. 1, with exception of the version demonstrating the role of the off-mass-shell intermediate states in the diagrams of the nucleon-nucleon rescatterings, which in this case has not been considered.

The polarization measurements demonstrate unambiguously that the IA (dash-dotted lines) fails to describe the obtained data. For the A_{yy} in the framework of the IA a scaling must exist for the A_{yy}, i.e. in the IA it must depend only on the internal deuteron momentum for different settings of the spectrometer. The absence of the scaling means that the pure impulse approximation is not valid, whichever deuteron wave function being used. On the contrary, the model with the rescatterings and complete account of the spin variables discussed above gives a good description of the polarization observables, particularly for the A_y. In the case of the A_{yy} the data description is satisfactory and the corrections to the IA have the right sign. The results on the polarization transfer to the fast proton are not discussed in this paper.

Thus, the joint analysis of both experiments shows that the exceeding over the IA (starting from 0.2–0.3 GeV/c), having been observed earlier both in exclusive and inclusive reactions, is most probably due to the contribution from the nucleon rescattering diagrams of the Glauber type and of the final state interaction. The classical wave functions (Paris or Bonn) represent the deuteron structure sufficiently well up to rather high internal momenta of 0.5 GeV/c. New experiments are needed advanced to higher internal momentum region (shorter internucleon distances) in order to try to make feasible observation of the relativistic internal nucleon structure effects.

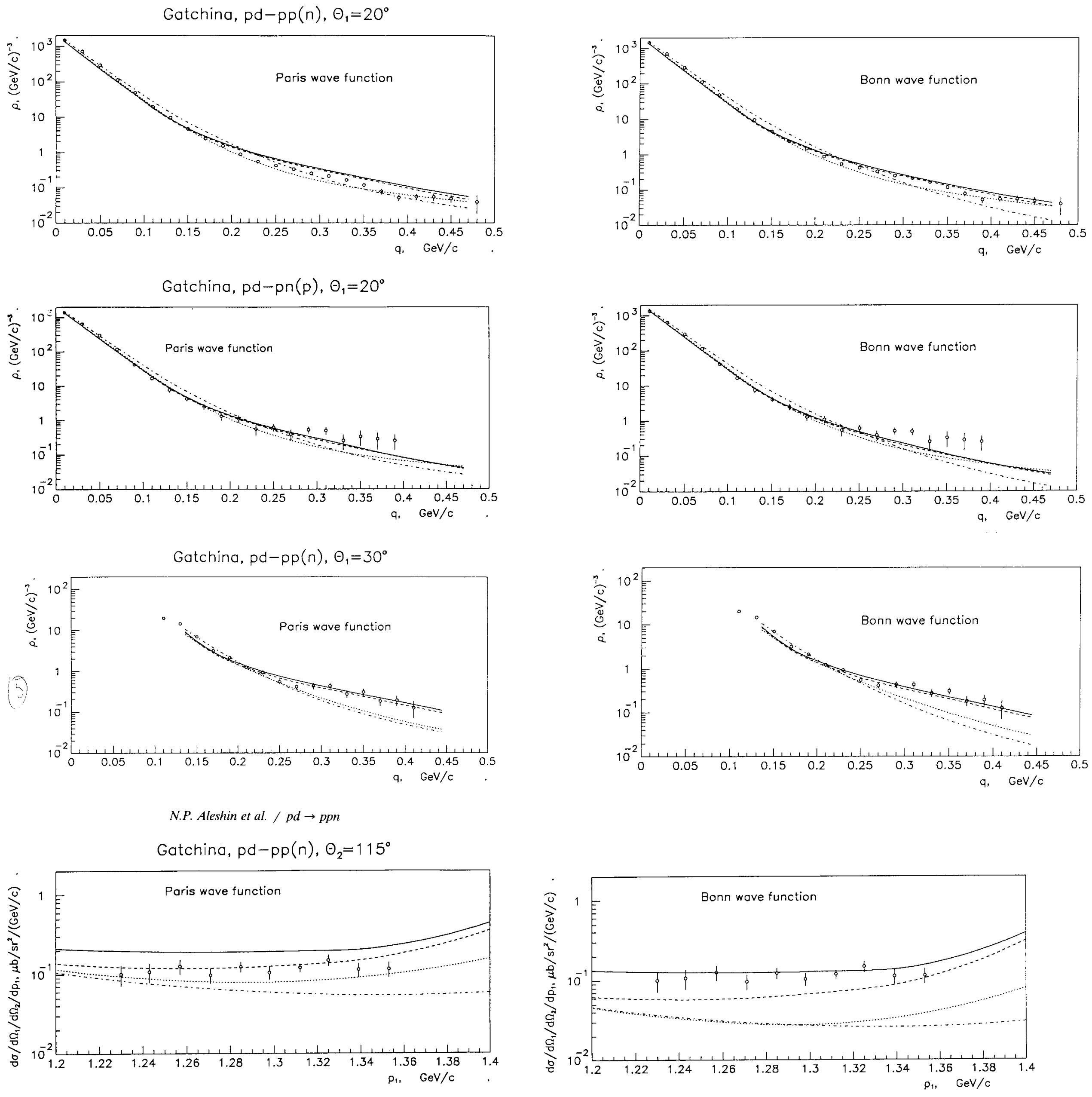

Fig. 1. Experimental and calculated momentum distributions of the nucleons in the deuteron.

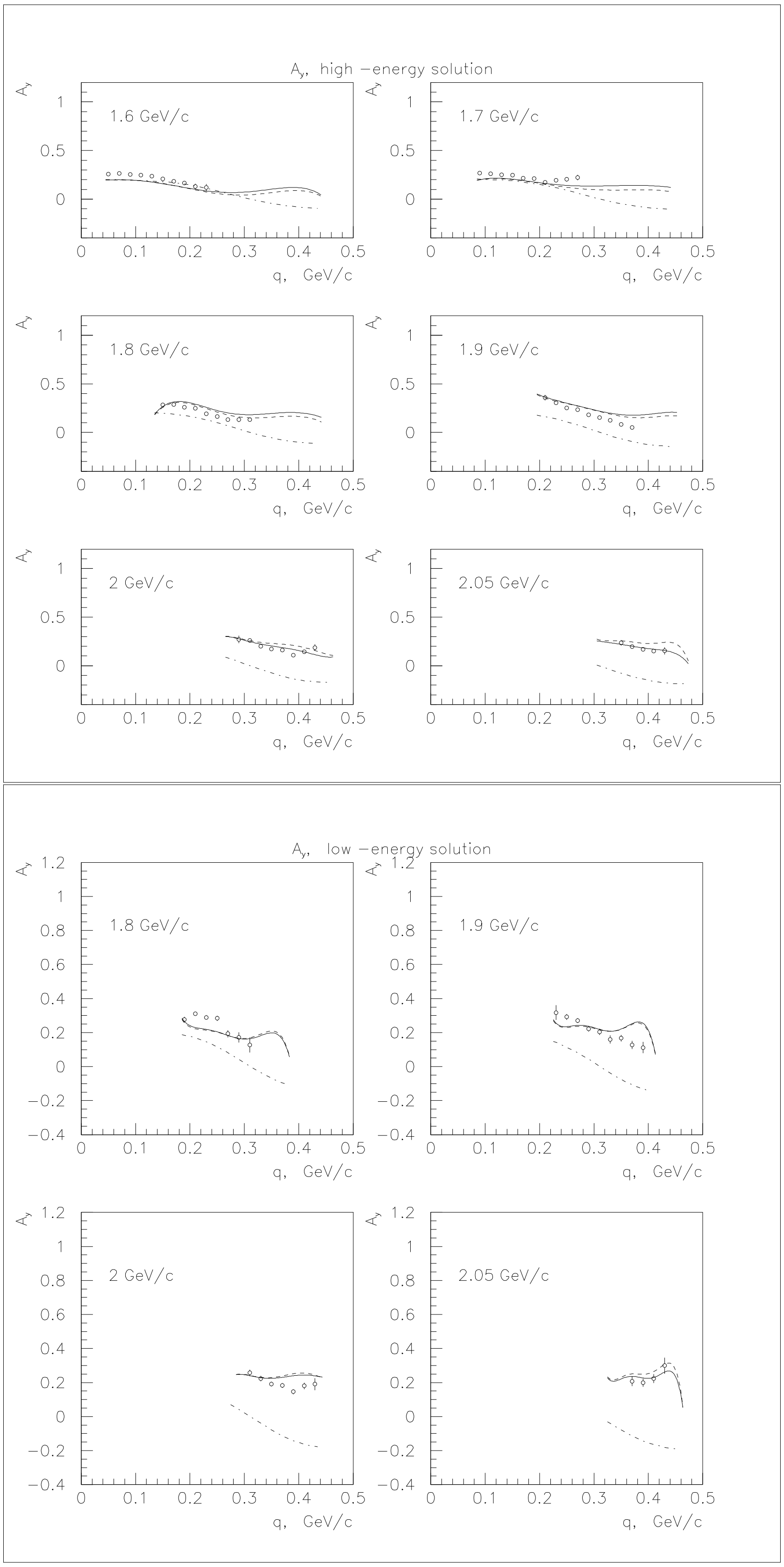

Fig. 2. Vector analyzing power A_y.

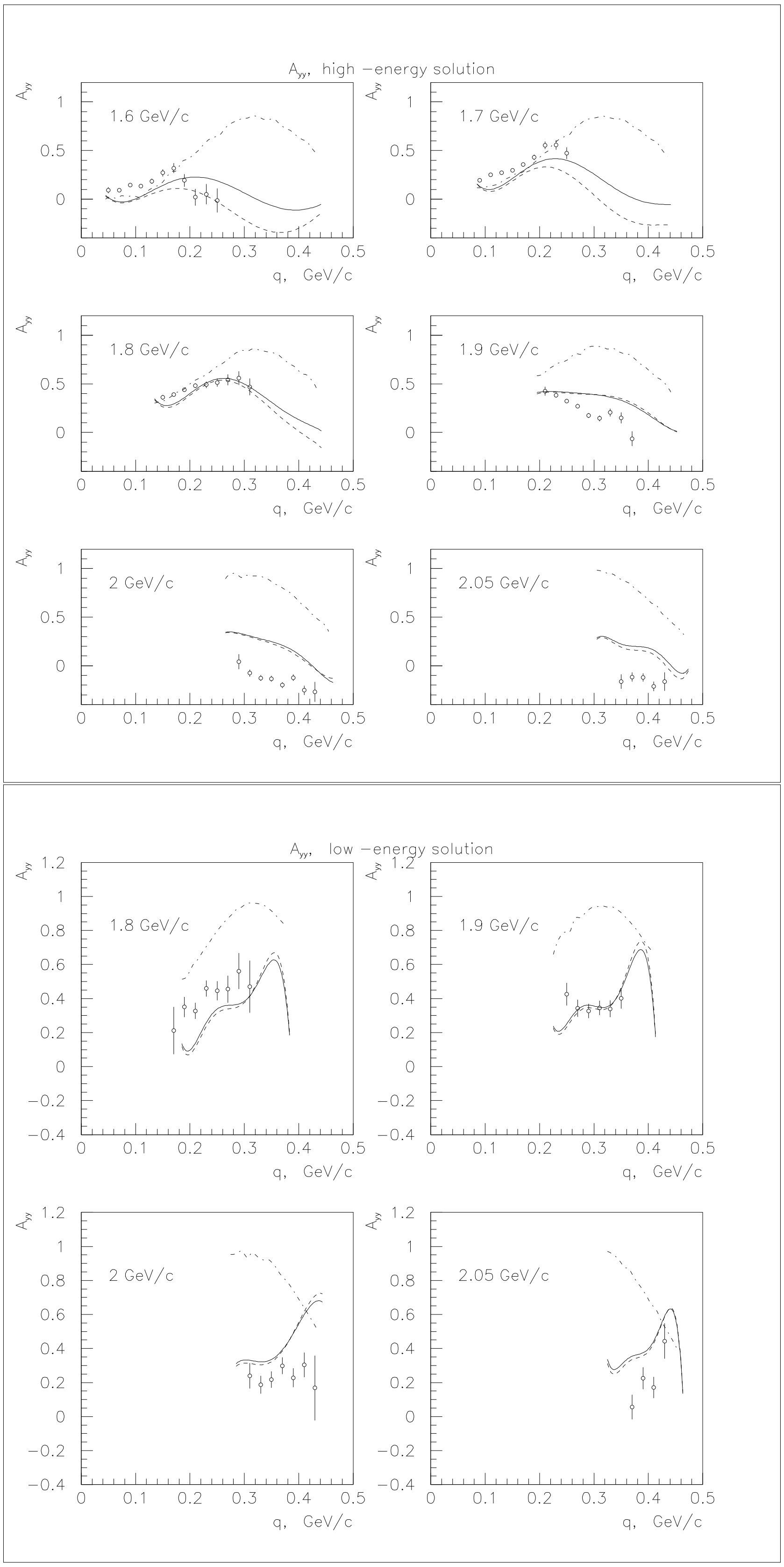

Fig. 3. Tensor analyzing power A_{yy}.

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