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Measurement of analysing powers for neutron scattering on CH2, CH, C and Cu target for momenta from 3.0 to 4.2 GeV/c

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PoS(SPIN2018)151

During two beam runs in the years 2016 and 2017, the analyzing powers (Ay) for protons and neutrons scattering on CH2, CH, C and Cu targets were measured at the nucleon momentum from 3.0 to 4.2 GeV/c with the ALPOM2 setup at the Nuclotron accelerator. The data for polarized neutron beam are obtained for the first time, thanks to the unique polarized deuteron beam that is presently available up to 13 GeV/c. Earlier, analyzing powers for polarized **neutrons** had been measured only for thin hydrogen targets. Cross sections and analyzing powers for np, for both elastic scattering and charge exchange are known up to 29 GeV/c. No data existed for thick analyzers. The measurement of the angular dependence of Ay for the neutron is essential to the continuation of the neutron form factor measurements to the highest possible transferred momentum-Q^2 at the Jefferson Laboratory. The reaction p+Cu(W), with the detection of a neutron in the forward direction by a hadron calorimeter, can be used for the measurement of the proton polarization at the future NICA collider.

23rd International Spin Physics Symposium - SPIN2018 -
10-14 September, 2018
Ferrara, Italy

1. Introduction

The electromagnetic form factors (EMFF) of elastic electron-Nucleon (eN) scattering are representative of the charge and the magnetic currents of the nucleons (for recent reviews on electromagnetic form factors see Refs. [1, 2]).

Early determinations of the EMFF used Rosenbluth separation [1] of differential cross section measurements, but as electron accelerator technology has developed to produce high-current, high polarization, continuous-wave electron beams, the measurement of polarized observables has become the method of choice. Polarization observables are especially useful in separating a small amplitude from an otherwise dominant one.

The use of polarization had been firstly proposed by the Kharkov school [3, 4] as an alternative method to Rosenbluth separation to determine the nucleon EMFF from polarized elastic electron-proton (e↑p) and electron-neutron (e↑n) scattering (where the neutrons are in a deuteron or 3He target): the ratio of the longitudinal to transverse recoil nucleon polarization in elastic eN scattering, with longitudinally polarized electrons, is directly related to the ratio of electric to magnetic form factors, whereas the unpolarized cross section depends on the square of form factors. This type of double-polarization experiments, denoted, in the following, recoil polarization experiments (RP), requires the measurement of the polarization of the recoiling nucleon in elastic eN scattering. Experiments of this type started in the late 1990 (see below) when high-intensity, highly polarized, high-duty-cycle electron beams became available.

The range of the squared four-momentum transfer, Q^2, was extended at Jefferson Lab (JLab), with polarized beams of energy up to 6 GeV, where the four form factors of elastic eN scattering (electric and magnetic, for proton and neutron) were measured. Proton data have produced unexpected and intriguing results [5, 6]. Contrary to the generally accepted scaling relation that the electric to magnetic form factor ratio μGe/Gm ~ 1 (μ is the proton anomalous magnetic moment) the RP polarization data show an approximately linear decrease of this ratio, clearly indicating that the electric and magnetic form factor have very different dependence on Q^2, and therefore that the radial distributions of charge- and magnetization, are not the same. This was an unexpected result and the various papers publishing these results [5-10] have been quoted in the literature with a frequency now larger than 2000. Proposed new experiments will extend the Q^2 range of Gep/Gmp measurements and should determine if the ratio does cross zero, as suggested by the existing data.

Note that proton analyzing power measurements at Dubna showed the feasibility of extending the JLab RP measurements to higher values of Q^2 when the recoil-proton momentum is higher. The third experiment for the proton form factor ratio [11] was approved by the JLab PAC after that the analyzing power measurements done in Dubna with the Synchrophasotron in 2001 [12] proved the feasibility of polarization measurements at the corresponding transferred momenta.

JLab has recently undergone an energy upgrade, and is producing polarized beams of energy up to 11 GeV. This opens the way for new measurements at larger values of Q^2, and therefore the extension of the analyzing power database to higher nucleon momenta is urgently needed, both for protons and for neutrons [13-15].

2. Proton and neutron polarimetry

Polarization experiments require the measurement of the azimuthal distribution resulting from a secondary scattering of the polarized recoil nucleon in a polarimeter. Optimization of the analyzing power of the secondary scattering is crucial to achieve an efficient polarimeter, and this determines the choice of analyzing material and the range of accepted scattering angles.

C or CH2 is often used as the analyzer in proton polarimeters and analyzing power measurements have been made with thick analyzers at Saclay [16] (and references therein) and Dubna [12], using thick analyzers, and as part of a program of study of elastic and quasi-elastic d↑+p reactions [17], up to incident momenta of several GeV/c. New measurements at Dubna will extend the incident momenta up to 7.5 GeV/c [18].

Neutron polarimetry is generally based on free elastic np scattering or elastic-like np scattering from nuclei and kinematic reconstruction is highly desirable to select the range of polar scattering angles where the analyzing power is relatively large. This may be achieved by using an active, position-sensitive analyzer to detect the recoiling proton and thus localize the interaction position of the incident neutron. Alternatively, charge-exchange neutron scattering may be used, where the trajectory of the energetic, forward-angle proton can be tracked.

In comparison to proton scattering, the analyzing power Ay for polarized neutron scattering at GeV energies is poorly known. Analyzing powers exist only for thin hydrogen targets. Cross section and analyzing powers for np, both for elastic and charge exchange reactions, are known up to 29 GeV/c. No data are known to exist for thick analyzers, made of scintillator material.

Free np scattering is in principle the best analyzer of neutron polarization, but the use of a hydrogen analyzer is challenging technically and up to now scattering from C, CH or CH2 has generally been used. However Ay for elastic-like scattering from nuclei is lower than for the free-scattering case.

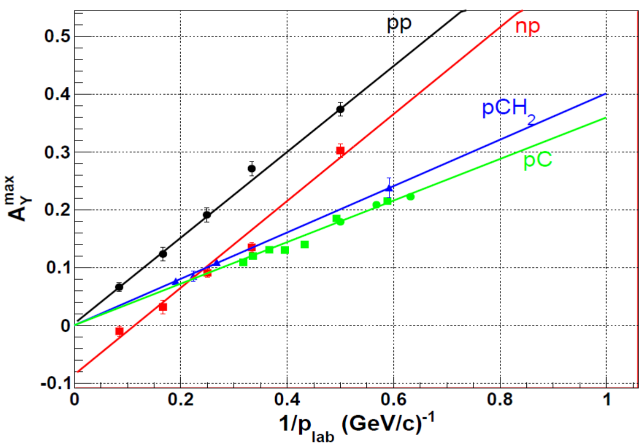

Figure. 1. The dependence of the maximum of Ay on $1/p_{lab}$. Black circles: ANL d(p↑; p')n data [19, 20]; black line: linear fit. Red squares: ANL d(p↑; n)p data [19] ; red line: linear fit. Blue triangles JINR: p↑ + CH2 → one charged + X; blue line: linear fit [12]. Green squares Saclay [16] and circles ITEP [21]: p↑ + C → one charged + X; green line: linear fit [12].

The data displayed in Figure 1 show a roughly linear dependence of the maximum value of the angle dependent analyzing power, Ay^{max} , on $1/p_{lab}$, but there is a significant negative offset of the pn data with respect to pp. There is a factor of two reduction in the analyzing power of p↑+C with respect to free pp scattering, but to our knowledge there are no data on polarized np scattering from nuclei in the multi-GeV energy domain.

The np (equivalent to pn) polarization is dependent on the incident nucleon momentum p_{lab}, whereas for charge-exchange np, given the spread in the data, there is no apparent strong dependence of Ay on p_{lab}, [22,23].

3. Polarized nucleon beams

ALPOM2 is placed at the beam line of the Nuclotron accelerator facility, at the Veksler Baldin Laboratory for High Energy Physics (VBLHEP) of the Joint Institute for Nuclear Research in Dubna. This beam line was used previously for several experiments using (polarized) neutron beams [24], such as the measurement of the Δσ(n↑p↑) total cross section difference [25].

The polarized deuteron beam is provided by the Source of Polarized Ions (SPI), which is an atomic beam polarized ion source with a plasma (H, D) charge exchange ionizer and a storage cell in the ionization region. The parts of the former polarized source CIPIOS from Indiana University Cyclotron Facility (Bloomington, Indiana, USA) were used in the SPI [26]. The deuteron polarized beam was tagged with its three polarization states, down (plus, +, Pz = +1, Pzz = +1), up (minus, -, Pz = -2/3, Pzz = 0), and unpolarized (zero, 0), where the state is changed after each spill. The beam polarimeter (F3), located at the focus F3 of the extracted beam line, is based on quasielastic pp scattering, where analyzing powers are known from previous measurements [27]. F3 has an ionization chamber (IC) as a beam intensity monitor for normalization, and four arms, forward and recoil, left and right. Each arm has three sets of scintillator counters at forward angle 8^o, 9^o, and 10.5^o for momenta 4.2, 3.75 and 3 GeV/c, respectively, and a bigger scintillator at backward angle about 69^o for the recoil particle. A coincidence between forward and recoil arms (left and right) and the IC counts were collected, spill by spill, by the data acquisition system. The beam polarization was constantly monitored and the stability of the beam was excellent, with polarimeter asymmetry fluctuations not exceeding 2%.

The deuteron beam, extracted over a period of 5 s was incident on a 30(25) cm thick C(CH2) target where the deuteron was fragmented into a proton and a neutron. Experiments on polarization transfer from deuteron to proton in break-up reactions showed that the proton (and therefore the neutron) polarization is equal to the polarization of the primary deuteron beam and constant up to internal momenta of the nucleons inside the deuteron q=0.15 GeV/c [28].

By setting the primary deuteron beam intensity in the range (1-3) x 10^8 particles/spill, the average number of protons or neutrons incident on the polarimeter target was kept at the level of 2 x 10^5 per spill.

4. The ALPOM2 setup

ALPOM2 represents an upgrade of the ALPOM polarimeter [12], which itself is based on the POMME polarimeter employed at Saturne [29].

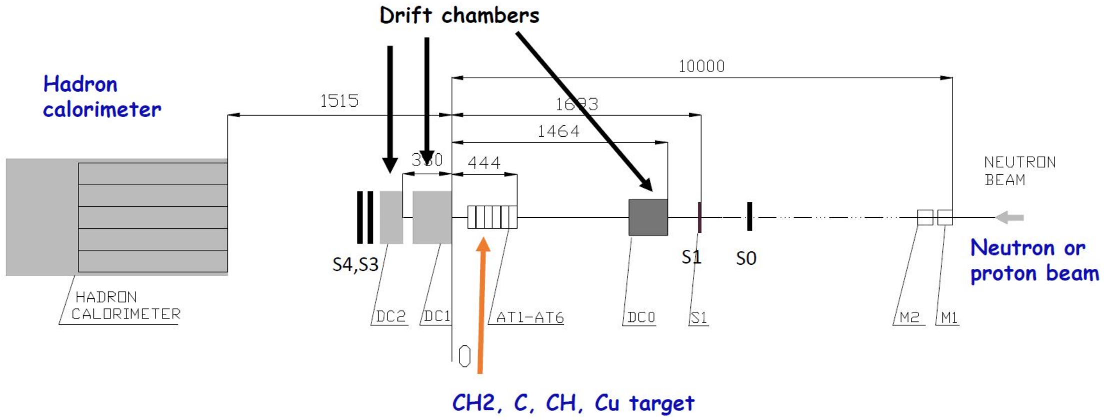

Figure 2. Schematic side view of the ALPOM2 set up positioned on the secondary proton/neutron beam line, including scintillation counters (S0, S1, S3, S4); drift chambers (DC0, DC1, DC2); hadron calorimeter; neutron monitor counter (M1, M2). The analyzing targets were located between DC0 and DC1. Here a CH active target (AT1 -AT6), is shown as an example. Dimensions are in mm. O is the origin of the z coordinate system.

A schematic view of the ALPOM2 geometry is shown in Figure 2, with the proton/neutron beam travelling along the z-axis, in the longitudinal direction. The main components consisted of:

- fast plastic scintillator counters (S0, S1, S3, S4 and AT1-AT6) for triggering purposes;
- drift chambers (DC0, DC1, DC2) for charged particle tracking;
- a segmented hadron calorimeter for energy and position measurements of the outgoing particles;
- the polarimeter analyzer (C, CH, CH2, Cu), where Figure 2 shows the segmented CH scintillator analyzer (AT1-AT6).
- neutron monitor counters (M1, M2) for monitoring neutron flux.

The scintillation counters were used to generate the trigger for the readout of data from all detectors in the set up. Coincident hits from S0 and S1 were used to trigger on incident protons, during proton polarimetry measurements, whereas S3 and S4, located downstream from the target were used in coincidence for triggering during neutron polarimetry measurements.

The drift chambers were used to reconstruct primary and secondary charged particle tracks traversing the ALPOM2 set up and are described in detail in Ref. [30]. To reconstruct a track, hits in at least three chamber planes were required. The hit-position resolution provided by the chambers was less than ~100 μ, which produced an angular resolution better than 0.4 mrad, and the reconstruction efficiency for charged tracks was close to 100%.

Moreover, as the analyzing power becomes smaller with increasing beam momentum, the calorimeter can be used to select the leading protons at smallest angles, which has the effect to increase the analyzing power. The hadron calorimeter makes it possible to select high momentum particles through their energy deposit.

The hadron calorimeter, built in Dubna for the COMPASS experiment at CERN [31, 32], is a sampling calorimeter composed of alternating plates of plastic scintillator and iron or lead. The iron/lead provides most of the stopping power for energetic hadrons, so that the incident energy is totally absorbed in a thickness of less than 1 m. As used in ALPOM2, it is comprised of 28 elements (Figure 3). Four bars with dimensions 75 mm x 75 mm, were used in the central

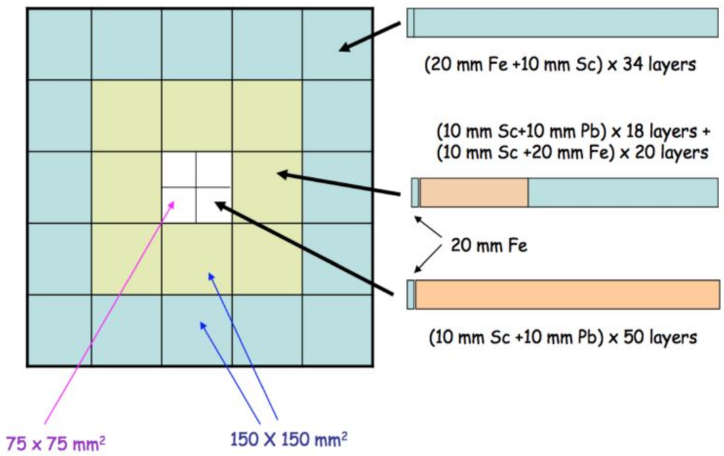

Figure 3. View of the different bars of the hadron sampling calorimeter used in the ALPOM2 set up. The different bar compositions are noted at the side.

region, at smaller scattering angles and where higher count rates were experienced, whereas at larger scattering angles, 24 bars with dimensions of 150 mm x 150 mm were used.

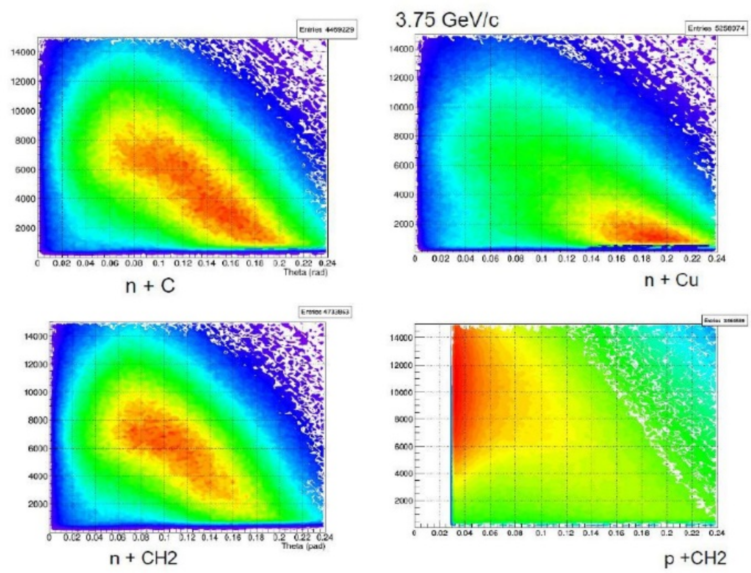

Figure 4. Response of the hadron calorimeter for n + C (a), n + Cu (b), n + CH2 (c), and p + CH2 (d). The channel amplitude is shown as a function of the detected particle angle. In subfigure (d) the events corresponding to the unscattered beam are removed by a small angle cut.

Moreover, as the analyzing power becomes smaller with increasing beam momentum, the calorimeter can be used to select the leading protons at smaller angles, which has the effect to increase the analyzing power. The hadron calorimeter makes it possible to select high momentum particles through their energy deposit.

The response of all calorimeter bars and their associated electronics was calibrated in dedicated cosmic-ray runs, where the calorimeter was rotated by 90 degrees so that the bars were aligned vertically. A further calibration, with the calorimeter in standard alignment, were performed with the proton beam.

5. Results

5.1 Control measurements

The analyzing powers for proton on CH2 at 3.0, 3.75 and 4.2 GeV/c momentum have been measured and compared to previous data obtained at 3.8 GeV/c [12]. The data (black solid squares in Fig. 16), follow a similar angular dependence and the systematic trend of a slight decrease of Ay with increasing incident momentum. The lines are drawn to drive the eye.

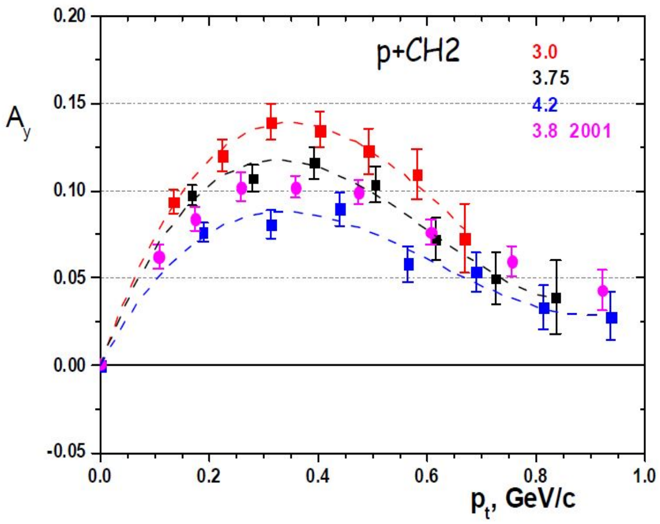

Figure 5. Analyzing power of proton at beam momentum 3.8 GeV/c (magenta circles), measured in previous experiment [12], compared with measured data at 3.0 GeV/c (red squares), 3.75 GeV/c (black squares) and 4.2 GeV/c (blue squares). The lines are drawn to drive the eye.

The asymmetry can be derived independently from the information given by the chambers and by the calorimeter. In order to check the reliability of the present analysis we reconstructed the asymmetry from the calorimeter (without the four central bars) with larger granularity. The results for p+CH2 at 3.0 GeV/c momentum are shown in Figure 6 (solid squares). They are compared to the values of the asymmetry from the drift chamber averaged on a large angular range, $0.03 < \theta < 0.24$ [rad] in (open circles). The maximum value is slightly smaller than the corresponding maximum value in Figure 5, as it corresponds to an averaged value.

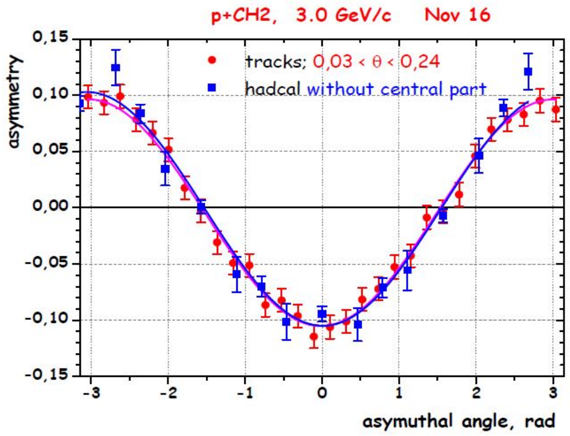

Figure 6. Average asymmetries of proton at beam momentum 3.0 GeV/c measured in this experiment from the hadron calorimeter data (blue squares), compared to the values reconstructed from the tracks given by the drift chambers (red circles).

2.5.2 Neutron scattering

The asymmetry for the nCH2 charge exchange reaction (one charged particle is detected) is shown in Figure 7 at different momenta and for different polarimeter targets: CH2, CH and C as function of p_t. One can see that the analyzing powers decrease slowly with energy, left panel. Increasing the hydrogen content of the target slightly increases the analyzing power, right panel. Charge exchange can be studied also with a proton beam, where neutral particles are detected with the condition that no charge track is recorded in the downstream chambers, but there is a signal in the hadron calorimeter, corresponding to an energy deposit, from the interaction of a forward neutron with the hadron calorimeter material. In this case one can not appreciate a large difference of analyzing powers with the incident proton momentum.

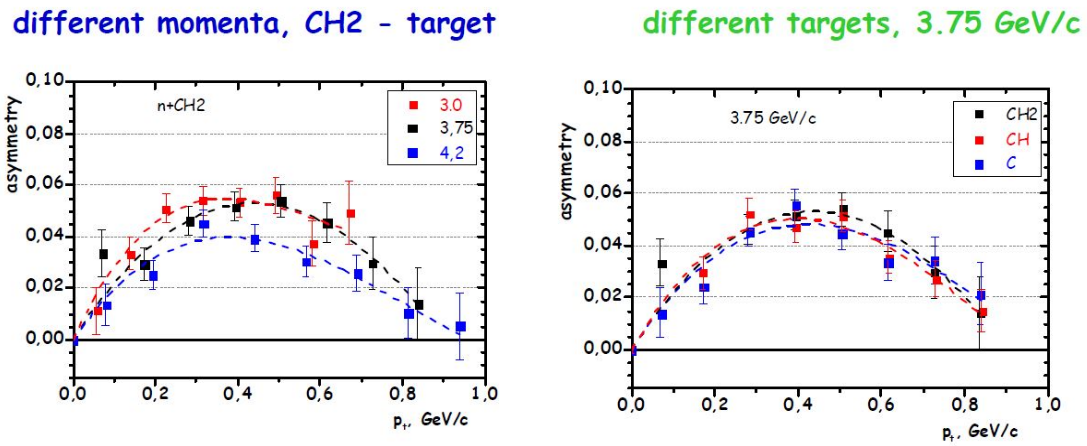

Figure 7. Analyzing power as a function of pt-distribution (left panel) for different momenta and for nCH2 scattering at 3.0 GeV/c (red squares), 3.75 GeV/c (black squares), and 4.2 GeV/c (blue squares), (right panel) for 3.75 GeV/c neutrons on different polarimeter targets: CH2 (black squares), CH (red squares), and C (blue squares).

5.3 Cu target

For the first time, data were taken with a Cu target, detecting a charged particle emitted forward and a proton or a neutron beam of momentum 3.75 GeV/c. The analyzing powers on a Cu target for neutron induced charge-exchange reaction is shown at 3.75 GeV/c in Figure 8 (red solid squares) and it is compared with the (quasi) elastic reaction induced by a proton (blue solid squares). Proton (quasi)elastic scattering show twice as large maximum analyzing power. Figure 8 shows also that Ay can be dramatically increased by selecting a large energy deposit in the hadron calorimeter. This effect is much larger for neutron charge exchange reaction, that shows 100% increase for nCu and 30% increase for the pCu reaction, both with charged particles detected in the final state.

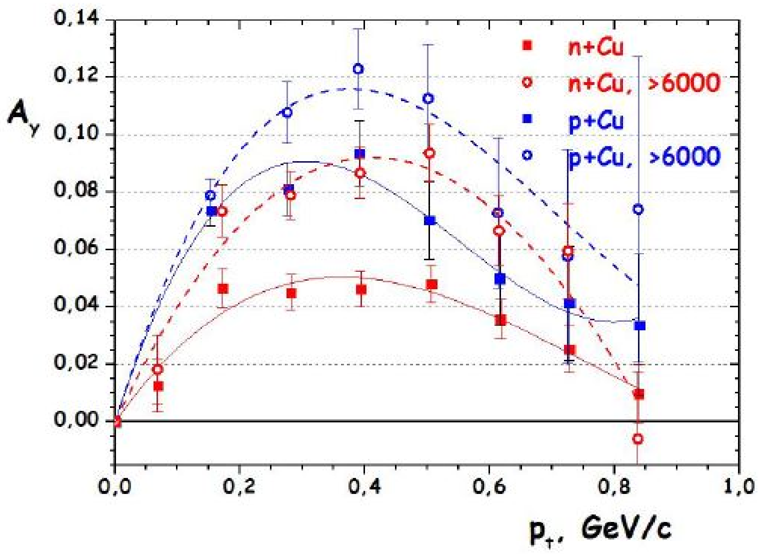

Figure 8. p_t -dipendence of the analyzing power for the charge-exchange reaction pCH2 (a neutral particle in final state-blue squares) and nCH2 (a charged particle in final state- red squares) scattering at 3.75 GeV/c, with a neutral particle in the final state, for Cu polarimeter target. Corresponding empty symbols indicate to the same data, after the rejection of events with large energy deposit in the calorimeter.

3.6. Conclusions

Analyzing powers for polarized protons and neutrons scattering on CH2, CH, C and Cu targets were measured at nucleon momentum from 3.0 to 4.2 GeV/c by the ALPOM2 polarimeter at JINR Dubna. The unique polarized deuteron beam from the Nuclotron accelerator, which has a maximum momentum of 13 GeV/c, has been used to produce both polarized protons and (for the first time) polarized neutrons.

Analyzing powers have been obtained for elastic-like proton scattering and charge-exchange neutron scattering, both of which entail detection of a single, forward charged particle.

Selection of high energy particles, using energy deposit in the calorimeter is found to boost the analyzing power by a factor 2 in the neutron case and 1.3 in the proton case.

Analyzing powers have also been obtained for charge-exchange proton scattering, yielding values that are very similar to the neutron charge-exchange case. The measured analyzer materials include Cu and show that Ay in the multi-GeV/c domain is essentially the same for light and heavy nuclei. A heavy nucleus analyzer has the advantage of being much more compact for a given effective thickness of material.

These two features: adding a calorimeter for the selection of high energy particles, and replacing a hydrogen reach light target by heavier nuclei open the way to simpler and more effective polarization measurements for proton and neutrons in the GeV region. Future experiments at JLab, requiring such measurements have already integrated these concepts, as in the case of the experiment [13]. Moreover, the inverse reaction p+Cu(W) with the detection of a neutron in the forward direction by the hadron calorimeter can be used for measurement of the proton polarization at the NICA collider. Spin effects in hadronic and heavy-ion collisions may be studied at NICA, using non-polarized, longitudinally and transversally polarized beams, constituting a consistent spin physics program [14].

This work was supported under Slovak Grant Agency VEGA No. 1/0113/18

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