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Physics Results from the AmPS Electron Scattering Facility

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Abstract

The programme in intermediate energy hadronic physics at NIKHEF (Amsterdam) with the Amsterdam Pulse Stretcher and Storage Ring (AmPS) is now in full operation. With the ring operating in stretcher mode a beam with a current of $\geq 10 \mu\text{A}$ and with a (50 - 70) % duty factor has been used to probe high momentum components in ^{208}Pb with the quasi-free proton knockout reaction. Ongoing coincidence experiments of type $(e, e'p)$ and $(e, e'2p)$ with broadband proton detectors of 500 msr solid angle are presented. We discuss an experiment with the beam in storage mode interacting with a tensor-polarized deuterium target, a storage cell fed by an atomic beam source.

1 Introduction

One limitation - the low duty factor of the available beam - has until recently hampered the realisation of the potential of exclusive electron-hadron scattering experiments. With the recent commissioning of continuous-beam electron facilities a new generation of coincidence experiments have become feasible. The impressive improvement in signal to noise ratio achieved in coincidence experiments is illustrated in figure 1. In addition, a new tool - the use of polarization degrees of freedom - has become available for the investigation of the spin structure of hadrons and composite hadronic systems. Key physics questions are high-momentum components in light and heavy nuclei, the direct observation of nucleon-nucleon correlations by the knockout of a correlated nucleon pair which is detected in a triple coincidence experiment, e.g. of the type $(e, e'2p)$, the neutron formfactors, the electroproduction of neutral pions from hydrogen and the spin structure of few-body systems. In the present paper some selected examples of experimental results obtained at the Amsterdam Pulse Stretcher with a high-duty factor extracted beam and a beam in storage mode in the Internal Target Facility will be discussed.

2 AmPS facility

AmPS features two modes of operation [1] - stretcher mode and storage mode. The layout of the facility is shown in figure 2.

In stretcher mode the energy-upgraded linear electron accelerator (MEA) injects at a repetition rate of 200 Hz (max) pulses with a width between 0.6 and 2.1 μs and with a peak current of $\geq 20 \text{ mA}$. In between injection pulses the circulating beam is slowly extracted by a 1/3-integer resonant extraction process controlled by the power level and phase of a RF cavity located in the vicinity of the extraction septum. In the fall of 1993 the level of 10 μA of extracted current had been reached with three turn injection mode and 40 mA peak current injected. A duty factor of better than 50 % was achieved. This is the crucial step forward relative to the ≈ 1 % duty factor, characteristic of the previous generation of electron accelerator facilities.

In order to reach $> 10 \mu\text{A}$ extracted current it is mandatory to push the efficiency of the extraction process very close to 100 %, given the power level of $\geq 10 \text{ kW}$ stored in the beam.

In storage mode a 1/e lifetime of > 10 minutes has been demonstrated with a beam of 440 MeV, injected with a peak current of 20 mA. Conditions of beam position, beam halo and lifetime turn out

Figure 1: Missing energy spectrum of the $^{12}\text{C}(e,e'p)$ reaction obtained with a low duty factor beam (upper panel) and a stretched beam (lower panel).

to be reproducible. A minimum-intensity of the beam halo is crucial for experiments with a storage cell as internal target. In order to optimize the effective density of the stored atoms the smallest possible cell diameter is required and one wants to minimize the rate of background events due to halo-cell wall interactions. This issue has been investigated in detail with moveable collimators. In order to further reduce the halo intensity a halo scraper has been installed. In section 5 an exploratory experiment with tensor-polarized deuterium in a storage cell will be discussed. Pulse stacking has been implemented (stored current ≈ 100 mA) and the beam lifetime will improve by installing additional vacuum pumping capacity. Ramping of the ring magnetic lattice in order to reach an energy of 900 MeV, the maximum the ring can sustain according to beam-dynamics simulations, will be implemented in the winter of 1994.

3 High-momentum components in ^{208}Pb

In the modification of the nuclear mean field by correlations the central issue is the role of short range correlations (SRC) that are due to the repulsive core of the nucleon-nucleon potential. Consequently independent particle motion, incorporated in the mean field approximation, is modified due to the finite size of nucleons. A simple estimate of the probability (P) of such correlations can be made by calculating, for a system of A fermions constrained in a volume V, the volume excluded for independent particle movement: $R = \text{volume}(\text{excluded})/V = r_0^3 A / (1.2)^3 A \approx (0.2 - 0.3)$, depending cubically on the hardcore radius r_0 . (Notice that the effect of Pauli-correlations is included already in the mean-field solution.) Whereas exact many-body calculations of correlations are yet out of reach except for the lightest nuclei, various phenomenological approaches based on the notion of quasiparticles are available. On general grounds one expects the effect of short range correlations to show up in the single nucleon spectral function at momentum values larger than 300 MeV/c and at relatively large separation energy

Figure 2: The lay-out of the AmPS ring (circumference 212 m) with the internal target hall and EMIN internal target hall (ITH) and the external-beam experimental facility (EMIN).

since the two correlated nucleons will both be emitted if one of them is hit by the virtual photon in a $(e, e'p)$ experiment. In figure 3 the total momentum probability $n(k)$ calculated with a meanfield wave function (Φ) and with a variational wavefunction (Ψ_v) are shown.

Conflicting theoretical predictions exist for the separation-energy dependence of high momentum components in finite nuclei. With a self-consistent Green's Function method, Mther and Dickhoff [2] have explicitly included SRC in the calculation of the ^{16}O momentum distribution. They observed no significant increase at high momentum and low excitation energy compared to the mean-field result. For finite nuclei Pandharipande et al. [3] obtained quasi-particle wave functions which include the effects of SRC by applying the results of variational Monte-Carlo calculations of correlated quantum drops of liquid ^3He to nuclear systems. In this calculation long-range correlations are *not* accounted for.

Other authors do predict an enhanced probability of high-momentum components for transitions at low excitation energy. Ma and Wambach [4] and Mahaux et al. [5] employed an effective mass for the nucleon in the nuclear medium to account for the effect of correlations. In their approach the quasi-particle wave functions are suppressed in the nuclear interior and enhanced at the nuclear surface due to long-range correlations.

With the high-duty factor facility AmPS at NIKHEF-K a $^{208}\text{Pb}(e, e'p)$ experiment has been performed with adequate real-to-accidental ratios.

The experiment was carried out with the continuous electron beam from the Amsterdam Pulse-Stretcher facility (AmPS) at NIKHEF-K [6] at an energy of 487.3 MeV. The scattered electron and knocked-out proton were detected in coincidence by two high-resolution magnetic spectrometers.

The data were measured under kinematical conditions where the center of the acceptance corresponded to fixed values of the three-momentum transfer ($q=221$ MeV/c), the energy transfer ($\omega=110$ MeV) and the proton kinetic energy ($T_p=100$ MeV).

The reduced cross section, which is defined as the six-fold differential cross section divided by the off-shell electron-proton cross section $\sigma_{\text{e1}}^{\text{ep}}$ as given by De Forest and by the kinematical factor, have been determined for excitation energies in ^{207}Tl from (0 - 25) MeV. From the reduced cross section, momentum distributions have been obtained by integrating individual peaks corresponding to knockout from specific quantum orbits.

In figure 4 the momentum distributions for the transitions to the dominant $\frac{1}{2}^+$, $\frac{3}{2}^+$, $\frac{11}{2}^-$, $\frac{5}{2}^+$ and $\frac{7}{2}^+$ single-hole states in ^{207}Tl as measured in the present experiment (solid circles) and the previous-generation data of Quint (plus-marks) [7] [8] are shown. The solid curves in the figure are the result of calculations with meanfield wave functions in distorted-wave impulse approximation including electron and proton distortions. Calculations including correlations as proposed by Pandharipande et al. [3], Ma and Wambach [4] and Mahaux and Sartor [5] are represented by dash-doubledotted, dashed and

Figure 3: Total momentum probability distributions for a heavy nucleus as calculated with meanfield wavefunctions (Φ) and variational wave functions (Ψ_v).

Figure 4: Momentum distributions for valence protons in Pb as a function of effective missing momentum. The new high momentum data obtained with the high duty factor beam and previously obtained lower momentum data [7] are shown. Calculated curves are explained in the text.

dot-dashed curves, respectively.

Here quasi-particle wave functions $\Phi^*(r)$ were used, constructed by converting the mean-field wave functions $\phi(r)$ by the relation $\Phi(r) = G(r)\phi(r)$ and $\Phi^*(r) = \phi(r)/\sqrt{R}$ is normalized to one. The function $G(r)$ is shown in figure 5.

Figure 5: The function $G(r)$ accounting for correlations in quasi-particle wavefunctions calculated with different theoretical ingredients.

The appreciable difference in shape between the function $G(r)$ of Pandharipande relative to that of Ma and Wambach, and Mahaux and Sartor is due to the presence of long-range correlations in the latter calculations. Long-range correlations are included via the coupling of the hole state to low-lying excitations, which leads to an enhancement of the E-mass, particularly at the surface.

From the comparison of the data for the hole states at low excitation energy with the model calculations three observations emerge:

1. The calculations of Pandharipande, that exclude long large correlations, disagree with the data; short range correlations therefore are not manifest in low-energy hole states.
2. The long range, surface dominated, correlations included in the calculations of refs. [4] [5] induce enhanced high-momentum components relative to the mean field predictions, and are in fair agreement with the data.
3. The enhancement of high momentum components appear to be independent of the particular quantum numbers of the hole states.

The bulk of high-momentum components appear to show up in the missing energy spectra at excitation energy values E_m larger than the particle-emission threshold in ^{207}Tl . This region of the spectral function is being analysed at present in terms of the structure of the specific short-range N-N dynamics employed in many-body calculations for finite nuclei.

In the interpretation of the data the basic assumption is that the virtual photon couples to one-body (nucleonic) currents only. In principle coupling to meson exchange currents must be taken into account as well. However, in the kinematics employed the photon is predominantly longitudinal and the effect of two-body currents in the momentum distribution of hole states at low excitation energy is estimated to be $\sim 10\%$ of the one-body part, according to a calculation by Boffi et al. [9].

4 Investigation of NN correlations with large solid angle detectors

Coincidence reactions of the type $(e, e'p)$ involving the high momentum and high-missing energy region of the single-proton spectral function and a fortiori triple-coincidence processes of $(e, e'2p)$ have relatively low yields. The investigation of the basic physics of NN correlations does not primarily require the typical energy resolution achievable with magnetic spectrometers but rather demand the use of broadband proton-detection systems with solid angles of several hundred msr. Relative to the previous generation of experiments with $\approx 1\%$ duty factor the luminosity achievable is increased by two orders of magnitude with the continuous current beam of AmPS. Two such hadron detectors consisting of highly-segmented scintillator telescopes and wire chamber systems have been constructed by a Free University - NIKHEF collaboration. A schematic view of the 500 msr hadron detector is shown in figure 6. The device accepts protons with kinetic energies in the range $T_p = (25 - 160)$ MeV and features an

Figure 6: Schematic view of the broadband proton detector with a 500 msr solid angle.

energy resolution of 2.5 % at $T_p = 120$ MeV. In a recent measurement of the ${}^4\text{He}(e, e'p)$ reaction, the device has been used in coincidence with the QDQ spectrometer that detected the scattered electron. The data, taken with a luminosity of $\sim 10^{36} \text{ cm}^{-2}\text{s}^{-1}$, cover the missing energy range $E_m = 0 - 150$ MeV, were measured with the aim to observe the evolution of the reaction strength in the broad (p_m, E_m) domain indicated. Helium-4, a compact system with a large nucleon density and strong binding, is a beautiful testing ground for correlation physics, that for this four-body system can be calculated with correlations incorporated both in the initial and in the final state. The performance of the QDQ-proton detector coincidence setup is illustrated (figure 7) by the coincidence timing spectrum obtained at missing momentum $p_m = 700 \text{ MeV}/c$.

There are several experiments underway at present with the proton detectors among which a study of the ${}^2\text{He}(e, e'p)$ reaction in the delta resonance region. However, I will not discuss these experiments here but refer to the papers that will be published in the near future.

5 Proton knockout from tensor polarized deuterium

Instrumentation for an experiment to scatter electrons from tensor polarized deuterium in the internal target facility of AmPS has been commissioned recently. The setup is shown in figure 8.

Figure 7: Coincidence timing spectrum for the reaction ${}^4\text{He}(\epsilon, \epsilon'p)$ at $p_m = 700$ MeV/c.

AmPS NIKHEF AMSTERDAM

Figure 8: Schematic view of the internal target setup with the atomic beam source, storage cell and detectors.

An Atomic Beam Source (ABS) feeds a storage cell, a T-shaped open ended configuration. The atomic beam source is based on a Stern-Gerlach separation of an atomic deuterium beam, produced by RF-dissociation with a nozzle cooled to 30°K. The $m = 1/2$ hyperfine states are focussed by a tapered sextupole magnet with a 1.1 T tipfield. The tensor polarization can be varied from $P_{zz} = -2$ to 1 by a strong-field transition unit. Intensity and polarization of the atoms are monitored with a polarimeter consisting of a Stern-Gerlach magnet, a chopper and a quadrupole mass spectrometer. A flux of $2 \cdot 10^{16}$ atoms per second with a polarization of 90% is fed into the storage cell. The use of the storage cell with a special teflon coating causes an increase by 2 - 3 orders of magnitude of the effective target density. The stored deuterium atoms ultimately diffuse out of the cell, causing a triangular-shaped density profile along the beam axis. A measured density profile is shown in figure 9 where the reaction yield with deuterium gas in the cell and the empty cell data are shown, demonstrating that the rate of interactions of the beamhalo with the cell walls is small. Scattered electrons are detected by an electromagnetic calorimeter consisting of 60 Cs(Tl) blocks with a thickness of 20 radiation lengths, covering a solid angle of 180 msr.

Figure 9: Density profile of gas in the storage cell as measured by the position dependent reaction yield. The shaded are the background from interactions of the beamhalo with the cell walls.

The knockout proton is detected in a range telescope with particle identification that covers a solid angle of 300 msr. Both electron and proton detector are equipped with (x,y) wire chamber configurations that allow to reconstruct the interaction vertex. With the range telescope protons can be separated from deuterons produced by elastic scattering events. The tensor asymmetry for these elastic scattering events will serve as an additional monitor of the polarization of the target.

In the experiment a luminosity of $2 \cdot 10^{31} \text{cm}^{-2} \text{s}^{-1}$ will be obtained by cooling the storage cell that has a diameter of 15 mm. The tensor asymmetries expected in a 100 hour run in the experiment is shown in figure 10.

The physics contained in the asymmetry is related to the D-state probability in the deuteron wavefunction, generated by the tensor part of the n-p interaction. These experiments carried out by a NIKHEF - University of Wisconsin - ETH Zürich - IPN (Novosibirsk) - Arizona State University collaboration.

Figure 10: Tensor asymmetry (simulation results) for proton knockout from deuterium as a function of the angle of the knocked out proton to $\vec{q}$ in the center of mass.

6 Summary

The scientific programme with the continuous beam extracted from the AmPS ring is at full momentum, since about one year ago (in fall 1993) a current of $10 \mu\text{A}$ became available for experiments in the EMIN experimental facility. In addition the stored beam and the Internal Target Facility have been commissioned in a first phase. The programme with AmPS focuses on four main research lines.

1. High-momentum components in the single proton spectral function of many-body systems. A first result on Pb has been obtained with high missing-mass resolution that addresses the role of short range and long range correlations. Spectral functions at large missing mass (up to 100 MeV) and missing momentum (700 MeV/c) are investigated with large solid angle proton detector systems.
2. The direct observation of NN correlations by knocking out correlated proton pairs with the $(e, e'pp)$ reaction. These experiments have started recently to take data with the AmPS beam, two broadband hadron detectors and a fully operational data analysis package. The package has been developed and tested with data taken previously with a low duty-factor beam from the linac MEA.
3. Pion production and delta excitation; medium modification of these basic processes. Both the stretched (external) beam and the stored beam are used for this class of experiments.
4. The spin structure of nucleons, deuterium and ^3He . Here internal polarized targets and polarized electrons are the novel tools. A first experiment to measure asymmetries of the proton knockout process with tensor polarized deuterium has been carried out.

In the scientific programme with AmPS a total of 70 physicists are participating. Among these the Dutch participation from NIKHEF, KVI and three Universities (Utrecht, Delft and the Free University at Amsterdam) amounts to 30 physicists. The number of participating institutes from abroad amounts to 19. Therefore AmPS at NIKHEF is a truly international (user) facility where all experiments are run by international collaborations.

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