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Hadron Physics studied at TJNAF with the Electro-Magnetic and Weak probes

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Abstract. This contribution presents general features of the hadron physics program developed at the Thomas Jefferson Laboratory. This is made using the EM and Weak probes provided by the electron beams of the CEBAF accelerator and address mostly the non-perturbative regime of QCD.

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1. Introduction

Hadron physics can be studied by the means of various probes and at different energy scales. The general topics of this conference is related to the Nuclear Dynamics studied in collisions between a large variety of hadrons as projectile and targets (from nucleons to heavy nuclei) at various accelerators which allows to reach high temperatures and densities. One key goal of these programs would be the observation of the QGP in present and future experiments.

The physics cases presented in this contribution are studied at the Thomas Jefferson Laboratory (nicknamed JLab here) [1]. Experimentally, one performs precision measurements where the final state is unambiguously determined and uses electron beams accelerated at energies of some GeV. This allows to probe the Electro-Magnetic or Weak structures of the hadron studied (mostly nucleons or light nuclei), at the level of their quark structure. The fundamental questions then addressed are related to QCD and the confinement when studying elementary hadrons. It also extends to the transition between color and strong force and to the nuclear structure via studies of light nuclei. The beam quality finally allows precision experiments which are of interest for tests of the Standard Model.

2. The Jefferson Laboratory

This laboratory [1] is located in Newport News in Virginia. It hosts the CEBAF accelerator which is in operation since 1995, as well as a Free Electron Laser.

2.1. CEBAF and the experimental Halls

Among the new accelerators, CEBAF (Continuous Electron Beam Accelerator Facility) is at present a worldwide competitive machine with beam intensities up to 100 μA, 100% duty cycle, and high polarization (>70%). This was made possible with the use of supraconducting radiofrequency accelerating cavities. Based on a recirculation scheme, this accelerator can deliver beams simultaneously in three experimental halls, and with energies in the range 1-6 GeV. If one also considers the progress made on cryogenic targets and spectrometers, electron scattering experiments can now be achieved in much shorter beam time or at much larger momentum transfers than a decade ago. Finally very high quality feedback controls allows polarization and Parity Violation experiments.

Another important asset of the laboratory is the performances of its three experimental halls (A, B and C). Two halls are designed for large luminosity experiments (some 10^{38}cm^{-2}s^{-1}) with beam intensity up to 120 μA and high power cryogenic liquid or gazeous targets. The Hall A is equiped with two high resolution spectrometers, and the Hall C with a high momentum spectrometer as well as a short orbit one for the detection of short lived hadrons. Hall C is also hosting the so-called big experiments where large specialized devices are needed and for which the typical installation and running times are several months long. The G^0 experiment is the one currently running. The Hall B is very different as organized around a 4π detector (CLAS) which allows the study of reactions with several particles in the final state. Another feature of Hall B is the possibility to perform electro- but also photo-production reactions with a photon beam (of some $10^7\gamma$s^{-1}) produced by bremsstrahlung of the electron beam in a radiator and tagged with the detection the scattered electrons. The beam intensities are limited to some nA in hall B, but this is balanced by the larger solid angle covered for the detection and luminosity of some 10^{34}cm^{-2}s^{-1} is reached.

2.2. Future upgrade

The energy upgrade of CEBAF has been under consideration since several years [2]. This could be achieved with a limited amount of changes thanks to the initial design of the reciculating arcs and the performances of their RF accelerating cryomodules. With the design of new cryomodules, a 12 GeV energy electron beam could then be available in a few years timescale. The CD0, first of the necessary steps, has been signed early April 2004 by the DoE.

The new energy range covered with the upgrade should allow to extend the physics program over a broader kinematical range and to reach the charm sector.

The project also includes the construction of a new experimental hall (D) [3]. This hall, equiped in particular with a set-up producing longitudinally polarized photons, will be very well suited for the search for hybrid mesons whose exotic quantum numbers are allowed when gluonic degrees of freedom are excited. This is a key program as gluons plays an important role in the hadron structure : half the mass of the proton could be gluonic, and quark confinement being due to gluonic forces.

3. Some Physics highlights

The physics program unerway includes 150 approved experiments involving a vast international user community of more than 1000 scientists from almost 200 institutions in 30 countries.

The new generation of experiments performed at JLab have extended the existing data set at larger momentum transfer or/and improved on their precision. They have also provided new results for the valence quarks domain and on nucleon spectroscopy. Recently they have produced the most convincing case about the discovery of a new class of hadrons, the pentaquarks. Evidently only a very restricted selection of these results can be discussed in this contribution.

3.1. Nucleon's Electromagnetic Structure

Experimentally, the electromagnetic structures of the hadrons are determined by the scattering of electrons which interact with the charge and magnetic moment distributions via the exchange of virtual photons. This versatile probe, pointlike and exactly described by QED, is well suited for this study. Indeed it is possible, by changing the kinematics of the reaction (incident energy and scattering angle), to tune the distance probed in the hadronic target, but also the ratio of longitudinal to transverse polarization of the virtual photon and, for inelastic scattering, the energy transfer [4].

The nucleons are basic objects which knowledge is a natural topic of interest. Their EM internal distributions (due to their quarks) are characterized in elastic scattering by 2 form factors (Electric and Magnetic) and have been studied at JLab.

For the neutron, besides the difficulty due to the absence of a pure target, the electric form factor is much smaller than the magnetic one and polarization measurements are needed. Such measurements have been made providing a new reference data set at much larger momentum transfers Q^2 [5].

For the proton, the existing data sets obtained using a separation technique (Rosenbluth, based on forward/backward angle measurements), did state that at large momentum transfers the charge and magnetization distributions were proportional to one another. This was in agreement with the prediction of pQCD. New data [6] measured in Hall A for polarization observables did not agree with this feature and lead to infer the role of the orbital momentum in the proton's quark wavefunctions. After a check of the Rosenbluth technique at JLab, which did confirm the previous data set, it has then been postulated that the discrepancy between the two techniques could be due to the effect of 2 photons exchanged at large Q^2, more important in the separation technique than in the polarization one.

3.2. Few Body systems

One goal of the hadron physics is to reach a coherent description of the nuclear few body systems. The physics ingredients of the models are similar (NN potentials, Meson Exchange Currents, relativity) and effects like the contribution of the 3-body force can also be investigated. At large Q^2 one expects a transition to quarks degrees of freedom. In this context, JLab has provided a wealth of new results on light nuclei (A=2-4), putting stringent constraints on the models [7].

The deuteron serves as a testing ground for the tests of a variety of NN potentials and nuclear models. The recent results obtained in several experiments at JLab have improved on the precision of the existing data set and extended it at larger Q^2. The agreement obtained on the node of the elastic charge form factor with the one deduced from A=3 nuclei supports the coherent description of the light nuclei by models based on nucleonic degrees of freedom. Also the predictions of pQCD did not describe polarization data measured at rather large Q^2 and thus for short interdistances between the 2 nucleons. In cross section measurements at the largest available Q^2 (5 $(\text{GeV/c})^2$) the data tends to follow the trend predicted by pQCD, and this was also observed in photodesintegration reaction data. Confirmation of this feature at much larger Q^2, is planned with the energy upgrade of CEBAF.

3.3. PV experiments : Strange Quarks in the Proton and beyond

Besides the three valence quarks, the nucleons are also formed by the gluons exchanged and the virtual quark-antiquark pairs they create. This sea of gluons and quark-antiquark pairs actually contributes in a significant way to the properties of the hadrons (mass, spin, ...) and it is important to study its dynamics. For this study the strange quarks, the lightest non valence quark of the sea, is of considerable interest. The determination of its contribution to the charge and magnetization distributions of the proton (10% of the proton magnetic moment is typically expected) is underway at JLab. One uses the weak interaction (Z exchange), and its property to violate Parity symmetry, as a probe to disentangle this contribution from the dominant effects of the u and d quarks. The HAPPEX experiment shows that the actual contribution is smaller than expected in most models [8]. A new project G^0 [9] should extend this study in the coming years by providing the separation of the electric, magnetic and axial parts of the form factors and this over a large Q^2 range.

When achieving PV experiment with very high precision one can even provide test of the Standard Model. This is the case when measuring very precisely the weak charge of the proton (giving access to θ_W), such an experiment being under development at JLab.

3.4. DIS in the valence quark domain

The large $x_{Bjorken}$ values accessible at JLab in Deep Inelastic Scattering, not covered usually with the machines of higher energies, is related to the domain of the valence quarks. Using 5.7 GeV polarized electron beam on a polarized ^{3}He target, similar to a polarized neutron target, asymmetry data [10] were taken in Hall A. Combining these new neutron data with existing proton ones, has allowed to infer that the spins of the proton's two valence up quarks are aligned parallel to the overall proton spin but anti-aligned for the down quark. This result disagrees with predictions from an approximation of perturbative quantum chromodynamics (pQCD), not accounting for the quarks' orbital angular momenta. At variance, the results agree well with predictions from relativistic valence quark model, which this time consider the orbital angular momenta of the quarks in the nucleon.

If DIS performed in exclusive reaction addresses the quark distributions, exclusive measurement when performed in the right kinematical domain can provide much more detailed information, i.e. correlations between quarks [11]. These new structure functions, the GPD's, are studied at present at JLab but this field will clearly benefit from the CEBAF upgrade.

3.5. Nucleon spectroscopy

As the proton is made of three spin-1/2 quarks, its "atomic" excitation spectrum must contain a certain number of levels with given quantum numbers. At present many low-lying states expected in this framework are not observed and might then be missing. Recent data from the CLAS detector in Hall B shed new light on this situation thanks to its large kinematic coverage and the high duty cycle of the CEBAF beams. In the region around 2 GeV in excitation, where many of the missing states are located, a large number of events are seen in the omega channel, consistently with theoretical predictions. The second feature of the data is that their quality should allow to perform the phase shift analysis essential to identify the missing states [12].

3.6. Search for exotic hadrons

Nucleon spectroscopy has received renewed attention following theoretical predictions on the existence of the pentaquarks, a new class of hadrons and part of an antidecuplet. Such a pentaquark, the Θ^+ resonance, was first recently observed in SPRING8 in Japan at the mass location predicted, and later in old set of data reanalyzed with guidance of these predictions. However the data of JLab in photo-production reactions measured on both proton and deuterium targets have at present provided the largest significance to support such a discovery [13]. Experiments are underway worldwide, but JLab is developing a coherent and steady effort to first enhance the statistics on the observed peaks, but also to find the predicted partners and in a second generation of measurements establish the quantum numbers and parity of these states.

4. Conclusions

Hadron physics studied with the EM and Weak probes have made considerable progress these last years. This is due on the experimental side to the operation of new accelerators with large duty cycles and high intensities. New developments also occur on the theoretical side in QCD based models, relativistic calculations and also, thanks to increase of CPU, new predictions are available from Lattice QCD calculations. This should thus permit a better understanding of the color/strong force. In this context this talk has presented, after an overall description of the CEBAF machine and the associated experimental halls and their standard or specialized equipments, some highlights of the results obtained at the Jefferson Laboratory.

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