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Authors
Moltz, Dennis M.
Griffioen, K.A.
Bibber, K. Van

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D.M. Moltz, K.A. Griffioen, and K. van Bibber

November 1992
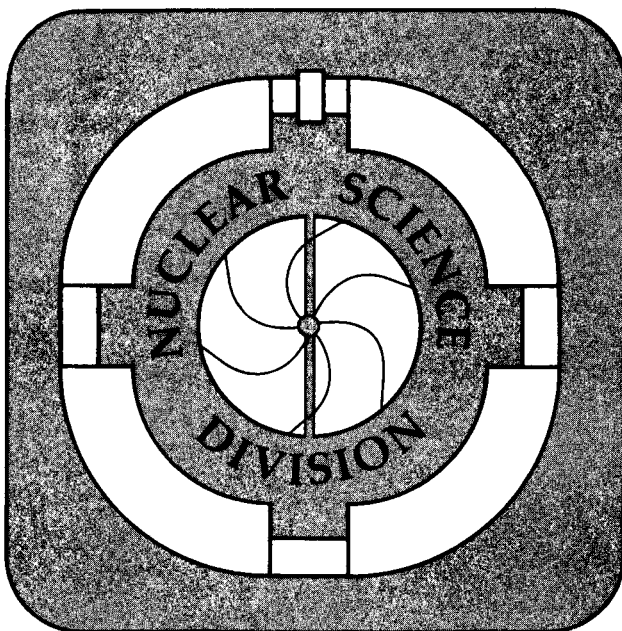
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Electron-Nucleus Collisions

D. M. Moltz
Nuclear Science Division
Lawrence Berkeley Laboratory
Berkeley, CA 94720 USA

K. A. Griffioen
Department of Physics
University of Pennsylvania
Philadelphia, PA 19104 USA

K. van Bibber
Physics Division
Lawrence Livermore National Laboratory
Livermore, CA 94550 USA

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Problems: Relativistic Nuclear Physics and Quantum Chromodynamics

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D. M. Moltz
Nuclear Science Division
Lawrence Berkeley Laboratory
Berkeley, CA 94720 USA

K. A. Griffioen
Department of Physics
University of Pennsylvania
Philadelphia, PA   19104 USA

K. van Bibber
Physics Division
Lawrence Livermore National Laboratory
Livermore, CA 94550 USA

Abstract

Much is understood about the interaction of both high energy electrons with nucleons and lower energy electrons with nucleons and nuclei. Although a number of experiments involving high energy inelastic scattering of electrons from quarks bound in nuclei have been performed, many interpretations of the data are still discussed. A project called PEGASYS was conceived at PEP to further investigate this physics. Unfortunately, the termination of PEP operations curtailed this experiment and much of the physics remains unexplored. In this paper we present some details of one proposed part of this project (tagged nuclear structure functions) and some considerations made in designing a detector suitable for observing very low momentum nuclear fragments around a cold-cluster gas target.

1. Physics Motivation

At the outset it is important to briefly review the physics that motivated the design of a general state-of-the-art vertex dectector suitable for observing nuclear fragments produced in high-energy lepton-nucleus scattering. A more complete review can be found elsewhere [1]. We wish to ask the questions: what happens when a high-energy lepton scatters off a quark bound in an atomic nucleus, how are the quark distribution functions affected by embedding a nucleon in the nuclear medium and how does the nucleus itself respond to the ensuing hadronization process? In order to study these effects, one must measure in the deep-inelastic regime which requires beam energies ≥ 10 GeV.

These measurements would be part of a larger program studying hadronization, Compton scattering, exclusive pion production, higher twist effects, nuclear transparency, searches for unusual particles such as dibaryons, intrinsic charm measurements and structure functions tagged on nuclear decay.

The physics motivations for a general-purpose vertex detector include the following:

Short range correlations [2]: If an electron scatters from one nucleon in a correlated pair of nucleons, the spectator is typically liberated with a momentum greater than the nuclear Fermi momentum. Backward-going protons with energies between 50 and 300 MeV are excellent candidates for correlations and must be measured in coincidence with the scattered electron.

Δ-degrees of freedom: To reconstruct slow-moving Δ's liberated from a nuclear target we must be able to identify pions with energies less than 200 MeV. One possible application is to look for double-Δ components in the deuteron wave function.

Evaporation: If a nucleus comes into statistical equilibrium after being heated by hadronization, one can measure the extent of the heating by observing the energy spectra of evaporated light particles (p, d, t, ^{3}He and α). Low-energy thresholds for protons and alphas should therefore be close to the corresponding Coulomb barriers in a small nucleus like ^{14}N (~1-3 MeV).

Multifragmentation: If the hadronization process heats a nucleus to very high temperatures, the nucleus may break into a number of heavier fragments. Measurement of energy distributions and multipicities of these light nuclei such as Be will extend measurements of deposited energy to larger values. The low-energy threshold for Be will be 10 MeV.

Recoiling light nuclei: Another method for selecting high-momentum nucleons from a light nucleus like ^{4}He is by observing the ^{3}He recoil. If the

struck neutron had a momentum of 300 MeV/c, the ^{3}He would acquire 16 MeV kinetic energy.

All of these requirements point to very low-energy thresholds and good energy resolution which is possible only with a segmented detector.

2. PEGASYS and the Vertex Detector

The PEGASYS collaboration consisted of more than 20 institutions. The spectrometer design evolved to that depicted schematically in Figure 1.
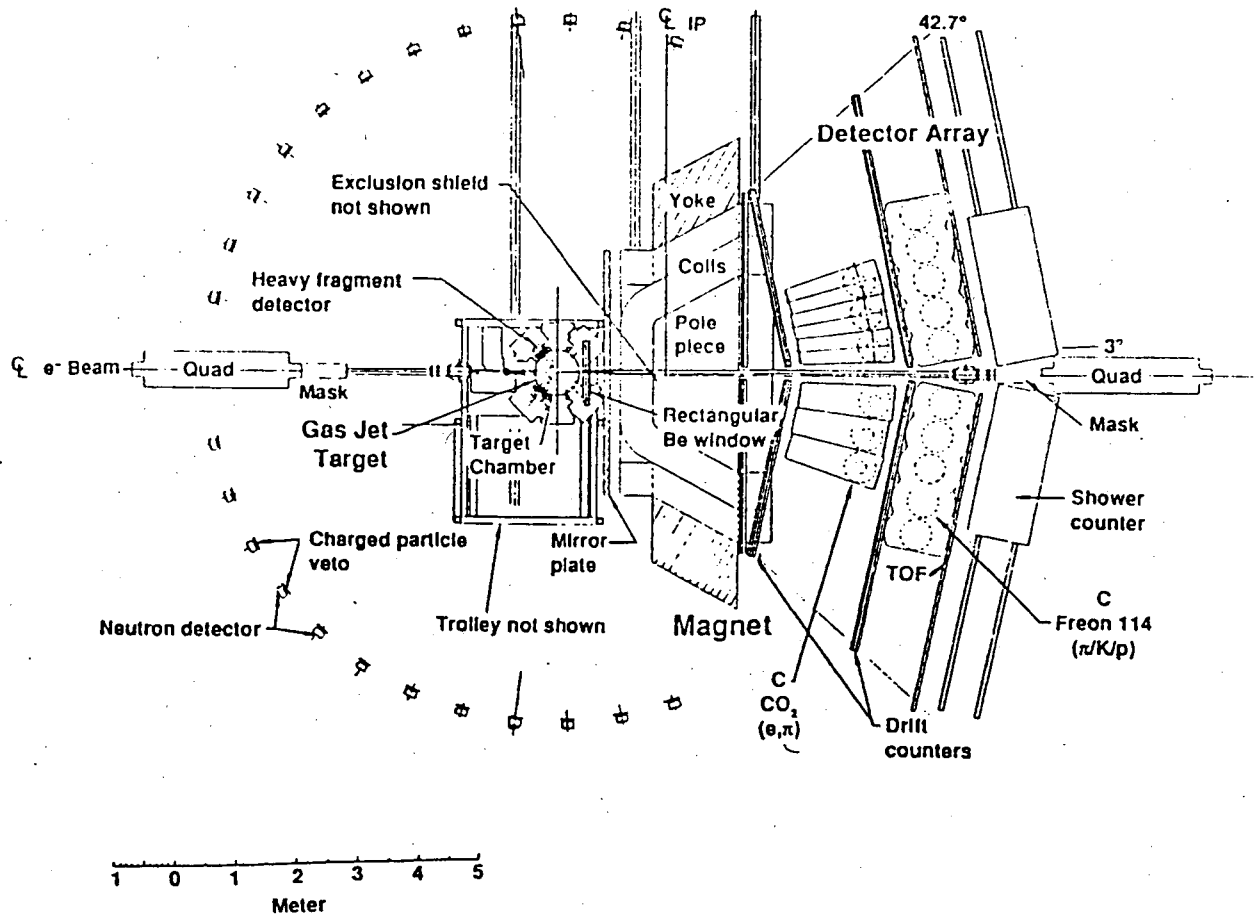
Figure 1. Schematic diagram of the proposed PEGASYS spectrometer (top view).

Large muon chambers were later added to the design at the back of the system. The essential elements of this system included a cold-cluster gas target (modeled after the GSI-ESR gas target system) which had the feature that any one target cluster would have at most one interaction with the circulating beam. The spectrometer, downstream from the target, consisted of detectors suitable for identifying and tracking the inelastically scattered electron as well as all high-energy hadrons and leptons within the spectrometer acceptance angles (different in x and y). The complete design details may be found elsewhere [1]. We shall concentrate, however, on the properties of the heavy-fragment vertex detector which is relevant for any experiment requiring particle identification and energy determination over the wide range discussed below.

The requirements for the vertex detector were as follows: coverage of as much of 4π solid angle as possible, the ability to sustain large counting rates (~50 kHz), particle identification to distinguish electrons, pions, protons and heavy ions, and sufficient granularity to permit accurate multiplicity determination. Additionally, the system had to be modular, radiation hardened and compatible with long term operation in a synchrotron radiation environment. Because of the severe restrictions placed on the overall design by the incoming and outgoing beams and the gas target assembly, the stadium design shown in Figure 2 was utilized. This detector layout yields a granularity of 48 units in two basic shapes. Figure 3 shows the cross section of a single detector unit consisting of a gas-Si-CsI-plastic scintillator hybrid detector with a dynamic range for identified protons between 1 and 300 MeV. The total energy range observable for other spectators can be scaled from these numbers.

This design for a single module was driven by the need to observe very low energy particles in the backward hemisphere. A simple silicon-CsI detector would have a 5 MeV threshold for protons for any silicon counter that was thick enough (300 μm) to have a sufficiently small capacitance so as to minimally affect the intrinsic resolution. This implies a threshold of more than 500 MeV for neon; this was deemed unacceptable. Gas counters have been used for heavy-ion identification for many years. However, the large ranges in the gas and the parallel Frisch grid constructions generate unacceptably long charge collection times. Fortunately, work has progressed on a gas-based detector suitable for detecting and identifying protons with energies down to 250 keV [3]. By utilizing this detector design at a higher gas pressure and thicker HAVAR entrance window (higher gas pressure operation reduces the Landau tailing, thereby improving the particle identification capabilities; the higher gas pressure necessitates the use of a thicker entrance window), the 1 MeV threshold is easily achievable. The choice to use CF_4 as the detection gas is based upon the observed short charge collection times (< 1 μs) in the proportional counter mode. CF_4 also has the
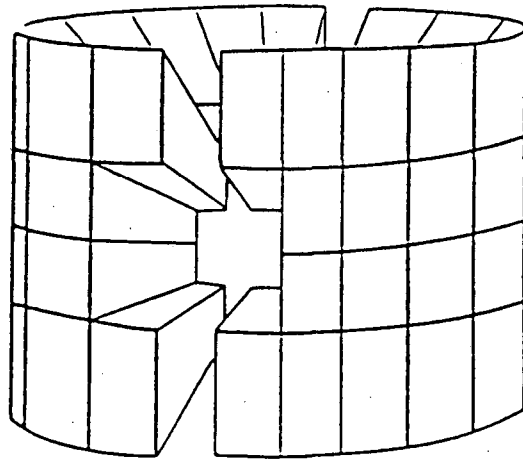
(a) Perspective
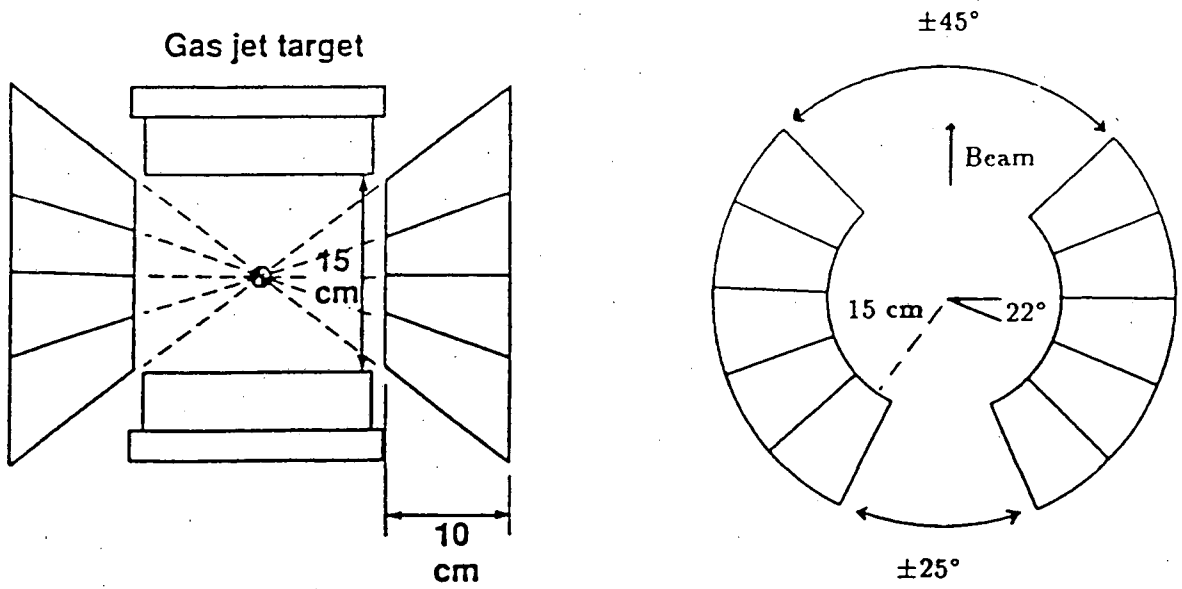
Gas jet target

(c) Side view (beam into page)

(b) Top view

Figure 2. Overall geometric design of the nuclear-fragment detector. Each module of roughly square cross sectional area fits into a cylindrical form surrounding the gas-jet target. Openings are left for the entrance of the beam and for the exit to the spectrometer.

Hybrid Module

Au-plated W grid wires

0.13 mm Al

HAVAR Window

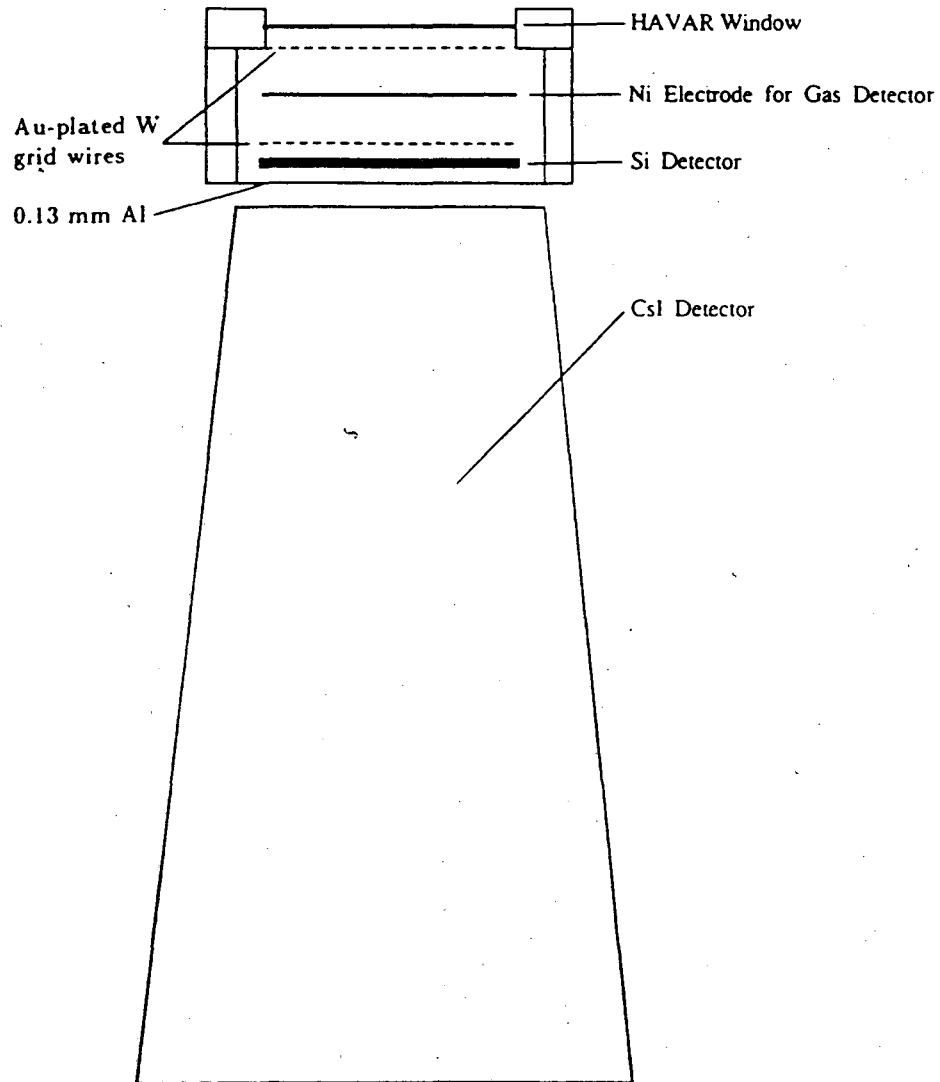Ni Electrode for Gas Detector

Si Detector

CsI Detector

Figure 3. Schematic diagram of an individual module, which consists of a thin gas counter followed by a silicon detector and the CsI crystal. The plastic scintillator to be used as a veto counter is not depicted.

advantage of containing no hydrogen which can yield a significant proton background from n-p reactions. Because the gas counters utilize a continuous gas flow, they are insensitive to the long-term radiation environment.

Large silicon detectors (≤ 100 cm^2) of almost any shape are now commercially available in 300-500 μm thicknesses. The neutron damage profiles of ion-implanted silicon detectors has been well characterized; this damage can be offset by cooling the silicon detectors to -20 C. Damage due to large electron and photon fluxes are minimal because they do not change the impurity levels in the crystal. A material with a large stopping power is required for measuring the energy of higher energy protons (≤ 100 MeV). We decided to utilize CsI scintillators ~10 cm thick instrumented with photodiodes. This relatively inexpensive material can be operated outside of the detector vacuum system making each of these units individually replaceable. The vacuum wall between the silicon and CsI detectors effectively cuts out only about 200 keV of proton-energy range near the stopping energy in the silicon counters. Finally, a small plastic scintillator was placed at the rear of each triples telescope to act as a veto counter for particles passing through the CsI detectors.

3. **General considerations**

With the module design finalized, a few more general issues were considered. Radiation damage (particularly to the CsI) has been previously characterized. Placing the CsI elements outside of the vacuum, which allows their retraction during the beam fills of the storage ring when most of this damage occurs, limits the radiation absorbed by the scintillator to aceptable levels. Prior knowledge about the quality of these fills suggested a running time of about two years before the CsI detectors would be 50% degraded. The anticipated total detector counting rate was divided into three components: hadrons, photons and Moller electrons. Previous fixed target experiments (e.g., NE11 at SLAC [4]) have observed inclusive pion cross sections. Scaling these rates for a storage-ring experiment with luminosities ~10^{33} cm^{-2} s^{-1} yields a total hadron counting rate on the order of 1 kHz. The photon rate with appropriate shielding would be similar to this; this estimate is based upon a simple radiation dosimeter measurement taken at the surface of the PEP beamline[5]. Neither rate constitutes any problem for these telescopes. The expected detection rate for Moller electrons in any module could well exceed 10^8 /sec. Therefore the design required Helmholtz coils to curl up all Moller electrons with energies below ~ 10 MeV. It should also be noted that RF heating would not be a problem because the windows would be made from the metallic alloy HAVAR.

As a test of overall detector performance we have simulated the reconstruction of the mass of the Δ resonance. Since this stadium design covers approximately 2π in solid angle, we can detect these two particles in coincidence about 25% of the time. Figure 4 shows the width of the reconstructed Δ invariant mass peak as a function of pion energy resolution assuming the proton is detected with 10% energy resolution and that the Δ has no intrinsic width. The Monte Carlo simulation gives a random Lorentz boost along the beam direction to the Δ. Clearly for pion energy resolution

better than 30%, the width of the Δ mass peak due to experimental effects only just approaches the intrinsic width of the Δ.
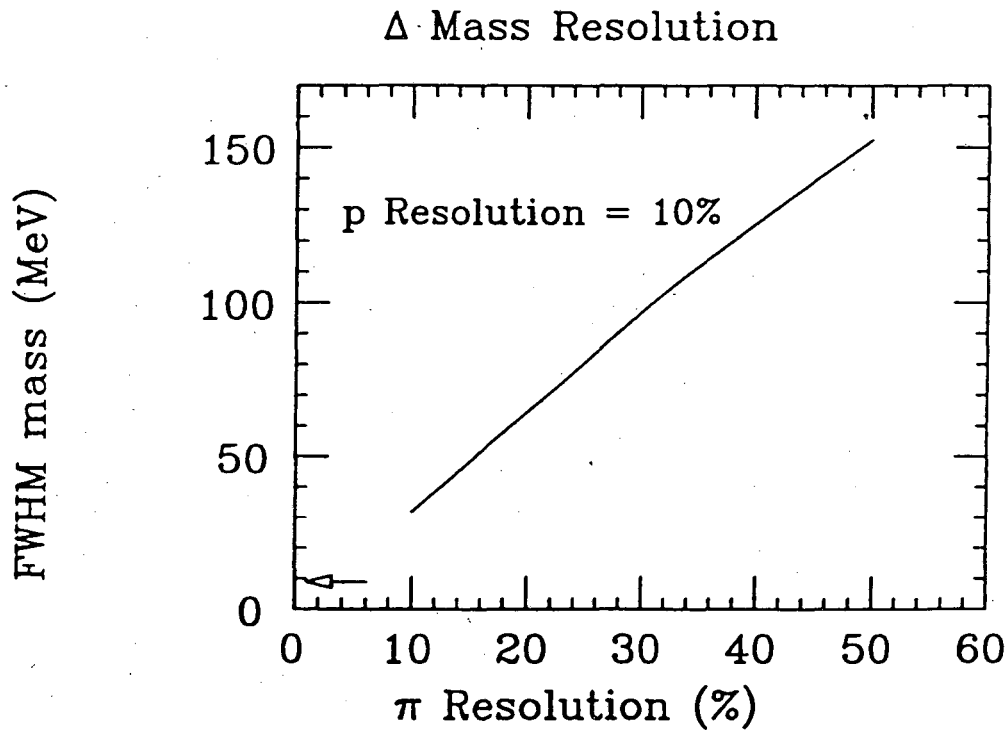
Δ Mass Resolution

Figure 4. FWHM of the reconstructed Δ mass for various values of the p and π energy resolution. The arrow indicates the point for perfect energy resolution; this shows the effect of the finite angular resolution. The intrinsic width of the delta (~100 MeV) is not included in this calculation. Thus for any reconstruction resolution < 100 MeV, the experimentally observed Δ resolution will not be much larger than the intrinsic Δ width.

These detector modules could be incorporated into any system with similar stringent requirements for particle identification and energy determination. The primary drawback to this design is the large expense associated with the electronics for each channel. These detriments are, however, easily outweighed by the tremendous dynamic range of a telescope such as this.

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LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
TECHNICAL INFORMATION DEPARTMENT
BERKELEY, CALIFORNIA 94720