Physics Program and Experimental Equipment at CEBAF

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Abstract. The initial complement of experimental instrumentation and the physics program at CEBAF are discussed. Using the power of the electromagnetic and neutral weak interaction, the structure of light quark mesons, baryons and light nuclei will be studied utilizing high duty cycle electron and photon beams with energies up to 4 GeV.

1 Introduction

Electron scattering as a probe of the internal structure of nucleons and nuclei has been employed for several decades, mostly in inclusive reactions and using low duty cycle machines. Experiments in the deep inelastic regime revealed the quark substructure of the nucleon, and more recently showed that the spin structure of the nucleon is more complicated than originally anticipated.

A more detailed understanding of the structure of nucleons and nuclei requires the measurement of more exclusive channels. For example, the study of the excited states of the nucleon requires the identification of spin, parity, and isospin of a state, which can only be accomplished by studying the resonance decay channels, and therefore requires exclusive measurements. In the past, low duty cycle machines have limited exclusive experiments to a few processes, mostly single pion production, and to restricted kinematics.

The construction of high current, high duty cycle electron accelerators has changed this situation in a significant way. Electromagnetic processes may now be studied with statistical sensitivities comparable to hadronic reactions. This brings to bear the full capability of the electromagnetic interaction as a probe of the internal structure of hadrons and nuclei.

2 The Accelerator and the Initial Experimental Equipment

The CEBAF electron accelerator is based on superconducting rf cavities operated in a continuous wave (cw) mode. A schematic of the machine is shown

Figure 1. Schematics of the CEBAF accelerator.

in Fig. 1. Two parallel linacs in a "race track" configuration boost the beam energy by 800 MeV for each turn. The beam is recirculated five times to reach an initial maximum energy of 4 GeV. The heart of the machine are the five-cell niobium cavities, which have a minimum gradient of 5 MeV per meter. The cavities perform significantly better than the specifications, therefore providing the technical basis for a future energy upgrade. The machine can deliver electrons to 3 experimental areas (Hall A, B, C) at either the same energy, or at multiples of 1/5 of the end energy. Due to the virtual lack of synchrotron radiation, the energy spread in the beam is $\Delta E/E \leq 10^{-4}$. Beams can be extracted at each recirculation, thus allowing the operation of the experimental halls with simultaneous beams of different, though correlated, energies. The 1.5 GHz rf structure allows simultaneous beams to be delivered to the halls at a frequency of 500 MHz. The micro bunches can also be loaded with different electron densities, which provides the basis for operating the experimental areas with currents spanning a large dynamic range. In addition, a polarized electron gun can be operated in parallel with the standard thermionic unpolarized gun.

The halls are equipped with spectrometers for complementary experimental programs (Fig. 2). Hall C, which is already fully instrumented, contains two magnetic spectrometers of medium resolution with $\delta p/p \leq 10^{-3}$ but different maximum momenta: the High Momentum Spectrometer (HMS) has a maximum momentum of 7 GeV/c, and the Short Orbit Spectrometer (SOS) of 1.8 GeV/c, respectively.

Hall A will house two high resolution spectrometers (HRS) with $\delta p/p \leq 10^{-4}$ and a maximum momentum of 4 GeV/c, instrumented for electron and hadron detection, respectively. The spectrometers are expected to be operational in spring 1996.

Figure 2. The initial equipment in the experimental halls.

Hall B will house the CEBAF Large Acceptance Spectrometer (CLAS) and a tagged photon facility. CLAS is based on a multi-gap magnet with six superconducting coils, symmetrically arranged to generate an approximately toroidal magnetic field distribution. Each of the six sectors is instrumented with drift chambers, time-of-flight counters, Cerenkov counters for electron identification, and electromagnetic calorimetry for photon and neutron detection. Completion of hall B is expected in the fall of 1996.

3 Structure of the Nucleon.

The interest in the structure of the ground state nucleon, its excited states, and their role in nuclear properties has dramatically increased in recent years and is one of the major motivations in support of the experimental program at CEBAF. The structure of the nucleon may be probed in elastic electron nucleon scattering and in inelastic reactions induced by electrons or photons. These experiments measure the charge and current distribution of the nucleons and the transition currents to their excited states. Knowledge of these quantities allows testing of models describing the nucleon structure at low and intermediate energy and momentum transfer. With increasing momentum transfer Q^2 , the transition from the non-perturbative regime to the perturbative regime can be studied, where simple quark counting rules and power law behavior may apply [1].

More than half of all approved experiments at CEBAF address questions related to the structure of light baryons and mesons some of which either require measurement of spin observables, or the sensitivity to fundamental quantities is increased significantly in spin observables. Polarized electron beams, polarized targets, and proton and neutron recoil polarimeters will be important tools in these studies.

3.1 Electromagnetic Form Factors.

In elastic electron nucleon scattering the hadronic current may be specified by the electric and magnetic form factors $G_E(Q^2)$ and $G_M(Q^2)$. The usual technique for measuring the elastic form factors is the Rosenbluth separation, where one makes use of the different angular dependence of the electric and the magnetic term in the unpolarized elastic cross section to separate $|G_E|$ and $|G_M|$.

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega} \right)_M \frac{E'}{E} [(G_E^2 + \tau G_M^2) + 2\tau(1 + \tau)G_M^2 \tan^2 \frac{\theta}{2}] \quad (1)$$

where $\tau = \frac{Q^2}{4M^2}$. This technique ceases to be useful, when either $G_E^2 \ll G_M^2$, or at high values of Q^2 , where the magnetic contribution dominates both the angular dependent and the angular independent term. Unlike for the proton, the Rosenbluth separation of G_E^n from G_M^n for a neutron target is difficult even at low Q^2 , because of the small size of G_E^n compared to G_M^n . At $Q^2 < 1 \text{ GeV}^2$, G_E^n has been extracted from elastic electron-deuteron scattering data assuming a model for the deuteron structure [2].

A model-independent determination of G_E^n can be obtained by measuring the polarization asymmetry

$$A_{en} = \frac{2\tau \cos \theta v'_T + 2\sqrt{2\tau(1 + \tau)} \cdot (G_E^n/G_M^n) \sin \theta \cos \phi v'_{TL}}{v_L(1 + \tau)(G_E^n/G_M^n)^2 + 2\tau v_T} \quad (2)$$

where v_L , v_T , v'_T , v'_{TL} are known kinematic quantities and ϕ and θ define the orientation of the nucleon spin relative to the scattering plane. From the

Figure 3. Projected data for a measurement of G_E^n using a polarized ND_3 solid state target.

asymmetry, the ratio G_E^n/G_M^n can be extracted. Knowing G_M^n the electric form factor can be determined. One method uses a polarized deuterium or ^3He target, either as an ultra thin gas target in an electron storage ring, or a solid state target ND_3 , or a dense ^3He gas target, in an external electron beam. If the polarization asymmetry is measured using vector polarized deuterium, it will be necessary to measure the recoil neutron in coincidence with the scattered electron to eliminate the much larger contributions from the polarized proton in the deuteron. The binding of the neutron in the deuteron has negligible effect on the polarization asymmetry and on G_E^n/G_M^n , as long as the recoil neutron is emitted at small angles with respect to the direction of the virtual photon [3].

A second method uses an unpolarized deuterium target, and the polarization of the recoiling neutron is measured in a second scattering experiment. Both methods will be employed at CEBAF [4] to measure G_E^n/G_M^n for Q^2 up to 2-3 GeV^2 (Fig. 3). In both cases, the scattered electron will be detected in the hall C HMS spectrometer, and the neutron will be detected in a narrow cone around the direction of the virtual photon. One experiment uses a polarized ND_3 solid state target, while the other one uses a plastic scintillator based polarimeter to measure the polarization of the recoil neutron.

The polarization techniques can also be employed to measure the electric form factor G_E^p of the proton. Most promising in this respect is the recoil polarization techniques using an unpolarized hydrogen target [5]. With a 4 GeV beam G_E^p can be measured for Q^2 up to 5 GeV^2 , with statistical errors of less than 5%.

Our knowledge of the magnetic form factor of the neutron is also unsatisfactory. Quasi-elastic electron scattering off deuterons appears to be the most promising way to determine G_M^n at high momentum transfers. Two experiments will measure G_M^n over a large Q^2 range [6]. A common problem is how to determine the neutron detection efficiency accurately. A large acceptance detector such as CLAS offers the possibility to determine the efficiency by measuring

the reaction $p(e, e'\pi^+)n$ using a hydrogen target, simultaneously. The neutron kinematics is completely constrained in this reaction, and can be used to determine the neutron detection efficiency. The ratio of quasi-free $e-n$ and $e-p$ coincidences allows to determine G_M^n using the known proton form factors as normalization.

3.2 Baryon Resonance Transitions.

A large number of resonances, attributed to the excitation of the nucleon have been observed in hadron scattering, the $\Delta(1232)$ being the most prominent one. Electromagnetic excitation of the resonances addresses fundamental questions about the interaction of quarks and gluons in confined systems. Specifically, one would like to study how the transition between the 3-quark ground state and excited states is mediated. Measurement of the Q^2 evolution of the transition form factors provides information about the wave function of the excited state. At high momentum transfer, one may observe the transition from the non-perturbative regime of QCD to the perturbative regime. A complete program to study nucleon resonance transitions involves measurement of polarization observables.

The lowest mass resonant state, the $\Delta(1232)$ is of special interest. In SU(6) symmetric quark models, this transition is explained by a simple quark spin-flip in the $L_{3Q} = 0$ ground state, corresponding to a magnetic dipole transition M_{1+} . In QCD based models, which include color magnetic interactions arising from the one-gluon exchange, the $\Delta(1232)$ acquires an $L_{3Q} = 2$ component, leading to small electric and scalar contributions (e.g. $|E_{1+}/M_{1+}| \simeq 0.01$ at $Q^2 = 0$). The ratio $|E_{1+}/M_{1+}|$ is predicted to be weakly dependent on Q^2 .

Experiments at CEBAF are in preparation to measure the electromagnetic transition amplitudes for the nucleon to the Δ [7], as well as to many higher mass resonances [8], over a large Q^2 range, using both unpolarized pion and eta electroproduction, as well as polarized electron beams and polarized targets or recoil polarimeters [9]. For the $N\Delta$ transition one obtains information about the terms

$$M_{1+}, \text{Re}(E_{1+}M_{1+}^*), \text{Re}(S_{1+}M_{1+}^*), \text{Im}(E_{1+}M_{1+}^*), \text{Im}(S_{1+}M_{1+}^*).$$

Projected data the $\Delta(1232)$ are shown in Fig. 4. The imaginary parts of the bilinear terms can be measured using polarization degrees of freedom.

Of topical interest are the transition form factors to the $N(1440)$, a candidate for a state with a large gluonic content [10]. Gluonic excitations of baryons are not distinguished by exotic quantum numbers from ordinary baryons. Electroproduction of these states may be the only available tool in the search for signatures of these states, as their transition form factors are expected to have very different Q^2 dependence [10].

The QCD motivated extension of the non-relativistic quark model [11] predicts many states which have not been observed in πN reactions. Several of these states are predicted to couple strongly to photons (real or virtual) and may thus be searched for in photoproduction or electroproduction experiments.

Figure 4. Data for E_{1+}/M_{1+} compared to quark model calculations. The error bars on the horizontal axis are projections of experiment E-89-037.

Search for some of these states in multi-pion and vector meson production are in preparation at CEBAF [12]. Virtual Compton scattering off nucleons $p(e, e'p)\gamma$ is also sensitive to the excitation of nucleon resonances and will be measured in an experiment using the HRS spectrometers [13]. One advantage is the absence of final state interaction, while the low rate makes it difficult to achieve sufficient kinematical coverage for a complete partial wave analysis. At small momentum transfers t to the nucleon, the reaction $ep \rightarrow en\pi^+$ is sensitive to the pion charge form factor and can directly be extracted from the longitudinal response function:

$$\sigma_L \sim -t \cdot g_{\pi NN}^2(t) \frac{F_\pi^2}{(t - m_\pi^2)^2} \quad (3)$$

where $g_{\pi NN}$ represents the πNN coupling. Much improved knowledge of $F_\pi(Q^2)$ over a large Q^2 range is expected from this experiment [14].

3.3 Parity Violation Experiments.

At low and medium energy ($Q^2 \ll M_{Z^0}^2$) neutral current interactions, the parity violating contributions arise from the interference between the one-photon exchange and the neutral weak boson Z^0 exchange graphs.

Parity violation in $\bar{e}p \rightarrow ep$ probes the strange vector current $\bar{s}\gamma_\mu s$. Sizeable $s\bar{s}$ contributions in the proton are suggested by the results of the polarized structure function experiments. The parity violating asymmetry in elastic ep scattering is given by:

$$A_{\bar{e}p} \simeq \frac{G_F Q^2}{\pi \alpha \sqrt{2}} \frac{\epsilon G_E^p G_E^Z + \tau G_M^p G_M^Z}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2} \quad (4)$$

Figure 5. Projected data for the polarized electron asymmetry $p(\vec{\epsilon}, e')p$.

In the Standard Model of particle physics:

$$G_{E,M}^Z = \left(\frac{1}{2} - \sin^2 \theta_W\right) G_{E,M}^p - \frac{1}{4} (G_{E,M}^n + G_{E,M}^s) \quad (5)$$

where $G_{E,M}^{p,n}$ are the usual electromagnetic form factors, and $G_{E,M}^Z$ are the neutral weak form factors. At large electron scattering angles the first term dominates. G_E^Z , G_M^Z can be separated by varying the electron kinematics and G_E^s , G_M^s can be determined using the known electromagnetic form factors.

Three experiments are in preparation at CEBAF to study parity violation in elastic electron scattering experiments [17]. Projected data of one of the experiments are shown in Fig. 5.

3.4 Q^2 Evolution of the Nucleon Spin Structure

The study of the spin structure of the nucleon has focussed on the short distance behavior where the measurements may be interpreted in terms of the parton structure of the nucleon. Studies of the Q^2 evolution of the spin structure functions g_1 and g_2 down to small Q^2 will give important constraints on the models aimed at describing the nucleon structure at larger distances. At $Q^2 = 0$, the Gerasimov-Drell-Hearn (GDH) sum rule constrains the slope of Γ_1 to the anomalous magnetic moment of the target:

$$\frac{2M}{Q^2} \Gamma_1 \rightarrow -\frac{1}{4} \kappa^2 \quad (6)$$

The negative value is in conflict with a simple extrapolation from the deep inelastic regime.

The GDH sum rule and its Q^2 evolution have never been studied experimentally. The only empirical information comes from the analysis of pion photo-

Figure 6. Projected data (full circle) on the double polarization asymmetry $\bar{p}(\bar{e}, e')X$ at fixed Q^2 .

and electroproduction experiments [15, 16]. There are plans to measure the sum rule at $Q^2 = 0$ for the protons and neutrons [18] using a circularly polarized photon beam and a polarized solid state target. The Q^2 evolution will be studied in three experiments [19] using polarized NH_3 , ND_3 , and ^3He targets, respectively. With information on the proton and neutron, the evolution of the Bjorken integral $\Gamma_1^p - \Gamma_1^n$ can be studied down to $Q^2 = 0$, where it should be constraint by the respective difference of the GDH sum rules. Fig. 6 shows projected data on the double polarization asymmetry using a NH_3 target.

3.5 Strangeness Production

Electromagnetic production of strange particles $\gamma p \rightarrow K^+ Y$ ($Y = \Lambda, \Lambda^*, \Sigma, \Sigma^*$) have been poorly studied in the past. Consequently, the production mechanism is not well understood. In a diagrammatic approach the process is sensitive to the $K\Lambda N$ and $K\Lambda N^*$ coupling constants. Coupling constants extracted from photoproduction data and from hadronic data disagree. Calculations indicate that the Λ polarization is very sensitive to specific ingredients of the model, in particular on assumptions about the coupling constants. Measurement of the Λ recoil polarization in photoproduction reactions will thus yield independent information about the hadronic coupling constants.

An efficient experimental program to study polarization degrees of freedom in the $K\Lambda$ channel benefit greatly from the use of large acceptance detectors with nearly 4π solid angle coverage. For example, the Λ polarization can be inferred from an analysis of $\Lambda \rightarrow \pi^- p$ decay. Using a longitudinally polarized electron beam, circularly polarized bremsstrahlung photons can be generated, and the polarization transfer reaction $\bar{\gamma} p \rightarrow K^+ \bar{\Lambda}$ can be studied as well.

Very little electroproduction data is available on $\gamma p \rightarrow K^+ \Lambda$. Similar to the π^+ production, the longitudinal cross section for this reaction may be related to

Figure 7. Missing mass distribution for $\gamma p \rightarrow K^+ X$.

the K^+ elastic form factor [20], although the model dependence is larger than for the π^+ form factor. An intriguing problem is presented by the $f_0(975)$. The state does not fit into the standard $q\bar{q}$ scheme for mesons. It is considered a candidate for an exotic $q\bar{q}q\bar{q}$ state, or a $(q\bar{q})(q\bar{q})$ molecule. If the $f_0(975)$ is a weakly bound mesonic molecule a strong t dependence may be expected in electromagnetic production. f_0 production will be studied both in the $\pi\pi$ and $K\bar{K}$ channels [21]. CLAS experiments will cover hyperon photoproduction on the proton [22] and deuteron [23], and hyperon electroproduction [24]. Figure 7 shows the expected missing mass distribution in $\gamma p \rightarrow K^+ X$ for a proton target. The Λ , Σ^0 , $\Lambda(1520)$, and a combination of $\Lambda(1405)$ and $\Sigma^0(1385)$ can be isolated.

Electroproduction of ϕ mesons probes the production mechanism as a function of the distance scale, and therefore can probe deviations from the dominantly diffractive behavior observed in photoproduction as a function of Q^2 .

4 Study of Light Nuclei

Nuclei containing only a few nucleons (≤ 4) provide the best hope for an accurate description of a nuclear system. Their study therefore provides a laboratory for the study of nucleon-nucleon interaction at short distances, relativistic effects, meson exchange currents, and possible quark effects.

4.1 Elastic Form Factors of Light Nuclei

Elastic scattering on the deuteron is described by three independent form factors. The standard Rosenbluth techniques allows to determine the magnetic form factor and a combination of charged and quadrupole (electric) form factors. Additional polarization measurements are required for a complete deter-

Figure 8. Charge form factor of ${}^4\text{He}$. Projected data of experiment E-89-021 are shown as full squares.

mination of all form factors. The magnetic and electric contributions will be measured using the spectrometers in hall A [25], while a specialized setup in hall C is required to measure the tensor polarization [26], which, at small scattering angles, is given by

$$T_{20} \simeq -\sqrt{2} \frac{\frac{3}{2}\tau G_Q(\frac{2}{3}\tau G_Q + 2G_C)}{G_C^2 + \frac{8}{9}\tau^2 G_Q^2} \quad (7)$$

Combined with the unpolarized measurements, the charged and quadrupole form factors G_C , G_Q can be determined, separately.

The charge and magnetic form factors of ${}^3\text{H}$ and ${}^3\text{He}$ have been measured up to $\sim 1 \text{ GeV}^2$ and the charged form factor of ${}^4\text{He}$ is known up to $\sim 1.8 \text{ GeV}^2$ at SLAC. Experiments at CEBAF will extend these measurements to $Q^2 \simeq 2.3 \text{ GeV}^2$ and $Q^2 \simeq 3 \text{ GeV}^2$, respectively [25]. Fig. 8 shows existing and projected data on ${}^4\text{He}$. Deviations from the diffractive pattern seen at lower Q^2 , could be a signature for quark effects.

4.2 Deuteron Disintegration

Results of experiments at SLAC on the photodisintegration of the deuteron (Fig. 9) seem to be consistent with a simple constituent counting rule behavior of the differential cross section at photon energies $> 1.3 \text{ GeV}$, and $\theta_p = 90^\circ$:

$$\frac{d\sigma}{dt} \sim s^{-11} \quad (8)$$

Figure 9. Deuteron photodisintegration cross section multiplied by s^{11} . The dashed line indicates the energy dependence expected from the quark counting rules (not normalized).

Using the HMS spectrometer the reaction will be measured [27] up to $E_\gamma = 4$ GeV. Additional information will come from a study of the proton recoil polarization [28] which is very sensitive to the reaction mechanism. At asymptotic energies QCD makes the simple prediction $P_N \rightarrow 0$. Any non-zero results would indicate that the asymptotic regime has not been reached, and the observed scaling behavior of the differential cross section must have a different origin. Information about the reaction mechanism will also come from the measurement of the angular dependence and the comparison of $d(\gamma, p)n$ and $d(\gamma, p)\Delta^0$ using CLAS [29]. Electrodisintegration of the deuteron $d(e, e'p)n$ allows probing the isoscalar and isovector parts of the hadronic current at varying distance. The HRS spectrometers in hall A will be used to separate the longitudinal and transverse contributions for protons emitted along q . A measurement of the recoil protons in the electron scattering plane but left and right of q , and for electrons scattered at forward and backward angles, will separate three response functions. This will allow stringent tests of microscopic models for this reaction [30]. Additional information about the deuteron structure and the reaction mechanism will be obtained [31] from measurement of polarization observables in coplanar $d(\bar{e}, e'p)n$ reactions. An experiment using in CLAS [32] will study $d(e, e'p)n$ for high momentum protons emitted at backward angles relative to q and probe the short distance structure of the deuteron wave function.

4.3 Hadron Emission from Nuclei

An important program in the past has been the measurement of single nucleon knockout processes such as $A(e, e'p)(A-1)^*$, where the remnant nucleus is

Figure 10. Nucleon momentum density distribution in ${}^4\text{He}$ versus missing momentum. For momenta greater than 350 MeV/c, multi-nucleon break-up becomes the dominant process.

left in the ground state or an excited state. Single nucleon densities have been measured up to ~ 600 MeV/c for the lightest nuclei, and up to ~ 300 MeV/c for heavier nuclei. At CEBAF energies missing momenta up to 1 GeV/c can be probed for ${}^4\text{He}$ using the hall A HRS [33], and the three in-plane response functions can be measured. Experiments on ${}^4\text{He}$ have shown that momenta > 350 MeV/c largely reside in multi-body breakup channels (Fig. 10), and their investigation becomes increasingly important at higher energy transfer. Using CLAS, measurements for multi-hadron final states will be carried out [34] on nuclei ranging from ${}^3\text{He}$ to ${}^{56}\text{Fe}$.

4.4 Properties of Hadrons in Nuclei

An important question in nuclear physics is how the properties of hadrons are modified in the nuclear medium. For example, the mass and decay width of vector mesons are predicted to change significantly if they are produced inside a nucleus. Masses and widths of vector mesons can be studied most effectively using the e^+e^- decay, which, in contrast to the hadronic decay, is not affected by final state interactions. Measurements of ρ and ω production are especially interesting as the short-lived ρ will decay mostly inside the nucleus, while the ω will decay outside the nucleus, and no effect should be observed in the latter case (Fig. 11). Photoproduction of e^+e^- pairs on various nuclei will be measured

Figure 11. Projected data of experiment E-94-002. The curves represent different assumption about the ρ and ω mass shifts in nuclei.

using CLAS [35].

Hadronic production of strange particles in nuclei has been studied for decades at proton machines. The electromagnetic probe has important features, which makes its use complementary to hadronic studies. First, it allows to deposit hyperons deep inside the nucleus. Second, it strongly populates unnatural parity states starting from a 0^+ nuclear target. A program at CEBAF will start with the study of the lightest hypernucleus produced in ${}^4\text{He}(e, e'K^+){}^4_\Lambda\text{He}$ using the HMS and SOS spectrometers [36]. Other experiments will require a specialized spectrometer setup with high resolution [37].

5 Summary and Outlook.

The CEBAF electron accelerator will be a powerful tool in probing the internal structure of baryons and light nuclei with unprecedented precision. The initial experimental equipment has been designed for complementary experimental programs. Already from the initial experimental program we expect significant insight into the manifestation of QCD in the confinement regime. We can also hope that limitations of the hadronic picture of light nuclei will be revealed as nuclear wave functions are probed at very short distances.

As of May 1995, the accelerator has reached 5 recirculations and a 4 GeV beam was transferred to hall C. First physics experiments are expected to run

in fall 1995. Completion of the hall A equipment is expected for spring 1996, and the instrumentation in hall B should be operational by the end of 1996.

There is an excellent possibility that the maximum energy of the accelerator will be upgraded to about 6 GeV in 1997. A further energy upgrade into the 10 GeV energy regime has been proposed [38], and appears feasible with relatively modest financial investment. This would be accomplished by installing additional accelerating cavities, and by replacing cavities with low field gradients with better performing cavities.

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