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CONF-8010138--2
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A. Evolution of Photonuclear Physics

FUTURE INVESTIGATIONS IN ELECTROMAGNETIC

NUCLEAR PHYSICS*

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ABSTRACT

Some basic problems in nuclear physics which may receive positive response from electro- and photonuclear research, are discussed. Future directions for this research are outlined and some specific experimental proposals compiled by a study group under the sponsorship of the Bates (MIT) Users Group are described.

*This work is supported in part through funds provided by the U.S. DEPARTMENT OF ENERGY (DOE) under contract DE-AC02-76ER03069 and the National Science Foundation.

**Permanent Address

Invited talk presented at the Symposium on Perspectives on Electro and Photonuclear Physics, Saclay

October 1980
CTP #884

It is possible to follow the evolution of electrons and photons as probes of the nuclear medium by means of a cursory examination of the Proceedings of International Conferences on Photonuclear Reactions.

The origin of photonuclear investigations can be traced to the 1950's and the measurements of nuclear charge distributions.¹ In the early 1960's, the major concerns revolved around measuring the cross sections for (γ, n) , (γ, p) and (e, e') reactions at the giant resonance region or close to it. From the theoretical point of view the mechanism for giant resonance excitations, and the quasideuteron effect, in addition to testing nuclear models, became subject of rigorous investigations.² Later in the 1960's, with the availability of beams of higher energy, new lines of research opened up in terms of pion and vector meson photoproduction, production of isobaric resonances and the nucleon electromagnetic form factors.³

In the early 1970's,⁴ it is mesonic exchange currents (MEC) and their role in modifying single-body charge and magnetization densities that mark an important stage in photonuclear investigations. In addition, photonuclear and electronuclear sum rules and their link to nuclear dynamics were added to the constantly expanding list of photonuclear investigations. In the mid 70's, we begin to hear about experiments in deep inelastic scattering.⁵ Quasi-elastic scattering and coincidence experiments begin to provide detailed information on electric and magnetic excitations.

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Finally, the proceedings of the conference in Mainz, June 1979, on Nuclear Physics with Electromagnetic Interactions⁶ provide an almost complete map of the photonuclear field. What is striking about this map is that it shows that virtually all the topics introduced since the origin of the photonuclear investigations in the 1950's are still under active investigation. A pessimistic interpretation of this circumstance may be that it reflects the inability of the electromagnetic probe to reveal in a definitive way the structure of nuclei and the dynamics that are in operation in the nuclear medium. An optimist on the other hand, would see in the multitude of research lines that have opened up since the '50's and remain open now, a reflection of the versatility of the electromagnetic probe. I tend to side with the latter view and suggest in addition that what is needed now is a great deal of hard work both experimentally in terms of increased accuracy in the data and theoretically in terms of devising imaginative ways to utilize photonuclear data.

Whether we are concerned with the deuteron or with more complex nuclei, the fundamental problem in nuclear physics is the nature of an interacting nucleon pair. We should be reminded of the fact that the models of the N-N interaction constructed on the basis of either NN scattering or the deuteron static properties are completely inadequate to explain even the simplest of properties of complex nuclei, as for example the density in the nuclear interior. Whatever success we have had in describing nuclear ground or excited states so far, it has been achieved by means of quasi-empirical forces that are not always obviously related to the NN interaction for free nucleons. Binding obviously changes the nature of the interacting

pair. It is of course an accepted fact supported by some experimental evidence that in a nuclear bound state there are at least pions and nucleon resonances in the medium, besides nucleons. There are however two important questions to be asked and ultimately answered. First, the non-nucleonic components of the nucleus are elements of the NN interaction in the medium; what then is the dependence of the interaction effect on internucleon separation? Clearly, the answer involves an understanding of both the production and the propagation of non-nucleonic components in the nucleus.

Second, how does the structure of the nucleons themselves, e.g., their size, sphericity and the possibility of their having constituent components affect their mutual interaction when they are forced to overlap or at least to exist at very close proximity to each other as it is certainly the case in the interior of nuclei? Are there additional non-nucleonic components that materialize under these conditions?

There is hardly a better probe to use in attempting to answer these questions than real photons or virtual photons from electron scattering. We may be reminded again that the entire nuclear volume participates in the charge scattering of electrons and hence the nuclear response function in this scattering, provided it can be separated from magnetic scattering, is an ideal tool to investigate the second question, e.g., the nature of the nucleon pair at very short separation in a bound state.

B. Future Directions

Having formulated these two fundamental questions in nuclear dynamics, we must now search for ways to reach for answers. A study group organized under the auspices of the Bates (MIT) Users Group⁷ has been attempting for about a year now to chart promising lines for future research in electro- and photonuclear physics so that these and other questions of nuclear dynamics and structure may be answered. Underlying this organizational effort is the notion that the NN interaction is central to the problems of nuclear physics.

A broad outline of the research proposed by the study group is presented in Table 1.

I summarize below some of the objectives to be attained by this research.

- $(e,e'N)$ experiments which specify the momentum of the electron and nucleon with good energy resolution, determine the transition of the residual nucleus to discrete final states whose wavefunction can then be tested against theory. At high energies for the nucleon, final state interactions do not play an important role.
- Disintegration near threshold (inclusive (e,e') but with large momentum transfer is sensitive to the high momentum components of the nuclear wavefunction and hence the short-range part of the NN interaction.

- Photo absorption via the quasi-deuteron process can give information on NN correlations in both the initial state when the pair is in the nuclear medium and in the final state.
- Magnetic and electric structure functions of the nucleus are sensitive to meson currents and/or relativistic effects. It is often useful to separate these two effects.
- The study of isobars will provide answers to the question of how important they are in the description of the NN force.
- Hypernuclei formed via $(\gamma, K^{+}, 0)$ processes will allow for the study of N- Λ interactions.
- Photoproduction of vector mesons will test coupling constants, the vector meson dominance model and details of the production amplitude.
- Magnetic form factors of very light nuclei give important information on the nuclear wave function.
- Parity-violating nuclear processes can be of fundamental importance in testing models of weak interactions, in particular the structure of neutral currents.

- While the signature of quark components of nucleons is usually thought to become apparent at very high energies, it is imperative to answer the question whether we can understand the short and intermediate range of the NN force and low-energy nuclear processes without explicitly invoking quark degrees of freedom; there are some indications already that inclusion of quark components or, at least, an explicit incorporation of the extended nature of nucleons in nuclear reactions is a necessity.

The study group has solicited proposals on specific electro- and photonuclear experiments that may yield the required information on the subjects which, in the opinion of the group, constitute the future of electromagnetic interactions. I shall review below several of these proposals. As it will soon become clear, carrying out some of the proposed work will require experimental facilities which are not presently available, hence, one of the logical outcomes of this planning effort is that it provides support for building at least one new electron facility of CW type, suitable for nuclear physics research but capable of delivering energies up to about 2 GeV.

SPECIFIC PROPOSALS

1. NN Correlations by Means of Quasielastic Scattering⁸

An accurate determination of the entire quasielastic spectrum for ${}^2\text{H}(e,e')np$ is proposed including the tail of the peak that stretches into the region of pion production. With the deuteron as a target, it is probably sufficient to do an $(e,e'p)$ coincidence experiment in the scattering plane⁹ and integrate experimentally over the proton angle in order to obtain the cross section $d^2\sigma/d\Omega_e dw$, where w =energy transfer, free from contamination from π -production events.

A Rosenbluth separation of the charge-scattering part of the cross section $\left(\frac{d^2\sigma}{d\Omega_e dw}\right)_C$ with an accuracy of 5% will allow us to compare against the standard Yukawa NN interaction theory including relativistic effects. A difference of 20% between experiment and theory can be interpreted with some certainty as evidence that there are serious problems with the Yukawa theory of the NN interaction via meson-exchange at intermediate as well as short range. Discrepancies of smaller magnitude on the other hand, will suggest that we may pursue the meson exchange theory and attempt to determine the short range NN correlations in coordinate space. The

integral $\int dw \left(\frac{d^2\sigma}{d\Omega_e dw}\right)_C / \sigma_{\text{mott}}$ is proportional to the deuteron structure function $s(q)$ ¹⁰ which in turn is the Fourier transform of the NN correlation function $\rho(r)$, where r =internucleon separation. It has been determined¹¹ that for an accurate evaluation of $\rho(r)$ to about

$r=0.5$ fm,, we should know $s(q)$ with an accuracy of 1% up to $q \leq 3$ fm $^{-1}$ and 3% for $3 \leq q \leq 4.5$ fm $^{-1}$. It is precisely this small experimental uncertainty that makes this a very difficult experiment. On the other hand, the value of the information that may be derived from it makes it worth pursuing. It is to be noted that for $q \leq 4.5$, scaling for the nucleon form factors has been shown experimentally to be valid¹² so that within this range of momentum transfer, we have no substantive uncertainties coming from these quantities.

2. Measurements of Nucleon Electric Form Factors

Should the Yukawa theory of the NN interaction prove viable at all separation distances, then the previous $^2\text{H}(e,e'p)n$ experiment at higher values of q^2 can be used for the determination of nucleon electric form factors beyond the value of q^2 where scaling seems to break down. For adequate Rosenbluth separations we would need electron beams of energy 3-4 GeV.

A second method for measuring nucleon electric form factors is by scattering longitudinally polarized electrons from hydrogen or deuterium. The information can be extracted from the polarization of the recoiling nucleon measured via the asymmetry following a second scattering. The relationship is

$$\frac{d^2\sigma}{d\Omega d\Omega_2} = \frac{d\sigma}{d\Omega d\Omega_2} \bigg|_0 [1 + a_p A_y \sin\psi_2]$$

where a is the electron polarization, $\frac{d\sigma}{d\Omega d\Omega_2} \bigg|_0$ is the double scattering cross section for unpolarized electrons and ψ_2 = azimuthal angle between the two scattering planes; A_y is the analyzing power of the second scattering. Finally the polarization

$$P_x = \frac{-2\sqrt{\tau(1+\tau)} G_E G_M \tan \frac{1}{2}\theta}{G_E^2 + \tau G_M^2 (1+2(1+\tau) \tan^2 \theta/2)}$$

is proportional to G_E .

It is estimated that 1% statistics will allow the evaluation of G_E within 10%.

3. Low Energy Quasielastic Scattering from ^1H , ^3He , ^4He ¹⁴

High momentum components of the nuclear wavefunction contribute primarily to the wings of the broad quasielastic peak. The use of ^3H and He isotopes in these experiments is recommended because the central density in these nuclei is sufficiently large to guarantee the presence of a great deal of high momentum components. In addition the possibility that quasielastic cross sections are subject to scaling will be explored by means of the same data. The kinematically favorable conditions are high momentum transfer and low energy transfer.¹⁵

4. Coincidence Electroproduction from Light Nuclei¹⁶

The prototype for these experiments is the reaction $\Lambda(e,e'a')X$, where $a' = \pi, p, n, ^2\text{H}, ^3\text{H}, ^3\text{He}$, etc. A kinematically complete experiment is suggested in the momentum region $0.5 \leq q^2 \leq 2 (\text{GeV}/c)^2$ in order to check (a) relativistic aspects of the nuclear wavefunction (b) the γ - a' vertex (c) the degree of compositeness of the spectator (d) the approach to scaling $\omega W_2^A(\omega, q^2) \rightarrow \omega W_2^A(x)$ of the longitudinal structure function W_2 of nucleus Λ , and ω =energy transfer.

5. Tensor Polarization in Electron-Deuteron Elastic Scattering¹⁷

The tensor polarization t_2 in $e^{-2}\text{H}$ scattering is known to be sensitive to the tensor part of the NN force, and the isoscalar meson exchange currents. The proposed experiment calls for measurements in the range $15 < q^2 < 30 \text{ fm}^{-2}$, and would require a high duty-factor electron accelerator with energy between 1.4 and 2.0 GeV and an average current of $\sim 100 \text{ nA}$. One of the immediate results of this experiment will be the precise localization of the minimum in the charge form factor of ${}^2\text{H}$.

6. $(\gamma, \pi\text{N})$ and $(e, e'\pi\text{N})$ Experiments at 1-2 GeV¹⁸

These experiments at a high duty factor electron accelerator are for the purpose of investigating the π -nucleus interaction and in particular the role of the Δ resonance and the possibility of the presence of a dibaryon resonance. The ${}^2\text{H}(e, e'\pi\text{N})$ experiment can measure the production of Δ 's in the nucleus. This information can be utilized in conjunction with $(e, e' \text{N})$ data in heavier nuclei to provide estimates of the presence of Δ 's in nuclear systems vs. Δ 's created by photon absorption and ultimately to map the Δ wave-function in the nuclear interior.

7. Photoabsorption Cross Section in the Delta Region by Forward Angle Electron Scattering¹⁹

Both single arm (e, e') and coincidence experiments $(e, e'\pi)$ are proposed for the purpose of measuring the large peak in the region 140-450 MeV due to the Δ resonance, free of contamination from either quasielastic scattering or radiative effects from scattering below the Δ region. For the (e, e') experiment, the appropriate

kinematics are $E_e = 750 \text{ MeV}$ and $\theta_e = 20^\circ$. The $(e, e'\pi)$ experiment becomes quite feasible with a 100% duty factor beam. The clean photoabsorption spectrum in the Delta region is useful in completing photoabsorption sum rules and checking the validity of the isobar-like model of π -nuclear reactions.

8. Photo- and Electro-production of $K^{+,0}$ from Nuclei²⁰

A report on recent theoretical calculations of (γ, K^+) is presented in this conference.²⁰ The objective of this work is to extract information on hypernuclear states involving deeply bound Λ and Σ hyperons. Preliminary estimates show that the favorable kinematical region for hypernuclear studies is in the region of 2 GeV electron beam energy. Cross sections for ${}^4\text{He}$ and ${}^{12}\text{C}$ have been estimated to be of the order of $0.07 \text{ } \mu\text{b}$ and $0.01 \text{ } \mu\text{b}$ respectively at this energy. This work takes advantage of the fact that $K^{+,0}$ is feebly affected by final state interactions.

9. Measurements of Parity Violation in the Scattering of Polarized Electrons from Protons²¹

It is proposed that the asymmetry A resulting from the elastic scattering of polarized electrons, from protons, e.g.,

$$A = \frac{\sigma_2 - \sigma_R}{\sigma_2 + \sigma_R}$$

be measured in the energy region between 0.5 and 2.0 GeV. The individual cross sections $\sigma_{L(R)}$ for left and right electron helicity, and hence A , are expressed in terms of the coupling constant of the four components of the hadronic weak neutral current. Different

linear combinations of the four couplings are measured at different kinematical points and hence the validity of various models of electroweak currents can be investigated.

These nine proposals represent only a small sample of the total number that is being compiled. Further proposals pursuant to the goals described in the outline presented earlier, are being prepared by several persons as indicated in the Appendix. Each proposal furnishes the physical justification as well as an account of experimental requirements for the proposed research including energy and beam characteristics and estimates of the accuracy necessary for elucidating the physical ideas of interest.

The study group expects to have its work completed by January, 1981, at which point a volume including both a detailed account of future directions in electromagnetic nuclear physics and the proposals for experimental investigations which will carry the field along these directions, will become available for distribution.

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7. The panel on Future Directions of Electromagnetic Nuclear Physics is constituted as follows:
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 L. Cardman (Illinois), B. Chertok (American University),
 T.W. Donnelly (MIT), F. Gross (William and Mary),
 E. Hadjimichael (Fairfield University), S. Hanna
 (Stanford), H. Jackson (Argonne), J. McCarthy (Univ.
 of Virginia), J. O'Connell (NBS), S. Penner (NBS),
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17. R.J. Holt, Argonne.
18. R.P. Redwine (a) and H.E. Jackson (b), MIT (a) and Argonne (b).
19. J.S. O'Connell, National Bureau of Standards.
20. A.M. Bernstein, T.W. Donnelly and G.N. Epstein, MIT.
21. P.A. Souder and M.S. Lubell, Yale University.

Table 1: Organization of Research in
Electromagnetic Nuclear Physics

I. Nuclear Forces and Nuclear Structure

A. Phenomena Involving Nucleons Only

1. NN Correlations
2. Ground state and Transition Charge and Magnetization Densities
3. Discrete States
4. Giant Resonances
5. Disintegration Near Threshold
6. Quasi-elastic, (e,e') , $(e,e'N)$, $(e,e'x)$
7. Absorption of Real Photons
8. Quasideuteron Effect

B. Phenomena Involving Non-Nucleonic Degrees of Freedom

1. Meson-exchange Currents
2. Isobars and Mesons
3. Hypernuclei
4. Relativistic Components

II. The Nucleus as a Laboratory

1. Electroweak Processes; Charged and Neutral Currents and Parity Non-conservation
2. Propagation of Unstable Particles
3. Effects of the Medium on Free Nucleon Phenomena
4. Optical Potentials
5. Pion Condensates

III. Subnuclear Structure

1. Meson and Baryon Spectra
2. Vector Meson Production
3. Dibaryons
4. Hadronic Form Factors
5. Nucleon Polarizability
6. Quark Components, Hidden Color and Bag Models

APPENDIX

Present status of the planning effort for future directions of electromagnetic nuclear physics; list of authors of experimental proposals and corresponding topics:

N-N Correlations	E. Hadjimichael
Ground State and Transition Charge and Magnetization Density	R. Arnold, W. Bertozzi, J. Heisenberg, R.J. Holt, F. Gross
Discrete Nuclear States	J. Heisenberg, W. Bertozzi
Giant Resonances	S. Hanna, J. Calarco, L. Cardman
Disintegration Near Threshold	D. Day, J.S. McCarthy
Quasielastic	I. Sick, C. Williamson, B. Chertok
Real Photons	J. Mathews, E. Hayward
Quasideuteron	J. Lightbody, K. Seth, J. McCarthy
Meson-Exchange Currents	J. Dubach, J. Peterson
Isobars and Mesons	R.P. Redwine, H.E. Jackson, J. O'Connell, I. Blomqvist, B. Schoch, A.M. Bernstein, T.W. Donnelly
Hypernuclei	T.W. Donnelly, A.M. Bernstein, J.N. Epstein, B.L. Roberts, J.P. Miller
Charged and Neutral Weak Currents	P.A. Souder, M.S. Lubell
Propagation of Unstable Particles	R.P. Redwine, H.E. Jackson
Vector Meson Production	R. Whitney, H. Crannell, J. Noble
Hadronic Form Factors	F. Gross