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# Nuclear Studies with Intermediate Energy Probes

Annual Performance Report
and
Continuation Proposal

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Summary

Nuclear studies with intermediate energy probes are being pursued at LAMPF, IUCF, NIKHEF-K (Amsterdam, Holland), SAL (Saskatoon, Canada), and THD (Darmstadt, West Germany). Proton scattering measurements of the calcium isotopes have been performed at both LAMPF and IUCF; preliminary measurements of selected s-d shell nuclei have also been made at LAMPF. Analysis of the collected data is underway. Measurements of electron scattering from $^{42}$Ca and $^{44}$Ca made at NIKHEF-K are also being analyzed, in conjunction with data obtained previously at the MIT-Bates Linear Accelerator. Initial electron scattering measurements of $4^-$ and $6^-$excitations in $^{18}$O have been performed at MIT-Bates and the analysis is underway. The analysis of measurements of the mercury isotopes made at NIKHEF-K have been completed and the results are being prepared for publication. Further results of our studies of the (e,e'd) reaction at NIKHEF have been analyzed and published.

New proposals for experiments at the Saskatchewan Accelerator Laboratory (SAL), NIKHEF-K, and THD (Darmstadt) have been approved. All are scheduled to run during the next two years. A gas jet target is currently under construction for use in the SAL storage ring to study the feasibility of performing internal target experiments in electron rings. We have received time to complete our electron scattering measurements of the calcium isotopes at NIKHEF-K. We will also study the threshold electro-production of neutral pions from the proton via the p(e,e'p)$\pi^0$ reaction at NIKHEF-K. Finally, we will perform electron scattering measurements of $^{14}$C at NIKHEF-K and THD. Of particular note in this experiment will be the extraction of the B(E1) value for the first excited state as it will help to determine which of a broad class of stars can collapse to form black holes.

The potential to perform polarized beam-polarized target experiments in the electron rings being constructed at MIT-Bates and NIKHEF-K is being studied. In particular, design studies of the ring modifications required to maintain the polarization of stored electrons is underway.

## Nuclear Structure Studies

### 1) Calcium Isotopes

Complementary electron and proton scattering studies of the calcium isotopes are being carried out at LAMPF, IUCF, and NIKHEF-K (Amsterdam). The isotopes $^{40}$Ca, $^{42}$Ca, $^{44}$Ca, and $^{48}$Ca are being studied by elastic and inelastic proton scattering at LAMPF and IUCF. Adequate data on electron scattering from $^{40}$Ca and $^{48}$Ca exist,[1] so measurements on only $^{42}$Ca and $^{44}$Ca are being carried out at NIKHEF-K. Previously we completed the measurements on $^{42}$Ca and made preliminary measurements on $^{44}$Ca. A proposal to perform a complete set of measurements on $^{44}$Ca was prepared, submitted, and accepted this year. The measurements will be made during the upcoming year.

The reduction of data from the proton scattering measurements (to states with excitation energies up to about 8 MeV) is underway at the University of Maryland. The reduction of the electron scattering data is being carried out by Mr. P. Karen, a graduate student of the University of Virginia, who is currently stationed at NIKHEF-K. The quality of the data is excellent (see Fig. 1), with energy resolution generally better than $1.5 \times 10^{-4}$. The precision of the form factors and transition charge densities extracted reflect this quality; see Figure 2.

The data from NIKHEF-K were obtained at small scattering angles where Coulombic excitations dominate. To extract electric (transverse) contributions to these states and to observe magnetic transitions require data at larger scattering angles. Data on $^{42}$Ca and $^{44}$Ca previously obtained at MIT-Bates as part of another experiment[2] involved large scattering angle (160°) measurements. These data are being analyzed as well to a) prevent unnecessary duplication and b) to help direct choices of kinematics for the upcoming running.

### 2) The $^{12}$(e,e'd)$^{10}$B Reaction

In connection with our previous work[3] on the reaction $^{6}$Li(e,e'd)$^{4}$He we also examined the reaction $^{12}$C(e,e'd)$^{10}$B.[3] Various final states in $^{10}$B are accessible and readily separable due to the excellent missing mass resolution of the NIKHEF-K electron scattering detection system; see Figure 3.

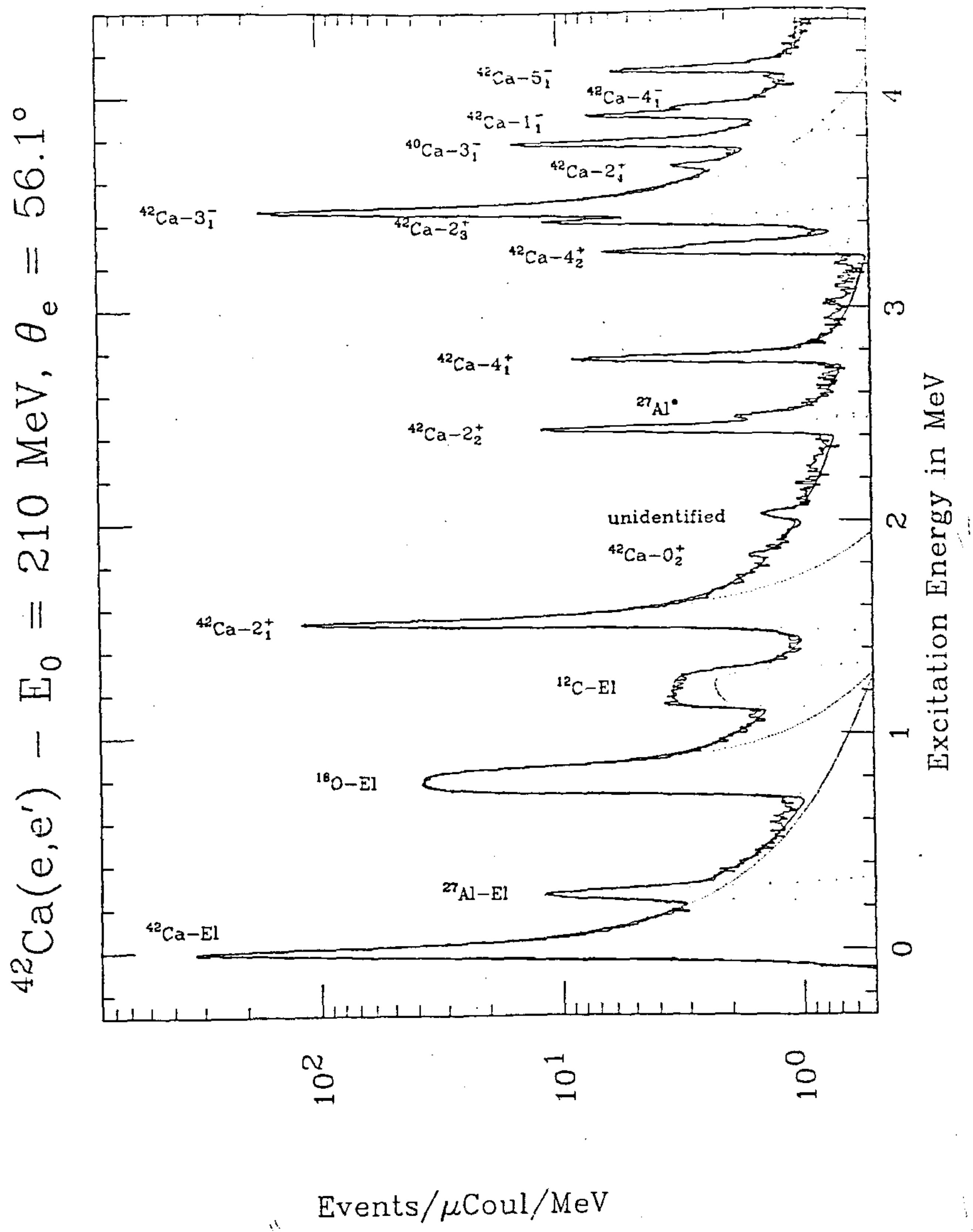


Figure 1. Spectrum of Electrons Scattered from $^{42}$Ca

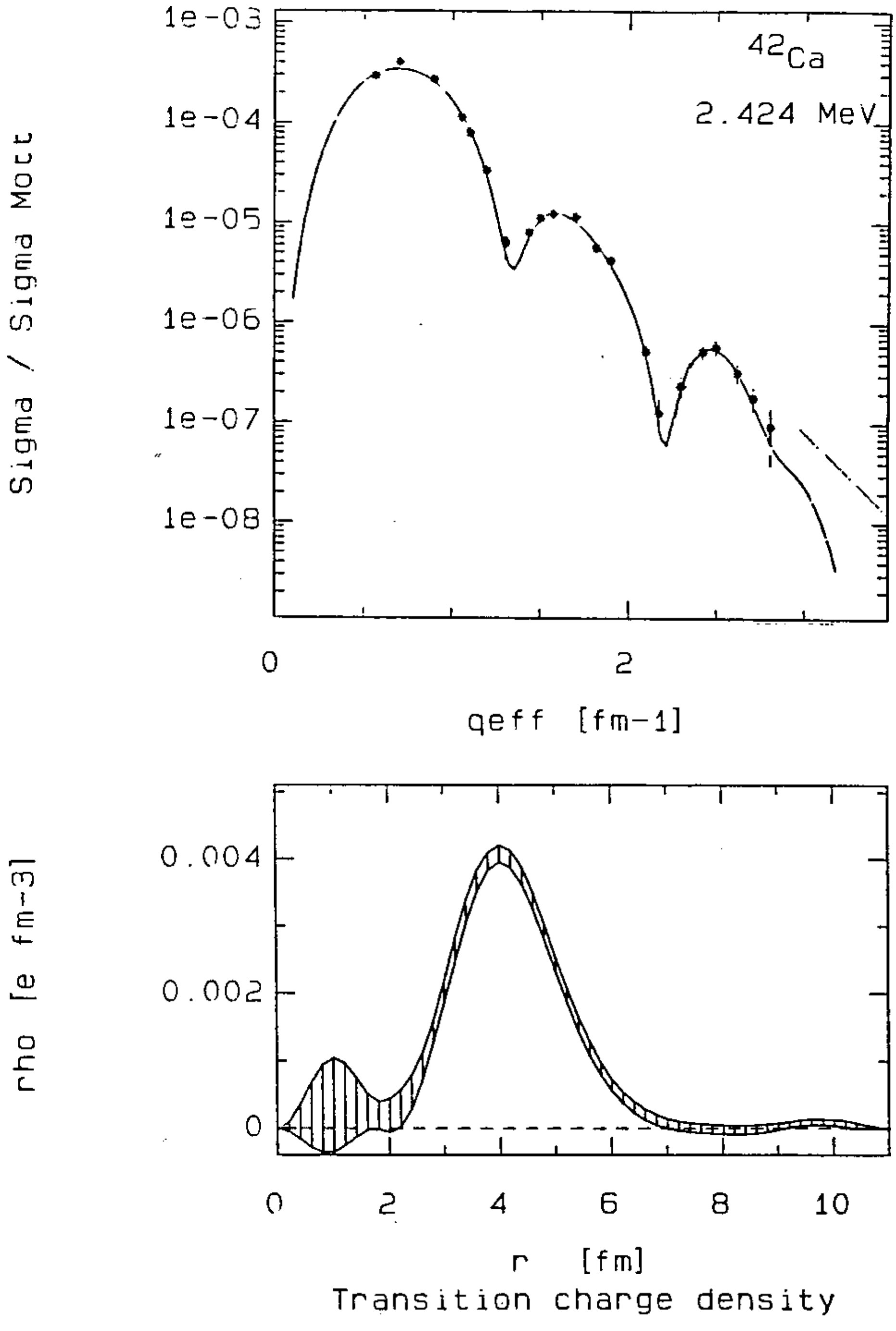


Figure 2. Form Factor and Transition Density for $^{42}Ca(2_1^+)$

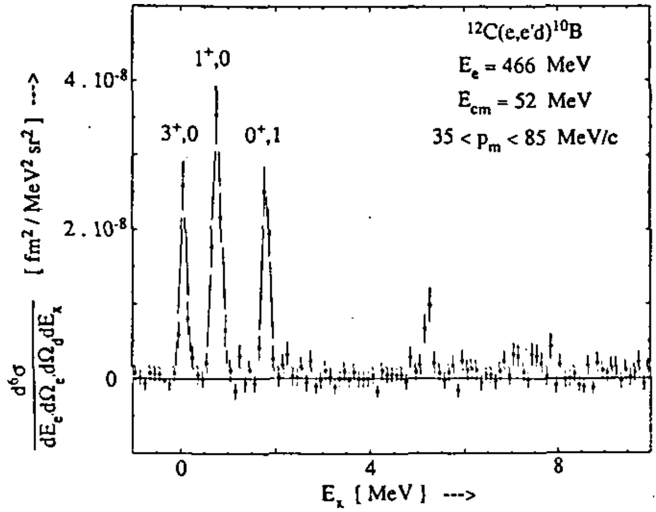


Figure 3. Missing Mass Spectrum for $^{12}C(e,e'd)^{10}B(0^+;1)$

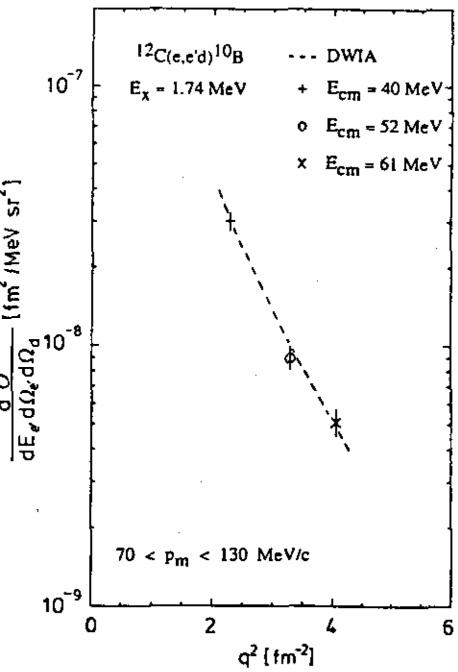


Figure 4. Measured Cross Section for $^{12}C(e,e'd)^{10}B(0^+;1)$
Dashed curve proportional to $d(e,e')[pn;^1S]$

In our previous studies it was found that the $^{6}Li(e,e'd)^{4}He$ reaction was dominated by direct deuteron knockout. The deuteron and $^{12}C$ both have T=0, so it was expected that in the $^{12}C(e,e'd)^{10}B$ reaction only final states in $^{10}B$ with T=0 would be excited. Transitions to final states in $^{10}B$ with T≠0 would be forbidden by isospin conservation. However, we observed that transitions to the lowest lying T=1 state in $^{10}B$ were as strongly excited as those to the T=0 ground state (see Fig. 3).

Two interpretations appeared possible. First, rather than direct knockout the reaction could proceed via the two step process $^{12}C(e,e'p)(p,d)^{10}B$. Since the strong isospin-allowed (and hence presumably dominated by direct knockout) transition to the ground state of $^{10}B$ and the isospin-forbidden transition to the excited state are of comparable strength it seems unlikely that the latter could involve a two-step process. Second, it was noted that when an electron scatters from a deuteron there is (measured[4]) probability that the deuteron breaks up into a slightly unbound relative $^{1}S$ state. Reversing the process, it would appear possible that when a p-n pair in a relative $^{1}S$ state inside a nucleus is struck by an electron it can emerge as a deuteron in an inverse electrodisintegration process. Since the cross section for this process would be directly related to that for electrodisintegration, the hypothesis could be tested by examining the momentum transfer dependence. The two were observed to scale (see Fig. 4). Moreover, the cross section for the $^{12}C(e,e'p)(p,d)^{10}B^{*}$ reaction was observed to be purely transverse, as would be expected for this mechansim. The mechansim is interesting in that it represents a means of obtaining information on $^{1}S$ correlations inside the nucleus.

### 3) Oxygen Isotopes

A study of $4^{-}$ and $6^{-}$ excitations in $^{18}O$ by inelastic electron scattering has been started at the Bates Linear Accelerator. The aim of the work is to improve our understanding of the quenching and fragmentation of magnetic strength in nuclei. The $^{18}O$ nucleus is particularly well suited for this work as it is the simplest system for which transition strengths can be compared directly to results of single nucleon transfer reactions. In particular, the results for the $6^{-}$ excitations will be compared with results recently obtained[5] for the $^{17}O(\alpha,^{3}He)^{18}O$ reaction.

We currently have data for five energies (140 MeV - 275 MeV) at 140° and two (220 MeV, 250 MeV) at 110°. The data span a range of effective transfers from 1.3 $fm^{-1}$ to 2.5 $fm^{-1}$, where M4 and M6 form factors are expected to be their largest. With the inclusion of an earlier measurement at 1.7 $fm^{-1}$, these data represent the only high momentum transfer, high resolution data in the excitation region between 10 MeV and 25 MeV in $^{18}O$.

The data are now being reduced to cross sections by R. Sellers, a graduate student at Kent State University.

4) Carbon-14

Under astrophysical conditions of high temperature (kT ≃ 20-50 keV) and high density ($\rho \sim 10^6$ g/cm$^3$) the cross section for radiative proton capture on $^{13}N$ is large enough to cause a modification of the normal CNO cycle.[6)] The rate of the normal cycle is limited by the 10 minute $^{13}N$ lifetime whereas the rate of the modified cycle is governed by the positron decay lifetimes of $^{14}O$ ($t_{1/2} \sim 71$ s) and $^{15}O$ (122 s). Accordingly, the burning rate of the modified cycle is much greater. If the temperature at which the modified cycle begins to dominate is low enough, then super-massive, metal-rich stars cannot collapse to form black holes.

The temperature at which the modified cycle begins to dominate is a function of the B(E1↓) for the first excited state of $^{14}O$. Efforts are currently underway to measure this reaction directly[7)] using secondary $^{13}N$ beams, but they are limited by the low beam intensity and cross section. This cross section can, however, be inferred indirectly from more easily performed measurements. The $^{13}N(p,\gamma)$ reaction is expected to go primarily via the first excited state ($\omega$ = 5.173 MeV, $J^{\pi} = 1^-$) of $^{14}O$. Therefore, the cross section for the $^{13}N(p,\gamma)$ reaction is determined by the particle width ($\Gamma_p$) and radiative width ($\Gamma_\gamma$) of this state:

$$\sigma(E) = \frac{3\lambda^2}{16\pi} \left[ \frac{\Gamma_p \Gamma_\gamma}{\left(E-E_r\right)^2 + \left(\Gamma^2/4\right)} \right]$$

Efforts are currently underway at LLNL to determine the proton width of this state. The radiative width poses a greater problem. However, to a satisfactory accuracy it can be inferred from the corresponding width of the analogous first excited state ($\omega$ = 6.0942 MeV, $J^{\pi} = 1^-$) in $^{14}C$.

We have received approval to perform the low momentum transfer measurements necessary to extract the B(E1) value at THD (Darmstadt). In order to be confident that the extrapolation is reliable we need a more complete understanding of the structure of the A=14 system. Accordingly, we have been approved to perform electron scattering measurements at higher momentum transfers at NIKHEF-K. The measurements at NIKHEF-K are scheduled for the spring of next year while the measurements at THD are scheduled for the early summer of this year.

The measurements on $^{14}C$ are also important in that they will complete a comprehensive set of measurements on the carbon isotopes. Previous data exist for $^{12}C$,[8,9] $^{13}C$,[10,11] and for transverse excitations of $^{14}C$.[12] The proposed measurements of longitudinal scattering from $^{14}C$ will complete the set and allow us to study isotope shifts in the ground state charge densities as well as polarization effects in transitions to excited states.

5) Mercury Isotopes

In 1986 we completed a series of electron scattering measurements on $^{198}Hg$ and $^{204}Hg$ using targets made of a mercury-lithium alloy. The results for the elastic scattering from $^{204}Hg$ were particularly interesting. The differences between the charge distributions of $^{205}Tl$ and $^{206}Pb$ extracted from previous measurements[8] of elastic electron scattering cleanly describe the 3s orbital where the proton, which is the difference between the two nuclei, is located. A proton in the 3s orbital is also the difference between $^{204}Hg$ and $^{205}Tl$. The differences between the charge density of $^{204}Hg$ and $^{205}Tl$ deduced from our measurements do not resemble the 3s density very strongly.

Measurements of both $^{198}Hg$ and $^{204}Hg$ have been completely analyzed and are currently being prepared for publication.

Internal Targets in Electron Storage Rings

1) Internal Target Feasibility Study

Calculations to examine the feasibility of performing electron scattering from gas targets in the electron storage-stretcher ring of the Saskatchewan Accelerator Laboratory (SAL) have been performed. The basic conclusion was that it is feasible. However, many important questions can only be tested by putting an actual target in place.

The SAL ring[13)] has been completed and is now in operation. Adequate vacuum has been achieved to permit storage times of the order of several minutes,[14)] much longer than that needed for internal target experiments.[15)] Provision was made in the design for an internal target area.

We have received approval to place a gas jet target in the ring and to use 96 hours of beam time to examine questions related to the use of such targets. These include

1) effect of the target on beam lifetime,
2) effect of the target on beam profile,
3) effect of the target on machine tunes,
4) backgrounds generated by the beam hitting the vacuum chamber,
5) effect of the beam on the target density,
6) effect of the target on ring vacuum, and
7) suitability of different detectors to ring environment.

The questions to be addressed in these measurements are common to the rings at SAL, MIT-Bates, and NIKHEF-K. Accordingly, we will be joined during these measurements by personnel from both MIT-Bates and NIKHEF-K.

We have been allotted a two meter long section of the ring where we can place our target and detectors. We have obtained and are having installed two all-metal gate valves to enable us to isolate this section of the ring so that we can install, remove, and work on our target and detectors without bringing a substantial portion of the ring up to atmosphere. This minimizes the time required to regain a useable vacuum. We are currently constructing a gas jet target capable of reaching densities of about $10^{14}$ atoms/cm$^2$ of nitrogen. It consists of a pressurized nitrogen source fed through a Laval nozzle with a diameter of 100$\mu$m into the throat of a 1500 l/sec turbo pump. Differential pumping both upstream and downstream of the target using addtional smaller turbo pumps will localize the pressure bump and enable us to maintain a $< 10^{-8}$ t vacuum in the rest of the ring.

A variety of detectors will be tested. First, several scintillators both inside the target chamber and outside will be used. Solid state detectors will be used inside the chamber. Particular emphasis will be placed on determining the longevity of such detectors in the "poor-vacuum" environment of the target chamber. We are also attempting to locate a small wire chamber in order to study how these devices behave in this situation.

We have obtained a silicon strip detector and will be using it inside the chamber. Much interest has been shown in the use of these devices as vertex detectors both with internal target configurations at MIT-Bates and NIKHEF-K as well as at CEBAF. Our studies will help to delineate their range of applicability in these situations.

The run is tentatively scheduled for the month of July.

Work on the design of a polarized $^6$Li target has been suspended, pending the results of the studies at SAL.

2) Polarized Electrons at MIT-Bates and NIKHEF-K

An upgrade of these electron accelerator by the addition of pulse stretcher-storage rings was recently begun. By the time the rings are complete the maximum energy of the MIT-Bates accelerator will be 1000 MeV while that of the NIKHEF-K accelerator will be over 800 MeV. The possibility of performing internal target experiments with electrons in this energy range is exciting. Moreover, the laboratories have made commitments to establish strong internal target programs.

Any internal target program would be greatly enhanced by the capability to store polarized electrons. In anticipation of extending the work at SAL to MIT-Bates and/or NIKHEF-K we have begun to examine this problem For the NIKHEF-K ring we found an attractive, cost effective solution in the form of a Siberian Snake of the First Kind[16)] wherein a solenoid capable of precessing the electron spin through 180° about the direction of motion is placed in the straight section opposite the target location where longitudinal polarization is desired. The strength of the required solenoid is large, 104.6 kG-m/GeV[17)], so control of the beam optics at that point is critical. A derivative of the Siberian Snake, the so-called Resonant Snake,[18)] was also considered. It requires a much weaker solenoid but has the disadvantage of working only at multiples of 440.65 MeV. Unfortunately, a decision to reposition the internal target hall negated this solution. We are currently working on new designs for both the NIKHEF-K and MIT-Bates rings.

## Electro-production of Pions

### 1) Electro-production of Pions from H

The production of pions by the interaction of a photon with a nucleon is one of the most basic subnucleonic processes. An understanding of it is a prerequisite to understanding more subtle subnucleonic degrees of freedom. However, while the production of neutral pions via the $\Delta(1232)$ and other resonances is reasonably well described, it is not well understood near threshold. Until recently, there was no reason to believe a problem existed. The photoproduction results of Adamovich[19] were in reasonable agreement with the predictions of the Low Energy Theorems[20] (LET) and the electroproduction results of Brauel et al.[21] were sufficiently vague to arouse few suspicions. Then, Mazzucato et al.[22] measured precisely the $E_{0+}$ amplitude for photoproduction and obtained a value of $(-0.5\pm0.3)\times10^{-3}/m_{\pi+}$, in sharp contrast with both the LET and previous experimental results; the new result was verified by Breitbach et al.[23] at Mainz.

That the newly determined value for $E_{0+}$ was incompatible with the chiral-Lagrangian theory was established by Davidson and Mukhopadhyay.[24] Interestly, they also found that the experimental results for the other two amplitudes which contribute at threshold, $M_{1+}$ and $M_{1-}$, were in excellent agreement with the theory. Nath and Singh[25] dropped the constraint of chiral symmetry and added a symmetry breaking term similar to the $\sigma$-term in pion nucleon scattering and obtained a description of the data. It thus appears that an investigation of the threshold production of neutral pions by photons, both real and virtual, will yield information on the chiral symmetry breaking effects in this fundamental process.

The new data on the photoproduction process at threshold are of significantly better quality than the existing electroproduction data. The electroproduction data were obtained at Frascati,[26] NINA,[27] and DESY.[21] These data are shown in Figure 1, which is reproduced from reference 10). Three points about the data are significant. First, the uncertainties are large. Second, they were all taken at relatively large values of $k_\mu^2$, the virtual photon mass; the lowest value $k_\mu^2$ is -0.2 GeV$^2$. Thirdly, and probably most significantly, the data were taken at least 18 MeV from threshold where several multipoles already contribute significantly to the cross section. To obtain a better understanding of the threshold production process one clearly requires quality data at lower values of W, the invariant mass of the final pion nucleon system, and $k_\mu^2$, a point which is made in reference 24).

We have received approval for 100 hours of beam time to measure the threshold electro-production of neutral pions from the proton starting in spring, 1990. Measurements will be made at four-momentum transfers ($k_\mu^2$) of -0.018 $GeV^2$ and -0.110 $GeV^2$. We will be able to use an existing target[28)] modified by the inclusion of a temperature feedback system so that it can run at a temperature just above the boiling point of hydrogen (77K), rather than just above that of helium (4K) where it has been operated.

Detection of neutral pions is very inefficient and complicated. Consequently, we will examine the process using the reaction $p(e,e'p)\pi^0$. The minimum kinetic energy of the protons we will detect is about 15 MeV. As a result, the standard detector system in the QDQ spectrometer will be adequate. It is notable that near threshold the reactions products are confined to a small cone about the direction of the virtual photon. The excellent angular resolution obtainable using the thin walled gas target and the precise QDQ spectrometer and detection system will enable us to obtain information about the direction (in the center of mass frame) in which the pions are emitted.

## 2) Electro-production of Pions from $^{14}C$

The electro-production of pions in light nuclei can yield information which can be compared and contrasted with a large body of results from other processes and hence provide stringent constraints on our understanding of basic nuclear processes. Such processes include pion-scattering, $\beta$-decay, $\Delta$ production, $\Delta$ propagation, and $\Delta$-hole interactions. In particular, we are interested in the $\Delta$-hole contributions.

Recent studies[29)] of $\pi^-$ production from $^{13}C$ and $^{15}N$ have produced contradictory results. Both of these cases involve transitions from $J^\pi=1/2^-$ initial states to $J^\pi=1/2^-$ final states. Consequently, contributions from the E0 multipole arising from the $\Delta$-hole interaction as well as those from the direct M1 multipole can contribute. In the case of $^{15}N$ the contribution of the E0 amplitude agrees well with theory while in the case of $^{13}C$ it is totally absent, in direct disagreement with theory. That two such similar processes should give such markedly different results is a puzzle.

Since the two mutipoles cannot (in practice) be extracted separately it would be interesting to examine a case where only one can contribute; that is, a case of a transition from a $J^{\pi}=0^{+}$ initial nuclear state to a $J^{\pi}=0^{+}$ final nuclear state. To make this case as similar as possible to those of $^{13}C$ and $^{15}N$ it would be useful if these intial and final states were isobaric analogs. The only case where such a transition is possible and where the final state is sufficiently well resolved as to be identifiable is the case of $^{14}C$ going to $^{14}N^{*}(J^{\pi}=0^{+},T=1)$. We plan to study the electro-production of negatively charged pions from $^{14}C$ using the reaction $^{14}C(e,\pi^{-})^{14}N$. The $^{14}C$ target we are preparing for the $^{14}C(e,e')$ measurements will be ideally suited for this measurement. A proposal is currently being prepared parasitic for submission to the SAL Program Advisory Committee.

As it is anticipated that we wll perform the single arm electron scattering measurements at NIKHEF-K prior to the availability of the SAL machine we plan to perform a parasitic test measurement during the electron scattering run by using the QDQ spectrometer. For the actual running at SAL (assuming we gain approval) no new target or detector development is anticipated.

## References


1) P. Harihar et al., Phys. Rev. Lett. 53 (1984) 152.

2) J. Wise et al., Phys. Rev. C31 (1985) 1699.

3) R. Ent et al., Phys. Rev. Lett. 57 (1986) 2367.

4) M. Bernheim et al., Phys. Rev. Lett. 46 (1981) 402.

5) M. Yasue et al., to be published.

6) F. Hoyle and W.A. Fowler, in "Quasi-Stellar Sources and Gravitational Collapse," ed. I. Robinson, A. Schild, and E.L. Schucking, University of Chicago Press (1965) 17.

6) R.K. Wallace and S.E. Woosley, Astrophys. J., Suppl. Ser. 45 (1981) 389.

7) R.C. Haight, Bull. Am. Phys. Soc. 27 (1982) 760.

8) I. Sick and J.S. McCarthy, Nucl. Phys. A150 (1970) 631.

9) R.S. Hicks et al., Phys. Rev. C26 (1989) 339.

10) D.J. Millener et al., accepted for publication in Phys. Rev. C.

11) R.S. Hicks et al., Phys. Rev. C36 (1987)485; R.S. Hicks et al., Phys. Rev. C34 (1986) 1161.

12) M.A. Plum et al., Phys. Lett. 137B (1984) 15.

13) J.C. Bergstrom et al., IEEE Trans. on Nucl. Sci. NS-30 (1983) 3226.

14) D. Skopik, private communication.

15) B.E. Norum, Report of the 1985 Summer Study Group, CEBAF (Jan. 1986) 12-70.

16) Ya.S. Derbenev and A.M. Kondratenko, Novosibirsk preprint 76-84 (1976).

17) A.W. Chao, PEP Note 301 (1979).

18) B.E. Norum, "Longitudinally Polarized Electrons for Internal Target Experiments," CEBAF Report (1984).

19) M.I. Adamovich, as cited in Reference 7.

20) S. Fubini et al., Nuoco Cimento 40 (1965) 1171.

21) P. Brauel et al., Phys. Lett. 50B (1974) 507.

22) E. Mazzucato et al., Phys. Rev. Lett. 57 (1986) 3144.

23) G. Breitbach et al., Report of the Institut fur Kernphysik, Mainz, May 1988.

24) R. Davidson and N.C. Mukhopadhyay, Phys. Rev. Lett. 60 (1988) 748.

25) L.M. Nath and S.K. Singh, "Neutral Pion Photoproduction on the Proton near Threshold and the Chiral Symmetry," International centre for Theoretical Physics Preprint IC/88/168 (1988).

26) E. Amaldi et al., Nuovo Cimento 65A (1970) 377.

27) D.R. Botterill et al., Nucl. Phys. B116 (1977) 65.

28) J.F.J. van den Brand et al., Nucl. Instrum. Meth. in Phys. Res. A261 (1987) 373.

29) B. Alberti et al., in "Physics with MAMI A 1983 - 1987," Johannes Gutenburg-Universitat, Mainz (1988) 123.

Appendix A: Articles Published

1) "Deuteron Formation in the Reaction $^{12}C(e,e'd)^{10}B$," with R. Ent et al., Phys. Rev. Lett. 62 (1989) 24.

Appendix B: Invited Talks

1) "Proposed Internal Target Project for the Saskatoon Electron Stretcher Ring," Topical Conference on Electronuclear Physics with Internal Targets, SLAC, January, 1989.

2) "High Duty Factor Electron Accelerators for Nuclear Physics," Seminar, Indiana University Cyclotron Facility, March 31, 1989.

Appendix C. Summary of Approved Experiments

The following is a list of experiments for which the Principal Investigator is the spokesman:

1) "Inelastic Electron Scattering from $^{44}$Ca," NIKHEF-K, 85 hrs.
2) "Elastic and Inelastic Longitudinal Electron Scattering from $^{14}$C," NIKHEF-K, 173 hrs.
3) "Electro-production of Neutral Pions from the Proton," NIKHEF-K, 100 hrs.
4) "Inelastic Electron Scattering from $^{14}$C at Low Momentum Transfers," THD (Darmstadt), 200 hrs (estimated).
5) "Internal Target Feasibility Study," SAL, 96 hrs.

The total running time amounts to 454 hrs (at NIKHEF-K and SAL) plus an estimated 200 hrs (at THD) for a total of approximately 650 hrs. All experiments are scheduled to run during the next two years.