Our research addresses the key questions that comprise the Nation's nuclear physics agenda. We place heavy emphasis on the prediction of phenomena accessible at Argonne's ATLAS facility, at JLab, and at other laboratories; and on anticipating and planning for a Future Rare Isotope Beam facility (FRIB). In theoretical and computational nuclear astrophysics we address such issues as the origin of the heaviest elements through the actinide region and the basic mechanisms of supernova explosions, and aim to identify critical nuclear parameters and systematic properties to be explored with a FRIB. We employ quantum chromodynamics to explore hadron properties: in vacuum, as relevant to programs such as those pursued at JLab; and in-medium, as appropriate to the early universe, compact astrophysical objects, and the RHIC program. Dynamical coupled-channel models are developed to investigate the structure of nucleon resonances by using meson production data from JLab, MIT-Bates, Bonn and Mainz, to investigate the quark-gluon reaction mechanisms to be explored with JLab’s 12 GeV upgrade, and also to predict the neutrino-nucleus cross-sections necessary for analyzing data from experiments measuring neutrino properties. The structure of atomic nuclei is explored in \textit{ab-initio} many-body calculations based on the realistic two- and three-nucleon potentials we have constructed. These potentials give excellent fits to nucleon-nucleon elastic scattering data and the properties of light nuclei. We use quantum Monte-Carlo methods to, e.g., compute nucleon-nucleus scattering phase shifts, transition amplitudes, and a variety of electroweak reactions important to astrophysics. Our nuclear structure and reaction program includes: coupled-channels calculations of heavy-ion reactions near the Coulomb barrier; studies of breakup reactions involving nuclei far from stability, the determination of radiative capture rates from Coulomb dissociation experiments; and studies of the effects of n-p pairing on nuclei near the proton drip-line and studies of the heaviest elements - in both cases using many-body wavefunctions. Our programs provide much of the scientific basis for the drive to physics with rare isotopes. Additional research in the Group focuses on: atomic and neutron physics; fundamental quantum mechanics; quantum computing; and tests of fundamental symmetries and theories unifying all the forces of nature, and the search for a spatial or temporal variation in Nature's basic parameters. The pioneering development and use of massively parallel numerical simulations using hardware at Argonne and elsewhere is a major component of the Group's research.
## WORK PROPOSAL REQUIREMENTS FOR OPERATING/EQUIPMENT

### OBLIGATIONS AND COSTS

### STAFFING (in staff years)

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### Obligations and Costs (in thousands)

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### Equipment (in thousands)

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### Milestone Schedule (Tasks)

### Reporting Requirements

*Technical services staffing includes ANL support divisions’ scientific effort.*
Purpose:

- Develop theoretical methods and tools to place reliable constraints on the spatial and temporal variation of Nature’s fundamental parameters, including the impact of spatial variations in the gravitational potential; identify the observables and suggest the experiments that may reveal this variation.

- Explore weak parity nonconserving (PNC) and superweak time-reversal-invariance violating (T-odd) interactions in atoms and nuclei, develop the theory necessary to use such phenomena effectively as tests of the Standard Model and its extensions, and identify those observables that can provide the strongest signals of non-Standard-Model effects.

- Explore the properties of hot, dense QCD, e.g., the phase structure of this theory and its equation of state, and the effects of temperature and density on hadron properties. Compare the results with inferences from contemporary heavy ion experiments. Study electroweak reaction rates relevant to astrophysical processes in dense nuclear matter. Predict observational signatures of quark matter in neutron stars.

- Explore the structure, spectrum and interactions of light- and heavy-hadrons using, in particular, symmetry-preserving truncations of the Poincaré covariant Dyson-Schwinger equations (DSEs).

- Develop a Poincaré framework with which to elucidate signatures of quark degrees of freedom in nuclei and thereby realize the opportunities presented by nuclei to study novel aspects of QCD, both experimentally and theoretically.

- Elucidate the relationship between parton properties on the light-front and the rest frame structure of hadrons, and calculate parton distribution functions.

- Interpret results obtained through experiment and numerical simulations of lattice-regularized QCD, using those which are robust to inform and improve contemporary models of hadron structure and interactions, and elucidate the properties of QCD in the confinement regime.

- Analyze the approximations made in lattice-QCD simulations in order to extract physical observables for comparison with experiment.

- Application and elucidation of complementary mathematical representations of hadron phenomena.
• Develop coupled-channel reaction models to interpret exclusive meson production data from Jefferson Laboratory in terms of nucleon resonance parameters predicted by hadron models and lattice-QCD calculations.

• Investigate the transition between the hadronic and the quark-gluon pictures of exclusive meson production reactions in the 2–10 GeV region.

• Develop reaction models for neutrino induced reactions on nuclei and use them in interpreting experiments aimed at measuring fundamental properties of neutrinos.

• Construct realistic two- and three-nucleon interactions, and consistent electroweak charge and current operators, to fit NN scattering data, properties of light nuclei and nuclear matter.

• Perform ab-initio many-body calculations of light (A = 3-12) nuclei and neutron drops using quantum Monte Carlo methods, and of nuclear matter and neutron stars using variational chain summation methods, all with realistic two- and three-nucleon interactions.

• Develop quantum Monte Carlo methods for ab-initio many-body calculations of nucleon-nucleus and nucleus-nucleus scattering and reactions using realistic interactions for light nuclei.

• Perform DWBA analysis, using ab-initio quasi-particle and quasi-hole wave functions, of rare-isotope transfer reactions in collaboration with ATLAS and other experimentalists.

• Identify critical nuclear properties; e.g., reaction cross-sections, lifetimes, nuclear masses, and trends in nuclear systematics, critical to problems in nuclear astrophysics, that can be addressed experimentally at ATLAS or with FRIB.

• Determine the relative roles of distinct nucleosynthetic environments in providing the inventories of nuclides in the solar system, the interstellar medium, and stars, by relating observed abundances to galactic chemical evolution models and nucleosynthesis calculations.

• Compute the effects of nuclear transformations in astrophysical environments, particularly the compositions of pre-solar grains found in meteorites, of the early solar system, and of Galactic stars.

• Interpret the distinctively non-Solar-like heavy element compositions of the oldest stars in our Galaxy as constraints upon the nucleosynthesis characteristics of the earliest stellar populations.
• Examine extant models for the operation of the astrophysical $r$-process of neutron capture synthesis of the heaviest elements (through the actinides).

• Explore the effectiveness of fission “recycling” in defining conditions yielding a robust $r$-process mechanism, as reflected in the patterns observed in the absorption spectra of low metallicity stars.

• Investigate the energetics of supernova flames, and of the strong and weak nuclear evolution of material behind a deflagration front in Type Ia supernovae.

• Explore detonation criteria for conditions compatible with expectations for Type Ia supernova environments.

• Investigate conditions favoring neutronization of Type Ia white dwarf progenitors and their implications for the peak brightnesses of supernovae associated with diverse stellar populations.

• Identify the critical dependences of the characteristics of classical nova explosions on the masses of the underlying white dwarfs and the rate of accretion of fresh envelope matter.

• Perform coupled-channels analyses of heavy-ion reactions near the Coulomb barrier, such as those measured at ATLAS.

• Develop models both for the structure and the reactions of nuclei far from stability, and test these models by analyzing measurements performed at radioactive beam facilities.

• Develop many-body methods for treating nuclear structure problems, with emphasis on nuclei accessible with a FRIB; apply our treatment of n-p pairing to nuclei near the proton drip-line; and apply the newly developed variational configuration-interaction method to studies of deformed nuclei, with particular emphasis both on nuclides near the proton drip line with masses heavier than the doubly magic nucleus $^{56}$Ni and on the heaviest known nuclei.

• Study a variety of problems in atomic physics, neutron physics, fundamental quantum theory and quantum computing.
### Highlights of Recent Results and Accomplishments:

- Effects of a temporal variation in the fundamental masses of the strong interaction on nuclear binding energies and Big Bang Nucleosynthesis (BBN) were calculated. Data on primordial abundances of deuterium, $^4\text{He}$ and $^7\text{Li}$ are consistent with a 1% variation of the fundamental constants between the time of BBN and the present.

- Enhanced effects of the fundamental constant variation were calculated for: the position of nuclear resonance in the reaction $n + ^{149}\text{Sm}$, and limits on the variation extracted from the Oklo natural nuclear reactor data; and the “nuclear clock” transition in the $^{229}\text{Th}$ nucleus.

- Effects of a variation in Nature’s fundamental constants on nuclear size and hyperfine structure were calculated. This is important to the search for the variation using microwave atomic clocks.

- Observations of compact stars have provided new data of high accuracy, which put strong constraints on the high-density behavior of the equation of state for strongly interacting matter that would not otherwise be possible. The evidence for neutron stars with large mass ($M_n = 2.1 \pm 0.2 M_\odot$ for PSR J0751+1807) and radii ($R > 12\text{km}$ for RX J1856-3754) argues against soft equations of state and focuses attention upon the possibility of quark matter within compact

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### Staff (support):

- H. Esbensen (100% from base budget)
- T.-S. H. Lee (66% from base budget and 33% from JLab via EBAC)
- K. M. Nollett (100% from base budget)
- S. C. Pieper (80% from base budget, working on reduced salary)
- C. D. Roberts (100% from base budget)
- J. W. Truran (joint with the University of Chicago, ANL 40%)
- R. B. Wiringa (100%)

### Postdoctoral Fellows (supported by base budget):

- I. C. Cloët (100%)
- B. El-Bennich (100%)

### Postdoctoral Fellows (supported from others):

- Th. Klähn (100% from LDRD)
- M. Pervin (50% from LDRD and 50% from SciDAC)
- R. D. Young (100% from OTD, E. P. Wigner Fellow)

### Number of Publications:

- 28 in refereed journals; 19 other (conference proceedings, book chapters, etc.). Also, 39 invited talks at conferences/workshops.
stars. Using a quantum field theoretical approach we showed that the deconfinement transition in a resulting stiff hybrid equation of state is weakly first order. This should be observable owing to the consequent changes in transport properties that govern the time evolution of rotation and cooling.

- We described hybrid neutron stars using a quantum field theoretical approach to quark matter that includes color superconductivity and a vector mean field. Color superconductivity plays an essential role in obtaining agreement between the cooling pattern and recently developed constraints. We argued that both pure neutron stars and neutron stars built around a quark matter core are consistent with modern compact star observations; and that hybrid star configurations with a color-flavor-locked quark superconductor core are unstable.

- We explored energy release in the neutrino untrapping transition as a new piece in the puzzle of identifying hybrid stars that masquerade as neutron stars. Quark matter searches in future generations of low-temperature/high-density nucleus-nucleus collision experiments, such as low-energy RHIC and CBM @ FAIR, might face a similar problem of trying to identify a deconfinement transition that is almost a crossover.

- We presented a hybrid equation of state for dense matter in which a nuclear matter phase is described within the Dirac-Brueckner-Hartree-Fock approach and a two-flavor quark matter phase is modelled according to a recently developed covariant, nonlocal chiral quark model. Modern observational constraints for compact star masses ($M \sim 2M_\odot$) are satisfied for a weak vector-like four quark interaction. The corresponding isospin symmetric equation of state is consistent with flow data analyses of heavy ion collisions and points to a deconfinement transition at a baryon density of roughly $0.55 \text{ fm}^{-3}$.

- It was shown that chiral symmetry and its dynamical breakdown in QCD place constraints on properties of mesons composed of two heavy-quarks, one of which is an identity relating the gauge invariant residues of these states in the inhomogeneous pseudovector and pseudoscalar vertex functions in the heavy-quark limit. In illustrating this identity, it was established that the leptonic decay constants for vector and pseudoscalar heavy-heavy mesons both increase linearly with current-quark mass on a domain that begins at approximately twice the $c$-quark mass.

- The applicability and viability of methods to obtain knowledge about bound-states from information provided solely in Euclidean space was examined. Rudimentary methods can be adequate if one only requires information about the ground and first excited state and assumptions made about analytic properties are valid. However, to obtain information from Schwinger functions about higher mass states, something more sophisticated is necessary. A method based on the correlator matrix was shown to be dependable when operators are carefully tuned and errors are small. That method is nevertheless not competitive when an unambiguous analytic
continuation of even a single Schwinger function to complex momenta is available.

• A comprehensive set of results for $B$-meson heavy-to-light transition form factors was reported. The calculation used a truncation of, and expression for, the transition amplitudes in which all elements are motivated by the study of Dyson-Schwinger equations in QCD. In this relativistic approach, which realizes confinement and dynamical chiral symmetry breaking, all physical values of momentum transfer in the transition form factors are simultaneously accessible. The results can be useful in the analysis and correlation of the large body of data being accumulated at extant facilities, and thereby in probing the Standard Model and beyond.

• The axial-vector Ward-Takahashi identity was used to derive mass formulae for neutral pseudoscalar mesons, which are exact in QCD. Adding that the $\eta'$ is not a Goldstone mode, exact chiral-limit relations were developed from the identity. They connect the dressed-quark propagator to the topological susceptibility. It was confirmed that in the chiral limit the $\eta'$ mass is proportional to the matrix element which connects this state to the vacuum via the topological susceptibility. The implications of the mass formulae were illustrated using an elementary dynamical model, which includes an Ansatz for that part of the Bethe-Salpeter kernel related to the non-Abelian anomaly. The model was employed in an analysis of pseudoscalar- and vector-meson bound-states. Despite its simplicity, the model is elucidative and phenomenologically efficacious; e.g., it predicted $\eta-\eta'$ mixing angles of $\sim (-15^\circ)$, $\pi^0-\eta$ angles of $\sim 1^\circ$, and a strong neutron-proton mass difference that is three-quarters of the $d-u$ current-quark mass difference.

• Continued application of a Poincaré covariant Faddeev equation to explain and predict nucleon properties enjoyed progress on numerous fronts. Preliminary results were obtained on the: distribution of the nucleon’s spin over that of its constituents and their orbital angular momentum; current-quark-mass-dependence of the nucleons’ magnetic moments; and flavor-separation of nucleon form factors.

• Moreover, we determined the nucleon’s transversity quark distribution functions. The calculations included, for the first time, the important effects of axial-vector diquark correlations. Only one preliminary measurement exists currently, inferred using data from the HERMES, COMPASS and BELLE collaborations. We found a transversity distribution larger than the central value of the experimental result – lying just outside the 1σ confidence interval. If the experimental result persists, it will represent a significant challenge to models of the nucleon based on the concept of a fixed-mass constituent-quark.

• Beginning with the Nambu–Jona-Lasinio model, we derived an equation of state for nuclear matter, expressed in terms of the parameters that characterize the model’s quark degrees of freedom. This relativistic, self-consistent framework enabled the study of finite quark-density effects on QCD observables. The inclusion of an isovector-vector field enabled us to study the
A nonrelativistic quark model developed earlier was applied to obtain the spectrum of baryons with strangeness -2 and -3. The model describes a number of well-established baryons successfully, and the application to cascade baryons allows the quantum numbers of some known states to be deduced.

We examined the spectrum of baryons containing heavy quarks using the quark model. The model gave masses for known heavy baryons that are in agreement with experiment, but for the doubly-charmed baryon $\Xi_{cc}$, reported by the Selex Collaboration, the model prediction is too heavy. However, that state needs to be confirmed, as a number of experiments (e.g., BELLE and BABAR collaborations), have searched for the state but failed to confirm the Selex result. In connection with the heavy cascade ($\Xi_Q$) spectrum, the model was used to determine the sextet-antitriplet mixing in known states. Mixing was found to be small for the lowest lying states. However, sextet-antitriplet mixing in the $\Xi_{bc}$ states was found to be large. We also examined heavy-quark spin-symmetry multiplets and found that many states in the model can be placed in such multiplets.

We have identified 22 excited states of the nucleon by performing a first dynamical coupled-channel analysis of the world’s data on pion-nucleon reactions up to an invariant mass of 2 GeV. The couplings of these excited states to meson-baryon states ($MB = \pi N, \eta N, \pi\Delta, \rho N, \sigma N$) have been determined. The resulting parameters are crucial input to the analysis of the world’s data on electromagnetic meson production reactions being performed by the Excited Baryon Analysis Center (EBAC) at Jefferson Laboratory.

The first results from a dynamical coupled-channel analysis of the world’s data on single pion photo- and electro-production reactions have been obtained. Coupled-channel effects in the $\Delta(1232)$ region have been revealed and meson cloud effects on $\gamma N \rightarrow N^*$ for 16 $N^*$ with mass $\leq 2$GeV have been predicted.

A method for extracting nucleon resonance parameters from data on $\pi N$ and $\gamma N$ reactions has been developed. It involves solving the dynamical coupled-channel scattering equations directly in the complex energy plane and thus does not have the uncertainties from using the conventional Speed-Plot method and/or Time-delayed method. Our technique is being applied to extract the nucleon resonance parameters from the scattering amplitudes determined via our analysis of the world’s data on pion-nucleon scattering and pion photoproduction.

The ratios of the nucleon structure functions $F_{2n}/F_{2p}$ at large $x (\geq 0.5)$ have been determined within a light-front model of inclusive lepton scattering on the proton and deuteron. Predictions have been made for analyzing the forthcoming data on $^3\text{He}$ and $^4\text{He}$. 

 effect of changing the proton-neutron ratio in the target. This is important for understanding the differing nuclear effects for electron and neutrino deep inelastic scattering on nuclear targets.
21. DETAIL ATTACHMENTS: (See specific attachments.)

- a. Facility requirements
- b. Publications
- c. Purpose (mandatory)
- d. Background

- e. Approach
- f. Technical progress
- g. Future accomplishments
- h. Relationships to other projects

- i. NEPA requirements
- j. Milestones
- k. Deliverables
- l. Performance Measures/Expectations

- m. ES&H considerations
- n. Human/Animal Subjects
- o. Security requirements
- p. Other (specify)

- A study was made of the effect of possible quark mass variation on the binding energies of light nuclei. Hadronic masses are predicted to change in a correlated way with changes in the current-quark mass by DSE calculations described above. The Argonne v14, Argonne v28, and Argonne v18 + Urbana IX Hamiltonians were parametrized for small changes in the nucleon, $\Delta$, $\pi$, and short-range meson (repulsive core) masses, and the rate of change of nuclear binding in $2n$, $^2$H, and $A = 3-8$ nuclei computed with Variational Monte Carlo (VMC) wave functions. These calculations were then used as input to studies of how quark mass variations could affect big-bang nucleosynthesis. They may also have a bearing on attempts to extrapolate $NN$ interaction properties from lattice QCD calculations made with large pion masses.

- VMC wave functions continue to be used to compute a large number of quasi-particle and quasi-hole amplitudes, and the corresponding spectroscopic factors, for $A = 3-10$ nuclei. Most recently, quasi-hole amplitudes were computed for a Ptolemy DWBA analysis of the $^9$Li(d,t)$^8$Li experiment led by R. Kanungo at TRIUMF.

- Our precise Green Function Monte Carlo (GFMC) calculations of charge radii of helium isotopes have made a prediction for the $^8$He radius that is in excellent agreement with the recent Argonne/GANIL experiment. Our work has also been an impetus for a recent JLab measurement of $^7$Li, $^9$Be and $^{10}$B radii that is now being analyzed.

- Work with the few-nucleon group at Pisa has detected an error in the programming of one term of the original Illinois three-nucleon potentials. We corrected this and produced a model designated IL7 which maintains excellent agreement with light-nuclei data.

- Our GFMC calculations of low-energy $s$- and $p$-wave scattering of neutrons on $^4$He were published. The GFMC calculations reproduced very well the zero-energy scattering length and low-energy phase shifts with the Argonne v18 + Illinois-2 Hamiltonian. Simpler interactions do not describe the $p$-wave data.

- GFMC calculations of electroweak matrix elements (E2, M1, Fermi and Gamow-Teller) were published for all experimentally measured transitions in $A = 6,7$ nuclei. In general the GFMC improves our previous VMC results. These are the first GFMC calculations of nuclear transitions. Preliminary calculations of $A = 8$ electroweak transitions have revealed difficulties in the GFMC determination of small components of the wave functions. We are working now to include meson-exchange current contributions which can make 10-20% corrections to the $M1$ matrix elements. We have also made calculations of $B(E2)$ transition rates for states in $^{10}$Be in support of a scheduled ATLAS experiment.
• We have used the same techniques to make GFMC evaluations of the isospin-mixing matrix elements of the AV18 interaction in the \(2^+, 1^+\) and \(3^+\) \(T = 0\) and \(T = 1\) excited states of \(^8\)Be. At present we obtain 120 keV out of the empirical 145 keV deduced for the \(2^+\) states. We are also investigating “Class IV” charge-symmetry-breaking terms (that connect \(T = 0,1\) np pairs), which heretofore have only been studied in medium-energy \(np\) scattering.

• Our VMC calculations of two-nucleon momentum distributions for the ground states of nuclei up to \(A = 8\) were published. We found that the density of np pairs with small total momentum and relative momentum in the range 300–600 MeV/c is much larger than that of the corresponding pp pairs. We showed this to be a result of tensor correlations induced by the one-pion exchange potential in this momentum range. Our result provides the basis for understanding a recent \(^{12}\)C(e,e'np) experiment at JLab and has led to an approved \(^4\)He(e,e'pN) experiment.

• We estimated the magnitudes of magnetic fields necessary to drive cool bottom processing inside red-giant and asymptotic giant stars.

• The \(r\)-process is understood to be responsible for the synthesis of approximately half of all the isotopes present in Solar System matter in the mass region from approximately zinc through the actinides. There remain open questions concerning how we might reconcile the apparent duplicity of \(r\)-process sites with extant models for the operation of the \(r\)-process in diverse astronomical environments. While we may yet remain theoretically challenged in our attempts to understand the \(r\)-process mechanism and to identify its site, significant clues have come from the observational side. Our analyses of two \(r\)-process-rich stars (CS22892-052 and BD +17\textdegree3248) and one \(r\)-process-poor star (HD 122563) further confirm an extraordinary robustness of the \(r\)-process mechanism and have led us to an exploration of the fission properties of the trans-actinide nuclei as a possible explanation of this behavior.

• The light-curves of Type Ia supernovae are known to be powered by the decay of radioactive nickel and cobalt isotopes, although many details of this process remain quite poorly understood. The need for a better understanding becomes ever more pressing with the constant improvement of observational data on both local and cosmological supernovae. In the dense core of the igniting white dwarf, matter is burned by a passing flame (the deflagration) to a hot soup of ashes in nuclear statistical equilibrium (NSE), where continuously occurring particle fusion is balanced by photodisintegration. This NSE state then evolves as the ashes undergo hydrodynamic evolution. As much as 40% of the available nuclear energy is released during this post-flame evolution, and proper treatment of this energy is essential to simulations of the early stage of a supernova. Together with researchers at the Chicago-based ASC Center for Astrophysical Thermonuclear Flashes, we developed a treatment of this NSE material that, in addition to modeling the evolution, accurately accounts for electron capture, neutrino loss, and screening of charged particle reactions and is for the first time fully consistent with the charged particle reaction screening used in the
dynamic burning (nuclear network) calculation which models the flame itself. This treatment has been implemented in the FLASH code, and is being used to simulate the early stages of a Type Ia supernova. This precise treatment of the energy release is also necessary for calculation of nucleosynthetic information for the ejecta. Comparison of this with observed spectral characteristics of the ejecta has consistently proven one of the most powerful observational tools for understanding the supernova process.

- One critical question concerning classical nova explosions is whether there might exist conditions under which “breakout” of the hot CNO burning sequences can occur, by means of the $^{14}\text{O}(\alpha,p)^{17}\text{F}$ or $^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$ reaction. This breakout may be understood on the basis of the identification of a population of cataclysmic variables that accrete hydrogen-rich matter at very low rates ($\sim 10^{-11} M_\odot \text{ yr}^{-1}$), such that ignition occurs at higher densities and temperatures exceeding 400 million K are realized. Using 1D models of nova thermonuclear runaways, we have demonstrated that breakout can indeed be achieved under limited but quite plausible runaway conditions. This may help to explain the large concentrations of intermediate mass nuclei (e.g. sulfur) observed to be present in the ejecta of some novae.

- We continued an exploration of the properties of reactive flows in the early stages of thermonuclear runaways leading to nova explosions. Our two dimensional hydrodynamic simulations suggest that convective undershoot mixing might serve to enhance the heavy-element content of the hydrogen-rich envelope. This is related to the more general issue of the identification of the mechanism of “dredge-up” of matter from the underlying white dwarf, which is responsible for the high observed concentrations of heavy elements ($\text{C},\text{O},\text{Ne},...$) present in nova ejecta. The timing of such enrichment can significantly impact the mass of the accreted envelope and the violence of the nova outburst.

- We have applied the close relationship that exists in a three-body model between the dipole response and the charge radius of a two-neutron halo nucleus to analyze recent measurements of $^{11}\text{Li}$. The goal was to use the data to put constraints on the structure of the two-neutron halo in $^{11}\text{Li}$. Thus, we were able to reproduce the dipole response extremely well using a three-body model that has a 25% s-wave component in the ground state of the two-neutron halo but to reproduce the measured charge radius we needed a model with a 50% s-wave component. The discrepancy between the two observables, namely, the dipole response and the charge radius of $^{11}\text{Li}$, is about $1.5\sigma$. Although this is a significant discrepancy, it is very encouraging that a three-body model of $^{11}\text{Li}$ works so well.

- Our numerical studies of heavy-ion fusion are based on the coupled-channels technique. The ion-ion potential we use is the M3Y double-folding potential, which we correct for the effect of the nuclear incompressibility. The correction is simulated by a repulsive interaction at short distances. The resulting entrance channel potential has a thicker Coulomb barrier and shallower pocket than
what is normally used. We have found that these features are essential for reproducing the
hindrance of fusion which has now been observed in many heavy-ion systems at extreme sub-
barrier energies.

- Using a shallow entrance channel potential in coupled-channels calculations also helps explain the
suppression of fusion that has been observed at energies far above the Coulomb barrier. However,
in order to reproduce the data at high energies (where many channels open up) it is necessary to
employ an imaginary potential that acts when the reacting nuclei overlap. The fusion hindrance at
extreme sub-barrier energies, on the other hand, can only be explained by employing ingoing wave
boundary conditions at short distances, without using an imaginary potential.

- We have applied our coupled-channels technique to analyze the fusion of the very asymmetric
system $^{16}$O + $^{208}$Pb, which has recently been measured down to very small cross sections. The
energy dependence of the measured fusion cross section for this system is very peculiar (even
without the new low-energy data) and has presented a challenge to theory for more than 20 years.
We find that it is possible to reproduce the data quite well (and better than what has been achieved
before) by considering the combined effects of excitations, the shallow entrance channel potential,
and couplings to one-neutron transfer channels. We were also able in this case to reproduce the
high-energy fusion data, which are suppressed compared to calculations that are based on a more
conventional ion-ion potential of the Woods-Saxon type.

- We are currently studying the fusion of the lighter systems that are of interest to nuclear
astrophysics. One problem in the coupled-channels approach is that inelastic channels become
closed at very low energies, namely, when the center-of-mass energy is smaller than the excitation
energy. This problem was solved by imposing the correct (radially decaying) boundary conditions
at large distances. Using this approach, it is possible to include the effect of couplings to the 2$^+$
and 3$^-$ states in the fusion of $^{16}$O+$^{16}$O and $^{16}$O+$^{18}$O, and the existing data could be reproduced quite
well. However, the extrapolation to energies that are relevant to astrophysics is still uncertain and
needs to be better constrained.

- One of the long-standing puzzles in nuclear structure studies is that mean-field potentials give
accurate predictions of single-particle energy level orderings and spacings within a shell, yet they
substantially underestimate the gaps between shells, as determined from mass differences. We
have shown that this discrepancy is resolved by taking n-p pairing interactions fully into account.
The calculated difference in n-p correlation energy of a closed shell $N = Z$ nucleus and the nucleus
having one less nucleon resolves this problem. We found that when this correlation energy is taken
into account, the mean-field spacings calculated for all shells and sub-shells between $^{16}$O and $^{56}$Ni
are in good agreement with the experimental data.
We have continued the development of a variational configuration-interaction method that can be applied to many-body wave-functions, providing solutions to any desired degree of accuracy. We have improved the code substantially, obtained an order of magnitude speed-up for systems with interactions that include like-particle pairing and particle-hole interactions. This is relevant for studies of the heaviest elements. We are developing a version of the code that includes $n$-$p$ pairing, in addition to like-particle pairing and particle-hole interactions.

We are working on problems of relevance to the basic energy science experiments being carried out at Argonne's Advanced Photon Source, and on studies of electron interactions with materials that are important for radiation physics and dosimetry. Comprehensive surveys of photo-interaction data for silicon and graphite are underway.

Construction of a dedicated beam line at the NIST reactor for our neutron electric-dipole-moment experiment was brought close to completion and a suitable monochromator designed. We have designed a new slotted perfect silicon crystal that will reduce the effects of surface imperfections on unwanted neutron spin rotation by the magnetic fields to an acceptable level. Such a crystal has been fabricated at Argonne and is ready for testing when the beam line is completed. All components needed for the reflectivity measurements on the new crystal are ready for installation. New magnetic field coils that are needed for neutron polarization tests that will follow the reflectivity measurements have been designed and are ready for fabrication.

Work on quantum theory representations of real numbers, as equivalence classes of Cauchy sequences of states of finite qubit strings, was extended to include sequences $\psi$ of states of finite qubit strings for any $k \geq 2$. As states of finite qubit strings, the elements $\psi(n)$ can either equal $|\gamma,h,s>$ which represents a specific rational number, or be linear superpositions of these states. Quantum theory representations of complex numbers were described by extending representations to include Cauchy sequences of pairs of states of finite qubit strings. Basic arithmetic relations and operations, described for the finite qubit string states, were lifted to apply to the Cauchy sequences. These are needed to prove that the finite string states represent rational numbers and the Cauchy sequences represent real or complex numbers.

Transformations were described on the space of finite qubit string states. These correspond to base transformations from $k$ to $k'$ and gauge transformations, as elements of $U(k)$ for each base $k$. The latter correspond to basis changes. It was seen that properties of the base transformations suggest that qubits, where $k$ is a prime number, may be elementary and that others are composites of these. This suggests the corresponding importance of the gauge transformations where $k$ is prime. Included are $U(1)$, $SU(2)$, $SU(3)$, $SU(5)$, [...]. The two degrees of freedom, base choice and basis choice, lift up to corresponding degrees of freedom of the quantum theory representations of real and complex numbers. These are represented as $R_{k,g}$, $C_{k,g}$ where g denotes a basis or gauge. The base and gauge transformations on the qubit string states induce transformations $R_{k,g} \to R_{k',g'}$. 

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A third degree of freedom was described that is based on the fact that qukit string states, as elements of a Fock space, are described in a mathematical structure that is itself based on the real and complex numbers. Iteration of the construction was described in which $R_{k,g}, C_{k,g}$ is used as the basis of another Fock space and the construction is repeated, etc. If $j$ labels an iteration stage, then $R_{j,k,g}, C_{j,k,g}$ are the corresponding real and complex number representations.

Combining this with the observation that all physical theories to date correspond to mathematical structures based on the real and complex numbers leads to the association of a frame $F_{j,k,g}$ with each $R_{j,k,g}, C_{j,k,g}$. Each $F_{j,k,g}$ contains representations of all physical theories as mathematical structures based on $R_{k,g}, C_{k,g}$. This leads to the construction of three dimensional frame fields with elements $F_{j,k,g}$. Some properties of these fields were described for the different types of iterations: finite, one-way infinite, two-way infinite, and cyclic.

We organized and hosted a JINA Special School on Nuclear Mass Models, held on the Argonne site during the period May 8-18, 2007. JINA is a National Science Foundation funded "Physics Frontier Center," the aim of which is the education of young researchers in both experimental and theoretical nuclear physics and nuclear astrophysics. Previous schools had addressed such questions as nuclear reaction networks and shell model calculations. This school was devoted to the exploration of mass models on both a theoretical and experimental basis. It provided reviews of experimental methods for mass determinations, theoretical modeling of nuclear masses, and their implications for outstanding questions in both nuclear structure and nuclear astrophysics. This school featured four lecturers who collectively presented discussions of theory, experimental methods, and applications to astrophysics: Mike Pearson, David Lunney, Guy Savard and Friedel Thielemann. These lectures highlighted the need for reliable mass laws that one can extrapolate to infer masses in both the proton- and neutron-rich domains, far removed from the valley of $\beta$-stability. Such masses constitute crucial input to studies of explosive nucleosynthesis events in astrophysics. In addition to the lectures, students were provided with representative exercises that allowed them to explore for themselves both the physics underlying the mass laws and the critical role they play in providing input nuclear properties for astrophysical studies. The students were also introduced to the experimental facilities at Argonne, which are employed to perform accurate measurements of nuclear masses. The school was jointly supported by JINA and Argonne LDRD funds. Additional information on the school can be found at:

phy.anl.gov/theory/index.html#massmodel
jinaweb.org/html/jinaworkshops2.html#event22

We hosted the twentieth Annual Midwest Theory Get-Together on October 5-6, 2007, for which the guest organizer this year was James Vary of Iowa State University. Nuclear theorists from eleven Midwest universities and ANL met to discuss problems of mutual interest. The meeting
provides a good chance for students to broaden their outlook and get some practical speaking experience in a friendly atmosphere. There were fifty registered participants: faculty, postdocs and students. Thirty-four presentations were made, covering topics such as: effective field theories; hadron physics and QCD; the nuclear shell model, nuclear pairing and nucleon matter; quantum Monte-Carlo methods; relativistic heavy ion collisions; and relativistic quantum mechanics for few body systems.

- We conducted an active theory visitor program, which brought internationally recognized visitors into the Division for seminars and keen discussions. These programs are key instruments for maintaining and enhancing the national and international reputation of the Theory Group and supporting its leadership role in contemporary nuclear physics.

**Plans for Future Research:**

- We will continue searching for systems with an enhanced potential for the detection of the effects of a variation in Nature’s fundamental constants and the violation of fundamental symmetries; and develop the general theory and perform specific calculations that are essential for related existing and future experiments at Argonne and elsewhere.

- We will resume studies of quantum electrodynamics in $2 + 1$ dimensions (QED3), with a particular emphasis on the chiral symmetry restoring and deconfinement transitions that occur as the number of fermion flavors is increased. There are indications that one can obtain information relevant to strong interaction dynamics from such studies.

- The chiral and deconfinement phase transitions in QCD at nonzero quark chemical potential and temperature will be studied in order to obtain an equation of state that can be employed to elucidate the nature of compact astrophysical objects. Amongst the critical questions are whether strange quark matter is stable, whether self-bound strange matter stars can exist, and whether neutron stars containing a quark matter core can exist and what observables would signal this. This research has direct bearing on our understanding stellar structure and the observational features of stars.

- We will continue our study of mesons in the mass region 1-2 GeV: both excited states of lighter mesons and ground states of axial-vector, hybrid and exotic mesons. The Poincaré covariant wave functions of these little studied systems contain material components that correspond to nonzero angular momentum. Hence, attempts to develop a veracious description focus attention directly on the long-range part of the quark-antiquark interaction.

- We will continue Poincaré covariant studies of mesons containing heavy-quarks and begin to explore the properties of baryons with one heavy-quark. The evolution of the properties of mesons composed of a heavy-quark and a heavy-antiquark are sensitive to features of the confinement
force in QCD, while those of heavy-light mesons and baryons containing a heavy-quark can be used to constrain Standard Model parameters.

- We will further develop a Poincaré covariant Faddeev equation approach to nucleon observables, in particular working toward retaining the pion cloud in a calculation of electromagnetic and hadronic form factors, and other properties. This will be a key step toward a parameter-free calculation of meson photoproduction from the nucleon; and enable direct, quantitative connections with the search for missing baryon resonances at JLab and elsewhere.

- We will continue to work toward an improved understanding of parton distributions in hadrons, particularly the pion and nucleon, with a near-term aim of performing a simultaneous calculation of meson valence and generalized parton distributions in a Poincaré covariant framework that is systematically connected with QCD. This promises to be a key step in addressing the important problem of developing an understanding of the relationship between parton properties on the light-front and the rest frame structure of hadrons. This is a critical issue because, e.g., dynamical chiral symmetry breaking and its corollaries, Goldstone’s theorem amongst them, which are keystones of low-energy QCD, have not been realized in the light-front formulation.

- We will continue work, based currently on the Nambu–Jona-Lasinio model, to build a self-consistent description of finite nuclei expressed in terms of the properties that characterize quark degrees of freedom. This research will aid progress toward resolving many longstanding problems; e.g., the EMC effect, and will likely expose new experimental avenues with which to explore QCD and nuclei.

- We will continue to develop improved methods in effective field theory (EFT) for the analysis of lattice-QCD results, with an emphasis on the comparison of theory with experiment. We will pursue advances in resummation techniques to systematically improve the convergence properties of the EFTs.

- The extraction of properties of resonances from finite-volume, Euclidean-space calculations will be investigated. A particular emphasis will be placed on identifying resonances in the presence of multiple scattering channels. This work will help guide the comparison of the physical results obtained by the Excited Baryon Analysis Center program at JLab and future lattice-QCD results.

- We will continue to provide theoretical support for upcoming low-energy experimental searches for new physics beyond the standard model. New theoretical research on hadron structure will also serve to strengthen the case for new experimental studies.
We will investigate the extent to which nucleon form factors can be described by a simple spectral representation of the mass operator and current density operators generated from kinematic impulse currents; and investigate quantitative relations between hadron model dynamics specified by Hilbert-space representations of Poincaré generators on the one hand and kinematically Poincaré invariant inner product measures of state vectors on the other.

The baryon wave functions obtained from a nonrelativistic quark model developed in previous work will be applied to calculate the form factors describing the semileptonic decays of double-heavy baryons. This project includes the calculation of decays from ground state doubly-heavy baryons to both ground and excited states of baryons containing two heavy quarks, as well as those containing one heavy quark. In addition to obtaining the decay widths, this calculation will provide us important information about the symmetries of the doubly-heavy baryon wave functions. A preliminary calculation indicates that hyperfine mixing in the wave function can lead to semileptonic decay rates that are significantly suppressed compared with the rates obtained using unmixed wave functions, in some cases. Polarization observables of these decays will also be examined using this quark model.

The application of coupled-channel reaction models in the analysis of meson production data from Jefferson Laboratory will continue, with the aim of testing the nucleon resonance parameters predicted by hadron models and lattice-QCD calculations.

We will continue to guide the development of the Excited Baryon Resonance Center at Jefferson Laboratory.

Exploration of the transition between the hadronic and partonic pictures of exclusive meson production reactions in the 2-10 GeV region will continue.

The study of neutrino-induced nuclear reactions and their use in interpreting experiments aimed at measuring the fundamental properties of neutrinos will continue.

Several results are showing that the Illinois three-nucleon potentials overbind neutron matter. With collaborators at Arizona State and in Trento, we are making modifications to the form of the potentials to solve this problem.

Quantum Monte Carlo studies of transitions in light nuclei will continue on several fronts. We will continue our GFMC calculations of electroweak transitions to $A = 8-10$ nuclei. Many of these transitions are from large to small components of the wave functions and hence are a stringent test of the wave functions and dynamics. We will also continue our calculations of isospin mixing in nuclei, specifically for $^4$He and $^{10}$C.
• Our precise calculations of charge radii will be completed and published.

• The study of higher excited states and unnatural-parity states in $A = 9,10$ nuclei will continue, including GFMC calculations of the one $\hbar \omega$ excitations in $A = 10$ nuclei, and first VMC studies of two $\hbar \omega$ states.

• Extensive work will be done on modifications of the GFMC program to enable efficient calculations of $^{12}$C on leadership-class computers and the development of the required trial wave functions. This work is jointly funded by proposal 1150.1; namely, "Low-Energy Nuclear Physics National HPC Initiative: Building a Universal Nuclear Energy Density Functional", and this FWP.

• We will continue working with JLab physicists on measuring correlations in nuclei via electron induced multi-nucleon knockout reactions.

• We will study $\alpha$-$p$, $^3$H-$n$, and $^3$He-$p$ scattering using GFMC techniques, and compute $\alpha$-$\alpha$ scattering as a first attempt at nucleus-nucleus scattering. Electroweak capture cross sections will be computed where capture is energetically allowed.

• We will compute asymptotic normalization coefficients (ANCs) of several light nuclei from VMC wave functions, by application of the Gell-Mann-Goldberger theorem. This theorem allows computation of the ANC for a nuclear breakup channel as an integral over the inner part of the wave function. The results will allow more effective use of the quantum Monte Carlo wave functions in several applications involving pickup, stripping, and radiative capture.

• One of the most important open questions in physics identified by the US National Academy of sciences in 2003 was: “How were the heavy elements from iron to uranium made?” The focus was on the operation of the $r$-process of neutron capture synthesis and on the identification of the astrophysical site in which it occurs. Over the next year, we will be investigating in detail the two designated sites for $r$-process synthesis – neutrino driven winds in supernovae and neutron star/neutron star or neutron star/black-hole collisions. In doing so, we will re-examine many feature of the nuclear physics critical to these calculations – fission, $\beta$-decay, $\beta$-delayed neutron emission and $\beta$-delayed fission. We will emphasize the need to reproduce the extraordinary robustness of this process, driven by observations of fossils stars, and the potential importance of using the uranium/thorium chronometer to date halo objects.

• We will work to understand the population distributions of nuclear abundances in stars and presolar grains, using a Monte Carlo model of galactic chemical evolution to examine both mean abundances in the interstellar matter and scatter about the mean. Major goals are to understand the origins of nitrogen and oxygen isotopes in presolar grains and the role of discrete nucleosynthetic
We will develop models of cool bottom processing during late stages of stellar evolution. We will determine consequences – particularly for lithium production – of flows carried by rapidly-rising bubbles and of bubbles that do not make it all the way to the surface layers. We will also make algorithmic improvements to speed up exploration of the parameter space that characterizes the processing.

We will identify constraints on the possible solutions to the discrepancy between the range of nitrogen isotopic ratios predicted by stellar evolution models and that found in presolar grains.

An outstanding issue with regard to novae concerns the timescale for nova systems to remain in outburst. The purely nuclear timescale for an outburst on a solar mass white dwarf characterized by a luminosity $\sim 3 \times 10^4 L_\odot$ is $\sim 100$ yr, in conflict with the typical timescales ($\sim 10$ yr) for observed nova systems to return to their pre-outburst states. We propose to explore the constraints these nuclear timescale considerations impose on other possible mechanisms for nova envelope depletion, such as wind-driven or common-envelope-driven mass ejection. We will identify nuclear signatures of these various mechanisms to permit observational tests.

Past observations with X-ray satellites (EXOSAT, and more recently Chandra and SWIFT) of classical novae at soft X-ray wavelength have confirmed the prediction that novae should be expected to evolve to super-soft X-ray sources (SSS) during later stages of decline. This is a forced consequence of the retreat of the photosphere to smaller radii while shell hydrogen burning continues at constant bolometric luminosity. Somewhat surprisingly, observations reveal that the onset of the SSS phase occurs quite early (about 6-9 months into outburst) for most systems, while the duration of this phase can range from one year to ten or more years. We will model the post-visual-maximum phase of evolution of novae in outburst in an attempt both to reproduce these observed timescales and to identify and confirm the dominant mechanism of envelope hydrogen depletion. We will also explore the relationship between this phase of nova evolution and the class of SSS events - not directly associated with novae – that are considered possible progenitors of Type Ia supernovae.

We will continue our study of the light-ion fusion reactions that are of interest to astrophysics. We want, in particular, to see whether the fusion hindrance observed in medium-heavy systems also plays a role in the fusion of lighter systems, and how it affects the extrapolation of the measured cross sections to very low energies. We will also analyze new measurements when they become available.

We plan to study the first-order theory of the Coulomb excitation of unstable nuclei at intermediate energies. The analysis of the excitation of $2^+$ (and other) states is currently based on straight line
trajectories, which makes it possible to include relativistic effects exactly. However, the analysis becomes unreliable at low energies, where Coulomb distortions of the trajectory can be large. We want to eliminate this limitation by devising a model that reduces to the conventional, non-relativistic Coulomb trajectory calculation at low energies and approaches the relativistic, straight-line trajectory calculation at high energies.

- It has now become possible to measure the decay energy spectrum of $^{11}\text{Li}$ in Coulomb dissociation experiments with much higher precision than in the past. It should therefore also be possible to extract reliable information about the (energy and angular) correlations of the two neutrons that are emitted. We intend to participate in these investigations and compare new experimental results to the predictions of our three-body models of $^{11}\text{Li}$.

- We shall apply the variational configuration method to studies of the heaviest elements, using realistic interactions and realistic single-particle energies. The problems of interest are octupole deformation effects and the structure of trans-plutonium elements. We shall continue to develop a code that includes particle-hole interactions in addition to $n-p$ pairing, in order to better understand the structure of nuclei near the proton drip-line.

- Studies of photon interaction data of selected materials will continue, with the use of sum rules and dispersion relations.

- Work will continue on a monograph entitled “Principles of Radiation Physics.”

- In FY2008, the dedicated beam line at NIST is expected to be completed and the monochromator installed and tested. Reflectivity measurements on the new slotted crystal will be carried out. A start will be made on the moving-MDM experiment. In FY2009, the moving-MDM experiment is expected to be completed and analyzed. That experiment will serve as a test bed for issues involved in the ultimate neutron EDM experiment, and a start will be made on detailed design work for that experiment. It is possible that we will be able to perform a preliminary EDM measurement in late FY2008 or FY2009, depending upon the results of the earlier experiments.

- Work will continue on elucidating the properties of the frame fields and more details of the construction of quantum theory representations of real and complex numbers. Moreover, work will continue in an effort to find some way of integrating this with physics.

- We will host an ANL/JINA sponsored school: Nuclear Astrophysics of the Cosmos, 2008, in July.

- We will organize and host a one-week meeting: July 25-29, to focus on the Nuclear Equation of State and its Implications for Astrophysics. Approximately twenty experts in this field will deliver
hour-long presentations on topics ranging from the traditional nuclear physics approaches to this problem, contemporary notions involving color superconducting quark cores within compact astrophysical objects, and the relevance of such inputs to novae and supernovae.

- We will also maintain an extensive and wide-ranging Theory Visitor program in all other areas of the Division's activities. This is a keystone of the Division's intellectual vigor.