Nuclear Physics Program at WNSL at Yale

Research Initiatives

In the last 5 years, the WNSL Program has been almost completely re-built, and WNSL has become a center for Nuclear Physics, attracting numerous long term visitors, collaborators and users. The core WNSL research program comprises three parallel and complementary initiatives:

- **Nuclear Structure**
- **Nuclear Astrophysics**
- **Relativistic Heavy Ions**

Nuclear Structure

The new Nuclear Structure program exploits a suite of new state-of-the-art instruments.

YRAST Ball:	Largest University based γ-ray spectrometer, 30 detectors including ~8 clovers.
SPEEDY+NYPD:	Doppler-shift lifetime experiments.
SASSYER:	Large acceptance gas-filled separator.
ICEY Ball:	Six-fold mini-orange spectrometer, hosted at Yale between Gammasphere runs.
SAMMY:	Superconducting magnet g-factor measurements following β-decay.
MTC:	β-delayed γ-ray spectroscopy with clover detectors.
GRAFIK:	Coulex of exotic beams in inverse kinematics.

While the nuclear structure program is entirely new, and the initial focus was on building a new group and developing new instruments, this program has already achieved a number of important research discoveries, as reflected in its publication record. From 1998, for example, this program has 27 Letters and 63 Invited Talks at International Conferences. The research comprises four broad themes.

- **Evolution of Structure**

The emphasis here is on the study of nuclear transitional regions as a function of N and Z and, in particular, the study of phase transitional behavior. Recent discoveries at Yale have shown that, to an extent heretofore largely unrecognized, finite nuclei do exhibit phase transitional behavior closely resembling that of other many-body systems, including evidence for phase coexistence, phase mixing, and critical point nuclei. This has directly inspired the invention of a new class of structural benchmarks for nuclei, specifically for critical point nuclei, which provide analytic, parameter-free (except for energy and transition rate scale factors) predictions for what have hitherto been considered the most complex and difficult nuclei to treat. The very productive collaboration between WNSL and the Yale theory group has led to the discovery of empirical manifestations of both the E(5) and X(5) paradigms for phase transitions of vibrator → γ-soft and vibrator → symmetric rotor types, respectively. These new structures arguably provide the first entirely new paradigms of structure since the vibrator, rotor, and γ-unstable concepts put forward in the 1950s.

· **Collective modes**

The emphasis here is on various types of collective excitations, especially phonon and multi-phonon modes in deformed nuclei. Extensive new data has been obtained with both stable and exotic beam experiments on $K=0^+$ excitations and to search for double γ-vibrations, considerably altering our understanding of these modes.

· **Proton-Neutron Collectivity**

Several aspects of proton-neutron collectivity have been another major focus of study. Studies of shears (scissors) bands have led to the first identification of these sequences in the trans-Bi region. The newly proposed concept of chiral bands has been explored near the A~140 region, in collaboration with scientists from Stony Brook, Tennessee, the UK, and elsewhere. Efforts are underway to establish unique signatures of these modes, to find solid empirical examples, and to map the extent of chiral symmetry breaking. Proton-neutron mixed symmetry states are another active research area, focusing on multi-phonon mixed symmetry states and quasi-deuteron states in N=Z nuclei.

· **Exotic Nuclei**

Current and forthcoming experiments at HRIBF and ISAC involve the study of collective modes (e.g., two phonon excitations) via β-decay with advanced γ-ray detector systems and of equilibrium structure with low energy Coulomb excitation. A mass measurement program at WNSL led by D. Brenner of Clark University is providing new data for important rp-process nuclei. Effort has also gone into the development of detectors for Coulomb excitation, using the infrastructure of the Joint Detector Development Laboratory(JDDL). Finally, WNSL faculty are playing leadership roles in the exotic beam effort worldwide and for RIA in the US.

Nuclear Astrophysics

The Yale Nuclear Astrophysics program is currently focused on problems related to explosive hydrogen burning in Novae and X-Ray Bursts environments, in which the temperatures and densities are sufficiently high so that proton and α-particle induced reactions can bypass β-decay processes. This program is carried out via nuclear reaction experiments, at Yale and at complementary radioactive beam facilities, such as ANL, ORNL, and TRIUMF. As an example, our current study of the locations and properties of ^{22}Mg resonances for the ^{18}Ne(α,p) and ^{21}Na(p,γ) reactions involves a combination of stable and radioactive beam measurements, including measurements using the ^{12}C(^{16}O,^{6}He)^{22}Mg reaction at WNSL, and collaborative measurements using radioactive ^{21}Na beams at ANL [^{21}Na(p,α)^{18}Ne] and TRIUMF [^{21}Na(p,γ)^{22}Mg], and of the ^{25}Mg(^{3}He,^{6}He)22Mg reaction at Yale. We are also carrying out similar complementary stable-beam and radioactive-beam studies of ^{14}O+α and ^{17}F+p resonances in ^{18}Ne; ^{18}F+p resonances in ^{19}Ne; and ^{25}Al+p resonances in ^{26}Si.

Developmental work focuses on implementing a "LEDA" array to be used in coincidence with our split-pole focal-place detector to measure proton and α-particle decays from resonances, such as the ^{22}Mg states mentioned above - i.e., the ^{12}C(^{16}O,6He)^{22}Mg(α)^{18}Ne and ^{12}C(^{16}O,^{6}He)^{22}Mg(p)^{21}Na reactions. These experiments can determine the strengths and importances of these various resonances for direct radioactive beam measurements. The installation of this array is now complete, and initial testing and calibration have been carried out. A first look at the $^{12}C(^{16}O,^{6}He)^{22}Mg(p)^{21}Na$ reaction has already taken place as well.

Relativistic Heavy Ions

The Relativistic Heavy Ion (RHI) Group, headed by STAR spokesperson J. Harris, and the Yale high energy physics group collaborate closely on STAR to provide a stimulating atmosphere and a strong effort on STAR. This, accompanied by Yale's relative proximity to the RHIC facility at Brookhaven National Laboratory, gives the program unique research opportunities.

The primary focus of the RHI physics program is to utilize the spectra of various types of particles (up to large transverse momenta) to better understand high density QCD and the possible formation of a chirally symmetric, deconfined state. Over the past three years, the RHI Group has led a successful effort to propose, modify, install, and operate in STAR a Ring Imaging Cherenkov (RICH) detector, developed at CERN for use in the LHC-ALICE experiment, to extend the particle identification capabilities of STAR to high transverse momentum. The group has also invested heavily in the STAR particle identification and general analysis software, in simulations to extend STAR's physics capabilities, and is heavily involved in the data analysis for physics from last summer's first RHIC run.

The RHI group is contributing significantly and will play a major role in the long-term STAR physics program. Present studies include innovative tracking and particle identification, and simulation studies to determine the future capabilities to measure open charm (D-mesons), $J/\psi \rightarrow e^+e^-$, and $\varphi \rightarrow e^+e^-$ in STAR. The group has been involved in detector R&D to determine an optimal implementation of new detectors to measure open charm. In accordance with the long range plan for STAR, the RHI group intends to construct a small CsI evaporation facility to test, develop and improve RICH detectors and to fabricate CsI pad planes for future RICH detectors for STAR.

Operations

In the operations area, the last 3-4 years have seen large improvements in efficiency and increased operating hours at the same time as a cost reduction effort has lowered operating costs by over 35% (actual dollars). In 1999-2000 the ESTU Tandem operated at the highest efficiency and for the most hours in its history, with more than double (115% *increase)* the beam-on-target hours compared to 96-`97, and yet with the lowest operations costs since 1991. Scheduled beam time was 5004 hours. Total experimental run time (including non-accelerated beam use) was 4850 hours. The Tandem operated well at voltages over 19 MV.

Improvements made to the ESTU since 1996 include installation of a new terminal, complete with charge state selector, a dead section foil stripper, new control system interfaces, and a more reliable negative ion source. A test ion injector was constructed, allowing ion beams to be developed independent of machine operation. At the same time, the Operations staff spent a significant amount of time on design, construction, implementation and maintenance of our new instruments, including the current efforts to install SASSYER, as well as to support the STAR project at RHIC. No major Tandem upgrades are envisioned, except possibly the addition of bunching capability.

Other Issues: Budgets, In-House vs. Outside Research, Students

FY2001 and FY2000 budgets are shown in the Table below. The current balance of effort among the Nuclear Structure, Astrophysics, and Relativistic Heavy Ion programs is expected to continue although some funding improvements to the RHI program are needed to replace a departing faculty member and to bring it to an asymptotic level of effort.

There are important needs for continued capital funds for the acquisition of clover detectors, the development of new instruments for studies with exotic beams, and new capabilities for the STAR detector. Also, the Nuclear Structure program is attracting numerous long-term visitors (9 sabbatical visitors in five years alone): it is vital to continue such highly leveraged, cost-effective enhancements.

Near-term funding needs reflect the continuation of the programs that have just been developed. Since salaries represent 80-85% of total budgets, constant budgets at the FY2001 level would present a serious intermediate and long-term problem. Consequences would be elimination of the cost-effective long-term visitor program, reduced running time at the Tandem, reduced productivity in all programs and collaborations, and a likely reversal of the research turn-around just achieved. A true constant level of *effort* budget, based on the FY 2001 level augmented by the minor (~$250K) additions for the RHI and visitor programs mentioned above, could provide a thriving sustainable research program.

In the Nuclear Structure and Astrophysics programs, continuing use of outside facilities, especially exotic beam facilities, is an important complementary (~25%) part of a coherent overall program. This effort will likely increase slightly in the next few years, and dramatically when RIA is operational. The RHI effort, of course, is based at BNL.

A particularly advantageous aspect of the WNSL program is access to outstanding graduate, as well as a large number of undergraduate, students who obtain extensive research experience at WNSL.

The entire WNSL program is new and flourishing, with new people (6 new faculty, 9 sabbatical visitors since 1995), new instruments, new research initiatives, and new results.

Table: Budgets, Staffing, Users/Collaborators[a)]

Funding		**FY2000**	**FY2001**
Nuclear Structure, Astrophysics, Operations	Total	$2,633,000	2,601,000
	Research	1,133,000	1,146,000
	Equipment	339,000	281,000
	Operations	1,161,000	1,174,000
RHI	Total	765,000	765,000

Staffing	**Perm. Ph.D.**	**Tech/Admin**	**Post Docs**	**G. S.**	**U. G.**
Nuclear Structure, Astrophysics, Operations	5	12	3	7	6
RHI	3	1	3	5	2

Users/Collaborators	**Total**	**PhD/G.S./Other**	**DOE/NSF/Other/Foreign**
Nuclear Structure and Astrophysics	47	60% 40% 0%	34% 28% 4% 34%

[a)] Does not include the recent addition of the Medium Energy program of V. Hughes.