The research project “*Nuclear Gamma-Ray Spectroscopy at the Limit of Particle Stability*” with sponsor ID “*DE-FG02-04ER41334*” started late-summer 2004 and aims at the investigation of highly excited low-spin states of selected key-nuclei in the vicinity of the particle separation threshold by means of high-resolution gamma-ray spectroscopy in electromagnetic excitation reactions. This work addresses nuclear structures with excitation energies close to the binding energy or highly excited off-yrast states in accordance with the NSAC milestones. In 2005 the program was extended towards additional use of virtual photons and theoretical description of the low-lying collective excitations in the well deformed nuclei.

The population of the nuclear low-spin states of interest is obtained by nuclear reactions using light projectiles, such as γ -rays or protons. The experiments were carried out with the γ -ray beams of the HI γ S facility at the Duke Free Electron Laser Laboratory, at the bremsstrahlung facility at the Universität Stuttgart, and at the bremsstrahlung facility at the Universität Darmstadt. Some of the proton-induced and light ion-induced reactions have been performed at the Stony Brook accelerator facility.

The experimental part of the program was extended towards use of virtual photon exchange reactions (Coulomb excitation) for study of highly-excited collective low-spin states in nuclei. This method is based on observation of low-multiplicity γ -ray events from inverse kinematics Coulomb excitation with a 4π γ -ray spectrometer. That part of the program has been performed at Argonne National Laboratory. We have shown that in this way we can identify and probe the 2^+ states of any vibrational nucleus that can be made available as an ion beam. Within this project we have studied the $^{136,138}\text{Ce}$ and ^{134}Xe nuclides that have natural abundances of 0.19%, 0.25% and 10.4%, respectively. The technique, however is completely generic and equally applicable to radioactive beams that can be produced with sufficient intensity ($\sim 10^6$ ions/s for detailed spectroscopy, $\sim 10^3$ ions/s for identification). The high selectivity for $J = 2$ states avoids much traditional searching and reveals the entire $E2$ strength distribution in a few hours.

In 2005, we also have made a special attempt to describe and understand the low-lying collective excitations in well deformed nuclei within the frame work of the Confined Betta Soft collective model [N. Pietralla, O.M. Gorbachenko, Phys. Rev. C 70, 011304 (2004)]. This attempt included a theoretical development of the CBS model and several experiments to test the predictions of the model. The experiments were performed at the Stony Brook accelerator facility.

EQUIPMENT: Four ORTEC HPGe γ -ray detectors have been purchased at \$108,000 with a total γ -ray detection efficiency of 200% (50% each) relative to a standard NaI detector. Comparing to the initially proposed EURISYS clover detector with an efficiency of 120% (current cost $\approx$ \$150,000 at time of available funds), we have chosen to procure the domestic detectors for more efficiency but at a lower cost. The detectors were delivered in February 2006. In addition, three SiLi-charged particle detectors were borrowed by our group on a permanent loan from FZ Jülich, Germany. They have thicknesses of 0.5, 1.0 and 3.0 mm, and each has an active area of 66 mm in diameter. They are 32-fold segmented and hence each has 32 sub-detectors. Depending on the particle mass and energy, different combinations of detectors can be used as a charged particle identification telescope. The detectors have been tested and incorporated in a particle- γ scattering chamber which have been designed at NSL Stony Brook. The chamber is intended for

future $(p, p'\gamma)$ experiments

EXPERIMENTS & PUBLICATIONS: According to the research plan in our initial proposal a number of experiments were performed already in 2004 and early 2005. The method of Nuclear Resonance Fluorescence (NRF) was employed in most cases.

NRF measurements in the reaction $^{94}\text{Mo}(\gamma, \gamma')$ with an end-point energy of 6.8 MeV and the reaction $^{93}\text{Nb}(\gamma, \gamma')$ with two end-point energies of 2.7 and 4.0 MeV, were performed at the S-DALINAC in Darmstadt and at the bremsstrahlung facility of the Stuttgart DYNAMITRON accelerator, respectively. The complex data from both bremsstrahlung-induced experiments is under analysis which is lead by our group.

An additional photon scattering experiment on ^{148}Sm has been performed in the $^{148}\text{Sm}(\gamma, \gamma')$ reaction with an end-point energy of 3.2 MeV in Stuttgart. The data were analyzed by us and were published recently with one of our students as the lead-author [T.C. Li, N. Pietralla *et al.*, Phys. Rev. C **71**, 044318 (2005)].

We have performed two more NRF experiments at the HI γ S facility at Duke University at the end of 2004 and early 2005. First, we studied $\text{Pb}(\vec{\gamma}, \gamma')$ photon scattering reaction in order to assign spin and parity quantum numbers to the doublet states in ^{207}Pb , which are resulting from coupling of the $\nu(p_{1/2}^{-1})$ neutron hole to the strong $E1$ excitation at 5.512 MeV in ^{208}Pb . Nearly monochromatic, linearly polarized photon beams of HI γ S at an energy at 5.6 MeV were employed in this study. Seven excitations were observed. The azimuthal intensity asymmetry allowed the determination of the spin and parity quantum numbers of the doublet states in ^{207}Pb as well as the other excitations in $^{206,208}\text{Pb}$. The results from this work are currently prepared for publication.

Another experiment aimed at the search for the $\pi(d_{5/2}) \rightarrow \pi(d_{3/2})$ proton spin-flip 1^+ state of the noble gas isotope ^{40}Ar . The $^{40}\text{Ar}(\vec{\gamma}, \gamma')$ photon scattering reaction was used to search for spin-flip $M1$ strength in ^{40}Ar . The nearly monochromatic, linearly polarized photon beam of HI γ S, in an energy region from 7.7 to 11 MeV, was employed in this study. Twenty-eight dipole excitations were observed. The azimuthal intensity asymmetry indicated that all of these states were $E1$ except for the state at $E_x=9.757$ MeV. Shell-model calculations were used to interpret this state as one fragment of the spin-flip $M1$ strength in ^{40}Ar . The results from this work are accepted for publication in Phys. Rev. C [T.C. Li, N. Pietralla *et al.*, Phys. Rev. C accepted, (2006)].

Additionally, we have collaborated on five NRF experiments of which the results have recently been published. They are: (i) measurements on dipole and quadrupole excitations in $^{88}\text{Sr}(\gamma, \gamma')$ up to 6.8 MeV in Darmstadt, [L. Käubler *et al.*, Phys. Rev C **70** 064307 (2004)]; (ii) parity assignments in ^{92}Zr and ^{96}Mo between 2.8 and 3.9 MeV at HI γ S at Duke University, [C. Fransen, N. Pietralla *et al.*, Phys. Rev. C **70** 044317 (2004)]; (iii) parity assignments in $^{172,174}\text{Yb}$ between 2.9 and 3.6 MeV at HI γ S at Duke University, [D. Savran *et al.*, Phys. Rev. C **71** 034304 (2005)]; (iv) measurements on dipole and quadrupole excitations in $^{100,98}\text{Mo}(\gamma, \gamma')$ up to 3.2 to 3.8 MeV, respectively, in Stuttgart [G. Rusev *et al.*, Phys. Rev. Lett. **95**, 062501 (2005).]; and (v) study of low-lying dipole excitations in vibrational nuclei in NFR experiments in Stuttgart [C. Kohstall *et al.*, Phys. Rev. C **72**, 034302 (2005)].

Two experiments on ^{93}Nb using $^{94}\text{Zr}(p, 2n\gamma)^{93}\text{Nb}$ and $^{94}\text{Nb}(n, n\gamma)^{93}\text{Nb}$ were carried out at the University in Cologne and at University of Kentucky in collaboration with C. Fransen, J. Jolie (Köln), N. Orce, S.W. Yates (Lexington). Excitation functions, lifetimes, and branching ratios

were measured, and multipolarities and spin assignments were determined. The $J^\pi = 3/2^-$ and $5/2^-$ states at 1840 and 2013 keV, respectively, are identified as mixed-symmetry states associated. The results from this study are published in [C.J. McKay *et al.*, Eur. Phys. J. **A 25**, Supplement 1, 377 (2005); Eur.Phys.J. A 25, Supplement 1, 773 (2005)].

Utilization of the proton beam available at NSL Stony Brook was an important part of our research program. We have measured the lifetime of the $T=0$, $J=3$ state of ^{58}Cu at 444 keV. The excited states in ^{58}Cu were populated with the $^{58}\text{Ni}(p, n)$ reaction. A lifetime $\tau = 0.468 \pm 0.085$ ns was found with the delayed γ -radiofrequency coincidence method with respect to the pulsed LINAC beam. It corresponds to an isoscalar E2 transition strength of 7.6(1.4) W.u. to the $T=0$, $J=1$ ground state. The result agrees with the interpretation of the 3_1^+ state as a collective quadrupole excitation of the 1_1^+ ground state of ^{58}Cu [A. Costin *et al.*, Phys. Rev. **C 72**, 054305 (2005)].

We have continue to work on the theoretical description the low-spin excitations in well deformed nuclei. Recently, we have demonstrated that the CBS model reproduces with an amazing precision the ground-state rotational bands of strongly deformed heavy even-even nuclei [K. Dusling and N. Pietralla, Phys. Rev. **C 72**, 011303 (2005)]. Moreover, we have used the available experimental set-up at NSL Stony Brook test further the predictions of the CBS model. Two experiments have been performed. First, medium- and low-spin states of ^{160}Er have been populated via the reaction $^{159}\text{Tb}(^6\text{Li}, 5n)$. In this experiment new levels have been identified and interpreted as the even-spin members of the γ -band and members of the β -vibrational band. Level energies and branching ratios are compared to the CBS rotor model predictions [K. Dusling, N. Pietralla *et al.*, Phys. Rev. **C 73**, 014317 (2006)]. Very recently we have performed an analogous experiment on ^{164}Yb using the $^{156}\text{Gd}(^{12}\text{C}, 4n)$ reaction. The results from this experiment are currently under analysis.

In an attempt to border the experimental possibilities we have extended the current program to the reactions involving virtual photon exchange. Excited states in ^{138}Ce have been studied via the $^{12}\text{C}(^{138}\text{Ce}, ^{138}\text{Ce}^*)$ Coulomb excitation reaction at 480 MeV at Argonne National Laboratory. The Coulomb excitation reaction can be considered as a virtual photon exchange reactions. In this experiment the relative population cross-sections in ^{138}Ce have been determined from the γ -ray yields observed with Gammasphere. The $E2$ and $M1$ strength distributions between the lowest six 2^+ states up to 2.7 MeV enables us to identify the 2_4^+ state in ^{138}Ce as the dominant fragment of the one-phonon $2_{1,\text{ms}}^+$ mixed-symmetry state. Mixing between this level and a nearby isoscalar state is observed and is more than four times larger than in the neighboring isotone ^{136}Ba . This is direct evidence that the stability of mixed-symmetry states strongly depends on the underlying sub-shell structure. The results from this study will appear in the next issue of Phys. Rev. Lett. [G. Rainovski, N. Pietralla *et al.*, Phys. Rev. Lett. **96 in print** (2006)].

The success of the ^{138}Ce initiated a new experimental program at Argonne National Laboratory. Two Coulex experiments on ^{134}Xe and ^{136}Ce have been approved by the ATLAS PAC and have been performed in the end of 2005. The data from these experiments are currently under analysis. Moreover, the ATLAS PAC has approved recently a proposal for Coulex experiment on the whole chain of stable Xe isotopes. This experiment is expected to be performed in the first half of 2006.

Additionally, we have become a vital part of a big international collaboration which aims on performing Coulomb excision experiments with radioactive (RIBs) beams. In the frame work

of this collaboration we have participated in a Coulex experiment on ^{134}Ce and ^{136}Nd which was performed in March 2005 at GSI, Darmstadt, Germany. In this experiment the yrast and non-yrast 2^+ States of ^{134}Ce and ^{136}Nd were populated in relativistic Coulomb excitation for first time. The results from this experiment will be submitted to Phys. Rev. Lett. very soon [T. Saito *et al.*, in preparation]. We also participated in an ISOL Coulex experiment on ^{88}Kr at REX-ISOLDE, CERN, Switzerland in September, 2005. The data from this experiment is currently under analysis.

CONFERENCE CONTRIBUTIONS:

1) Yale Workshop 2005: Nuclear Structure Physics near the Coulomb Barrier: Into 21st Century, Yale, June 23 - 23, 2005:

- G. Rainovski, "Identification of 2^+_{ms} Mixed Symmetry State in ^{138}Ce " - oral presentation;
- T. C. Li, "Search for the $d_{5/2} \rightarrow d_{3/2}$ spin-flip M1 Transition in ^{40}Ar " - oral presentation;
- A. Costin, "Sub-Nanosecond Lifetime Measurement for the $T = 0, 3^+$ State of Odd-Odd N=Z ^{58}Cu " - oral presentation;

- T. Ahn, "Measurement of the E2/M1 Multipole-mixing ratio in ^{136}Ce " - oral presentation;

- K. Dusling, "Excited K=0 band in ^{160}Er and Description of Collective Bands with CBS Rotor Model" - oral presentation;

2) Gordon Research Conference: Nuclear Chemistry, June 4-9, 2005, Colby-Sawyer College, New London, NH:

- N. Pietralla - invited speaker;
- G. Rainovski, K. Dusling, A. Costin - poster presentees;

3) The 12th International Conference on Capture Gamma-Ray Spectroscopy and Related Topics, University of Notre Dame, Notre Dame, September 4-9, 2005

- N. Pietralla - "In-Beam g-Spectroscopy of Low-Spin Mixed-Symmetry States of ^{138}Ce with Gammasphere in Singles-Mode" - invited speaker;

4) International Workshop: Symmetries and low-energy phase transition in nuclear-structure physics, 9-11 October 2005, Camerino, Italy

- N. Pietralla - "Nuclear structure beyond the critical point" - invited speaker;

STUDENTS:

Alin Costin, entered school fall 02, joining group fall 03, degree expected: 2006.

Tan Ahn, entered school fall 02, joining group fall 03, degree expected: 2006.

Kevin Dusling, entered school fall 04, joining group summer 04, degree expected: 2008.

Tak Chu Li, undergraduate student, joining group May 04, expected graduation to BS: spring 2006.

PUBLICATIONS:

[1] L. Käubler *et al.*, Phys. Rev C **70** 064307 (2004).

[2] C. Fransen, N. Pietralla *et al.*, Phys. Rev. C **70** 044317 (2004).

- [3] D. Savran *et al.*, Phys. Rev. C **71** 034304 (2005).
- [4] T.C. Li, N. Pietralla *et al.*, Phys. Rev. C **71**, 044318 (2005).
- [5] G. Rusev *et al.*, Phys. Rev. Lett. **95**, 062501 (2005).
- [6] C.J. McKay *et al.*, Eur. Phys. J. A **25**, Supplement 1, 377 (2005); Eur.Phys.J. A 25, Supplement 1, 773 (2005).
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- [8] K. Dusling and N. Pietralla, Phys. Rev. C **72**, 011303 (2005).
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- [11] T.C. Li, N. Pietralla *et al.*, Phys. Rev. C **accepted for publication** (2006).
- [12] G. Rainovski, N. Pietralla *et al.*, Phys. Rev. Lett. **96 in print** (2006).