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MICROSCOPIC HEAVY-ION THEORY

FINAL REPORT
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1 Final Report: Recent Milestones Achieved

The Vanderbilt nuclear theory group conducts research in the areas of low-energy nuclear reactions and in neutrino oscillations. Specifically, we study dynamics of nuclear reactions microscopically, in particular for neutron-rich nuclei which will be accessible with current and future radioactive ion beam facilities. The neutrino work concentrates on constructing computational tools for analyzing neutrino oscillation data. The most important of these is the analysis of the Super K atmospheric data.

Our research concentrates on the following topics which are part of the DOE Long-Range Plan:

- STUDIES OF LOW-ENERGY REACTIONS OF EXOTIC NUCLEI (Professors Umar and Oberacker), including sub-barrier fusion cross sections, capture cross sections for superheavy element production, and nuclear astrophysics applications. Our theory project is strongly connected to experiments at RIB facilities around the world, including NSCL-FRIB (MSU) and ATLAS-CARIBU (Argonne).

- PHENOMENOLOGY OF NEUTRINO OSCILLATIONS (Prof. Ernst), extracting information from existing neutrino oscillation experiments and proposing possible future experiments in order to better understand the oscillation phenomenon.

In particular, we have reached these milestones:

- We have extended our capabilities to pursue accurate microscopic calculations of heavy-ion reaction phenomena. We have developed a new formalism, the density-constrained time-dependent Hartree-Fock (DC-TDHF) method, to calculate ion-ion potentials $V(R)$, mass parameters $M(R)$, precompound excitation energies $E^*(R)$ in a fully microscopic and dynamical TDDFT framework. These microscopically obtained quantities allow the calculation of above and sub-barrier fusion cross sections for neutron-rich systems, quasi-fission dynamics in heavy-ion reactions, capture cross sections for superheavy element production, and nuclear astrophysics applications. In particular, we have investigated the energy-dependence of potential barriers and its effect on fusion cross sections for ^{40}Ca+^{40}Ca and ^{16}O+^{208}Pb. In collaboration with experimentalists at Indiana University (Prof. de Souza's group) we have studied sub-barrier fusion enhancement in ^{18}O+^{12}C. We investigated the dissipative dynamics of quasifission in the reactions ^{40,48}Ca+^{238}U. The results show that for neutron-rich ^{48}Ca beams quasifission is substantially reduced. In collaboration with experimentalists at NSCL/MSU (Prof. Zach Kohley's group) and at Australian National University (Prof. David Hinde's group), we calculated mass-angle distributions for neutron-rich and neutron-deficient Cr+W reactions and gave a detailed comparion with measured data. Also, we have been invited to write a paper on "Time-dependent HF approach to SHE dynamics", which has been accepted and will appear in a Special Issue of Nuclear Physics A (2015) devoted to Superheavy Elements. Finally, Prof. Umar has presented preliminary TDHF quasifission dynamics results for ^{48}Ca+^{249}Bk $\rightarrow Z = 117, A = 297$ at the International "Nuclear Structure and Dynamics 2015" Conference, in Portoroz,

Slovenia and at the "12th International Conference on Nucleus-Nucleus Collisions (NN2015)", in Catania, Italy. In particular, we studied contact time, masses and charges of the QF fragments, fragment excitation energies and mass-angle distributions (MADs).

- In the high-performance computing (HPC) realm our group is a major developer and maintainer of two modern TDDFT codes. Umar has authored or has been involved in authoring a number of the TDDFT codes developed since the mid 1980's. The current codes, developed around mid 2000's onward, make no simplifications about reaction geometry and work in full three-dimensional Cartesian space. They also employ the modern effective interactions. In addition, they make use of powerful numerical methods for highly accurate calculations. One of these codes, Sky3D, is in print in Computer Physics Communications as an Open Access code. We will provide world-wide user support for this code through a web site on our local computers. Our local code, VU-TDDFT, incorporates many additional features to allow for the calculations mentioned above and contains all of the time-odd and tensor terms for the effective interaction.

- We have completed a global analysis of neutrino oscillation data, the first to include fully the linear in θ_{13} terms and examined the size and sign of θ_{13} and our ability to determine the hierarchy. Prior to recent measurements of θ_{13} the effects were found to be less than one sigma. We have shown that the smallness of the effects governing the size and sign of θ_{13} and the hierarchy arises from a broken symmetry, the simultaneous interchange of the sign of θ_{13} and the hierarchy. We proposed an improved Bayesian method for theorists to calculate the allowed regions and the error bars for the mixing parameters.

2 LIST OF PUBLICATIONS (Feb. 2014 - Jun. 2015)

Refereed Journal Articles and Book Chapters

1. *Formation and dynamics of fission fragments*, C. Simenel and A. S. Umar, Phys. Rev. C 89, 031601(R) (2014).

2. *Eulerian rotations of deformed nuclei for TDDFT calculations*, D.A. Pigg, A.S. Umar, and V.E. Oberacker, Computer Physics Communications 185 (2014) 1410-1414

3. *Energy dependence of potential barriers and its effect on fusion cross sections*, A.S. Umar, C. Simenel, and V.E. Oberacker, Phys. Rev. C 89, 034611 (2014) [10 pages]

4. *Sub-barrier enhancement of fusion as compared to a microscopic method in* $^{18}O+^{12}C$, T. K. Steinbach, J. Vadas, J. Schmidt, C. Haycraft, S. Hudan, R. T. deSouza, L. T. Baby, S.A. Kuvin, I. Wiedenhöver, A. S. Umar, and V. E. Oberacker, Phys. Rev. C 90, 041603(R) (2014) [5 pages].

5. *Dissipative dynamics in quasifission*, V.E. Oberacker, A.S. Umar, and C. Simenel, Phys. Rev. C 90, 054605 (2014) [5 pages]

6. *The TDHF Code Sky3D*, J. A. Maruhn, P.-G. Reinhard, P. D. Stevenson, and A.S. Umar, Comp. Phys. Comm. 185, 2195-2216 (2014)

7. *Microscopic study of the effect of intrinsic degrees of freedom on fusion*, C. Simenel , M. Dasgupta, D. J. Hinde , V. E. Oberacker , A. S. Umar, and E. Williams, Proceedings of "FUSION14", EPJ Web of Conferences 86, 00047 (2015) [6 pages]

8. *Reduced quasifission competition in fusion reactions forming neutron-rich heavy elements*, K. Hammerton, Z. Kohley, D. J. Hinde, M. Dasgupta, A. Wakhle, E. Williams, V. E. Oberacker, A. S. Umar, I. P. Carter, K. J. Cook, J. Greene, D. Y. Jeong, D. H. Luong, S. D. McNeil, C. Palshetkar, D. C. Rafferty, C. Simenel, and K. Stiefel, Phys. Rev. C 91, 041602(R) (2015) [5 pages]

9. *Quantal description of nucleon exchange in a stochastic mean-field approach*, S. Ayik, O. Yilmaz, B. Yilmaz, A. S. Umar, A. Gokalp, G. Turan, and D. Lacroix, Phys. Rev. C 91, 054601 (2015).

10. *Impact of approximate oscillation probabilities in the analysis of three neutrino experiments*, B. K. Cogswell, D. C. Latimer, D. J. Ernst, Submitted to AHEP, Through Neutrino Eyes: The Search for New Physics (2014) (arxiv:1406.1478).

11. *Time-dependent HF approach to SHE dynamics*, A.S. Umar and V.E. Oberacker, invited paper to appear in Special Issue of Nuclear Physics A (2015) on Superheavy Elements; arXiv:1412.1755v1 [nucl-th] 4 Dec 2014; accepted, in print

12. *Density constrained TDHF*, V.E. Oberacker and A.S. Umar, invited paper honoring work related to Prof. Joachim Maruhn, to be published in "Progress of time-dependent nuclear reaction theory" in the eBook series: "Frontiers in nuclear and particle physics" by Bentham Science Publishers; arXiv:1502.04079v1 [nucl-th] 13 Feb 2015

Conference Organizing Committees / Sessions Chaired

1. Sait Umar, Organizer, *Session on Fusion and Fission*, Gordon Conference (GRC2015) Nuclear Chemistry, Colby-Sawyer College, New London, NH, USA (May 31 - June 5, 2015).

Invited talks at International/National Conferences and Workshops

1. *Dynamics of Quasifission and Fission* A.S. Umar, International Symposium on Super Heavy Nuclei, Texas A & M University, College Station TX, USA, (March 31 - April 02, 2015)
2. *Dynamics of quasifission* A. S. Umar, V. E. Oberacker, and C. Simenel, Proceedings of International "Nuclear Structure and Dynamics 2015" Conference, Portoroz, Slovenia
3. *Quasifission dynamics in TDHF* A. S. Umar, V. E. Oberacker, and C. Simenel, Proceedings of the "12th International Conference on Nucleus-Nucleus Collisions (NN2015)", Catania, Italy

Colloquia and Seminars given at other institutions

1. *Fusion and quasifission of neutron-rich nuclei using a Time-Dependent Density Functional Theory*, V.E. Oberacker, Nuclear Science Seminar, National Superconducting Cyclotron Laboratory at Michigan State University, April 23, 2014

APS Conference Abstracts

1. *Fusion, fission, and quasi-fission using TDHF*, Sait Umar and Volker Oberacker, APS Spring Meeting, Savannah, GA (April 2014), Bull. Am. Phys. Soc., vol.59 , No.5 (2014), p.161