STUDIES OF HEAVY-ION REACTIONS AND TRANSURANIC NUCLEI

Progress Report
September 1, 1990 - August 31, 1991

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University of Rochester
Rochester, New York 14627

August 1991

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TABLE OF CONTENTS

	Page
I. <u>ABSTRACT</u>	3
II. <u>INTRODUCTION</u>	4
III. <u>RESEARCH PROGRAM</u>	10
A. The Cold Fusion Episode	11
B. Statistical Decay Anomalies in the Fusion-Evaporation Reaction $^{32}\text{S} + ^{124}\text{Sn}$ at $E_{\text{lab}} = 130\text{-}180$ MeV	17
C. Decay Channels of the Compound Nucleus ^{156}Er Formed in $^{100}\text{Mo} + ^{56}\text{Fe}$ and $^{144}\text{Sm} + ^{12}\text{C}$ Reactions	34
D. Energy Partition in Near-Barrier Strongly Damped Collisions $^{58}\text{Ni} + ^{208}\text{Pb}$	57
E. Frictional Processes and Nuclear Disassembly in Very-Heavy-Ion Collisions in the Fermi Energy Regime	70
F. Neutron Multiplicity Measurements as a Test of the Character of the Collision	118
G. Formation and Decay of Hot and Heavy Systems Studied with a 4π Neutron Detector	128
H. Evaporation and Nonequilibrium Neutron Emission in Binary Au + Pb Collisions at 29 MeV/nucleon	136
I. 4π Measurement of Neutrons and Charged Particles in the Reaction $^{209}\text{Bi} + ^{136}\text{Xe}$ at 28.2 MeV/nucleon	151
J. Binary Reaction Character in Highly Dissipative $^{209}\text{Bi} + ^{136}\text{Xe}$ Collisions at 28.2 MeV/nucleon	187
K. Energy and Efficiency Calibrations of a 4π Neutron-Multiplicity Meter ...	210
L. A Microcomputer-Based Seven-Channel Stepping Motor Controller	219
IV. <u>PUBLICATIONS AND ACTIVITIES</u>	
A. Articles	232
B. Invited Lectures	233
C. Contributed Papers at Professional Meetings	234
D. Professional Activities	234
V. <u>PERSONNEL</u>	235

I. **ABSTRACT**

The development of the "cold-fusion" episode is reviewed. Ongoing studies of compound-nucleus formation and decay via the neutron multiplicity distribution confirm the validity of conventional statistical theory. The excitation energy partition in near-barrier damped $^{58}\text{Ni} + ^{208}\text{Pb}$ collisions is found to be largely independent of the direction of net mass transfer, supporting a diffusion-like nucleon-exchange mechanism. Exclusive experiments on the heavy reaction systems $^{197}\text{Au} + ^{208}\text{Pb}$ and $^{209}\text{Bi} + ^{136}\text{Xe}$ in the Fermi-energy domain have revealed important new insights into the reaction mechanism, which is found to be dominated by damped, binary processes. The effectiveness of the neutron multiplicity as an impact-parameter filter is demonstrated. It is shown that very-heavy-ion reactions lead to transient nuclear systems with temperatures in excess of $\tau = 6$ MeV and transfer of large, aligned spins to reaction fragments. The first measurements of neutrons in coincidence with kinematically identified reaction fragments provide evidence for the binary, sequential character of dissipative collisions in the Fermi-energy domain. Also for the first time, a full event characterization was achieved for nuclear reactions in terms of neutrons and charged particles. Technical information on this experiment is provided. First results yield strong evidence for dominantly binary primary reaction dynamics of even highly dissipative $^{209}\text{Bi} + (28 \text{ MeV/u}) ^{136}\text{Xe}$ collisions, associated with several intermediate-mass fragments.

II. INTRODUCTION

The research program of the University of Rochester nuclear chemistry group is supported by the United States Department of Energy under Grant DE-FG02-88ER40414. Experimental work by the group discussed in this report was conducted at the upgraded MP tandem accelerator of the University of Rochester Nuclear Structure Research Laboratory, at the SuperHILAC accelerator of the Lawrence Berkeley laboratory, at the cyclotron accelerator complex of the French heavy-ion research facility GANIL, and at the K1200 cyclotron of the National Superconducting Cyclotron Laboratory of Michigan State University. Joint experimental projects have been pursued with groups of nuclear scientists from the French research centers GANIL, LPC Caen, CRN Strasbourg, and IPN Orsay, from the Hahn-Meitner Institut Berlin, from Warsaw University, and most recently with groups from Indiana Academy/Ball State University, Michigan State University and Washington University at St. Louis. Preliminary and interim results of experimental and theoretical work performed by our group during the past year, summarized below, are discussed in detail in Section III.

This work includes the development of new and innovative experimental hardware and of computer simulation codes, experimental measurements and analyses, as well as theoretical investigations. For example, a medium-size 4π neutron multiplicity meter (NMM) was built, tested and commissioned by the group. This device has already been used in experiments at the University of Rochester Nuclear Structure Research Laboratory. The group has employed this NMM in conjunction with the St. Louis charged-particle detector array. This seminal experiment represents the first nuclear reaction study ever to accomplish a full event characterization in terms of 4π coverage of both neutrons and charged particles. Design studies, not further discussed in this report, are under way for an advanced, segmented NMM to be used in calorimetric studies of intermediate-energy heavy-ion reactions.

Energy dissipation and the formation of hot nuclear systems in heavy-ion reactions constitute the underlying theme of all research projects pursued by the group during this grant period. The exploration of aspects of dissipation and relaxation in complex nuclear

reactions has been the goal of studies of low-energy nuclear fusion, as well as of experiments on heavy-ion reactions in the Fermi energy regime.

To a certain extent, the general theme applies also to the first contribution to this report in which one of us (JRH) summarizes the contents of his monograph on the "cold-fusion episode". If claims of D-D fusion induced in an electrolytic cell had been substantiated, this discovery would have been revolutionary. As it stands, the development of this episode can serve as an illustration of the necessity to obey stringent standards in the generation and publication of scientific results.

In the regime of bombarding energies of a few MeV per nucleon, we have extended our series of investigations of the possible influence of entrance-channel effects on formation and decay of composite nuclei to the systems Dy and Er, both in the region of super-deformed nuclides. The new experiments study both neutron and charged-particle decay channels. First results on the multiplicity distributions of neutrons emitted in the $^{118}\text{Sn} + ^{32}\text{S}$ and the $^{124}\text{Sn} + ^{32}\text{S}$ fusion reactions indicate smaller heat capacities (level density parameters) for the heavier than for the lighter Dy isotopes. The measurement of first and second moments of the neutron multiplicity distribution permitted our collaboration to determine unknown parameters of the statistical model which is found capable of describing neutron and charged-particle distributions in a consistent fashion. There seems to be no need to invoke entrance-channel effects in the description of Sn + S fusion reactions. Investigations of the fusion reactions $^{100}\text{Mo} + ^{56}\text{Fe}$ and $^{144}\text{Sn} + ^{12}\text{C}$ leading both to the composite ^{156}Er follow a similar strategy. These latter measurements have just begun, and only raw experimental data are shown to give a general impression of experimental problems to be overcome.

Our ongoing systematical investigation of energy dissipation and relaxation in damped heavy-ion reactions was extended to near-barrier energies. The $^{58}\text{Ni} + ^{208}\text{Pb}$ reaction at only ≈ 80 MeV above the barrier was chosen for a direct determination of the magnitude of correlations between mass asymmetry and excitation energy partition by measuring the multiplicities and energies of neutrons emitted from the reaction fragments.

The experimental results indicate that the fraction of the total excitation energy deposited in a fragment is largely independent of the net mass transfer to or from that fragment. This observation provides evidence for a diffusion-like character of the multi-nucleon exchange processes, even at bombarding energies near the barrier.

A large effort of the group's work went into investigations of the transitional features of intermediate-energy heavy-ion reaction mechanisms. An overview over the reactions $^{197}\text{Au} + ^{208}\text{Pb}$ and $^{209}\text{Bi} + ^{136}\text{Xe}$ at approximately 30 MeV per nucleon is given in Section III, discussing the general strategy followed in the study to identify new reaction mechanisms, as well as calling attention to the increasing importance of nonequilibrium particle emission at higher bombarding energies. It is demonstrated by experimental results from both the above reactions that the total multiplicity of neutrons emitted in a heavy-ion reaction is an excellent, unique indicator of the collision impact parameter, covering the entire range from very peripheral to central collisions. It is further shown that dissipative reaction mechanisms dominate still in the Fermi energy domain, although for central collisions, massive remnants of the primary reaction partners are no longer observed in the experiments.

In separate contributions, the formation and decay of hot and heavy systems are discussed in terms of the total neutron multiplicity. The selectivity of the multiplicity observable for the collision impact parameter is shown for the $^{197}\text{Au} + ^{208}\text{Pb}$ reaction. This study also demonstrates the importance of angular-momentum transfer to the primary reaction products in reactions that contain angular momenta of the order of $1-2k\hbar$. This conclusion is based on the large anisotropies observed in the experiment for sequential-fission fragments with respect to the primary reaction plane.

Results of systematic measurements of multiplicities of neutrons, emitted in collisions of projectiles ranging from Ar to Pb with heavy targets, are discussed in terms of the average excitation energy deposited in the hot nuclear systems formed transiently in a reaction. For the most dissipative Kr-induced collisions at 32 MeV per nucleon, temperatures in excess of 6 MeV have been inferred from the data. Although neutron

multiplicities are observed to increase with increasing bombarding energy, their rate of increase is smaller than expected from the increase in available energy. This effect could possibly be due to the existence of a limit to the temperatures that a nucleus can sustain.

Since neutrons are the most abundant of all particles emitted in intermediate-energy heavy-ion reactions, an exclusive experiment has been performed for the reaction $^{197}\text{Au} + ^{208}\text{Pb}$ at 29 MeV per nucleon, to study multiplicities, energies, and angular correlations of neutrons in coincidence with charged-reaction products ranging from light particles to projectile-like fragments. For the first time, neutrons have been observed in coincidence with both kinematically identified binary reaction partners. Neutrons observed in this reaction are dominantly due to evaporation from the hot primary products of a reaction which is rather reminiscent of the damped-reaction process prevalent at lower bombarding energies. In addition, significant nonequilibrium components of high-energy neutron jets are observed at sideward angles.

Important new insights into the intermediate-energy heavy-ion reaction mechanism will be gained from the first nuclear reaction experiment accomplishing a full, 4π event characterization in terms of neutrons and charged particles. The reaction $^{209}\text{Bi} + ^{136}\text{Xe}$ was studied at 28.2 MeV per nucleon using a combination of 4π neutron and charged-particle detectors. Details of experimental setup, system performance, and detector calibrations are presented, and first results on multiplicity correlations are discussed. The relative sensitivities of neutron and charged-particle multiplicities to reaction impact parameter are pointed out.

A first analysis of the correlations of light-charged-particle emission patterns with the numbers of emitted neutrons has demonstrated the interesting potential of this method. Consistent with the results of the neutron time-of-flight study performed by the group for the $^{197}\text{Au} + ^{208}\text{Pb}$ reaction, the charged particles emitted in the above $^{209}\text{Bi} + ^{136}\text{Xe}$ reaction were observed to be largely due to sequential evaporation from the hot primary fragments of a binary heavy-ion collision. Unexpectedly, such binary emission patterns are observed also for central collisions which are associated with the emission of up to 12

intermediate-mass fragments. This observation must be viewed as the most convincing evidence reported so far for the persistence of the binary (and sequential) character in highly dissipative collisions induced in the Fermi energy domain of bombarding energies.

A series of calibration measurements were carried out to compare the performance of the new Rochester neutron multiplicity meter (NMM), used in the above experiments, with the expectations of a simulation code developed by the group from a less sophisticated original version. It was found that the internal scattering chamber of the NMM did not have a detrimental effect on the light-collection efficiency, and that the response of the NMM to neutrons was well modeled by the simulation calculations.

Due to the complexity and compactness of experimental arrangements used in the 4π measurements mentioned above, it was found necessary to effect an increasing number of functions, requiring mechanical motion of parts of the apparatus, under remote control. Two cooperating electronic microprocessor modules have been designed and built, allowing us to control up to seven stepping motors independently.

During the academic year 1990-1991, the principal investigators devoted 50% (WUS) and 25% (JRH) of their efforts to research supported by this grant, while for the summer months of 1991, these fractions were 100% and 30%, respectively. The research associates devoted all of their time to grant research. The advanced students (BMQ, SPB and BMS) have committed all of their time to grant research. One graduate student (XJ) was supported mainly by a teaching assistantship during the first half of the 1990/1991 academic year but spent on average about 20% of his time on group research. He has since elected to continue his graduate studies in more applied chemistry. All graduate students worked full-time in the group during June-August 1991. In addition, the group has been host for Ms. Lidia Hiu, a Rochester high school student and recipient of a SEED project fellowship sponsored by the American Chemical Society.

To the best of our knowledge, we have complied with all grant requirements. It is a pleasure to acknowledge the direct support of our research program by the United States Department of Energy. In addition, we are grateful to the National Science Foundation for

providing indirect support through the use of the facilities of the Nuclear Structure Research Laboratory of the University of Rochester.

III. RESEARCH PROGRAM

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IV. PUBLICATIONS AND ACTIVITIES

A. Articles

D. Pade, R.T. DeSouza, W.U. Schröder, J. Töke, and J.L. Wile "Trends in Fragment Heating in the Damped Reaction $^{165}\text{Ho} + ^{56}\text{Fe}$ at 7.2 MeV/u" *Phys. Rev. C* **43**, 1288 (1991).

E. Piasecki, B. Lott, R. Bougault, S. Bresson, J. Collin, E. Crema, J. Galin, B. Gatty, A. Genoux-Lubain, D. Horn, D. Guerreau, J. Jastrzebski, D. Jacquet, U. Jahnke, A. Kordyasz, C. LeBrun, J.F. LeColley, M. Louvel, M. Morjean, C. Paulot, L. Pienkowski, J. Pouthas, B. Quednau, W.U. Schröder, E. Schwinn, W. Skulski, J. Töke "Nuclear Disassembly," *Phys. Rev. Lett.* **10**, 390 (1991)

J. Töke, R. Planeta, W.U. Schröder, and J.R. Huizenga, "Correlations between Energy and Mass Partition in the Damped Reaction $^{165}\text{Ho} + ^{74}\text{Ge}$ at $E_{\text{Lab}} = 8.5$ MeV/nucleon", *Phys. Rev. C* **44**, 390, (1991)

M.B. Chatterjee, S.P. Baldwin, J.R. Huizenga, D. Pade, B.M. Quednau, W.U. Schröder, B.M. Szabo and J. Töke, "Energy Partition in Near-Barrier Strongly Damped Collisions $^{58}\text{Ni} + ^{208}\text{Pb}$ ", submitted to *Phys. Rev. C Rapid Comm.* 1991.

W.U. Schröder, "Frictional Processes and Nuclear Disassembly in Very-Heavy-Ion Collisions in the Fermi Energy Regime", Proceedings of the IVth International Conference on Nucleus-Nucleus Collisions, Kanazawa, Japan, June 10-14, in press.

B.M. Quednau, S.P. Baldwin, M.B. Chatterjee, J.R. Huizenga, W.U. Schröder, B.M. Szabo, J. Töke, U. Jahnke, D. Hilscher, H. Rossner, B. Lott, S. Bresson, J. Galin, D. Guerreau, M. Morjean, and D. Jacquet, Correlations of Neutrons with Massive Fragments in the Reaction $^{197}\text{Au} + ^{208}\text{Pb}$ at 29 MeV per Nucleon, Proceedings of the XI Workshop on Nuclear Dynamics, Key West, 1991, World Scientific, in press.

M. Morjean, S. Bresson, E. Crema, J. Galin, D. Guerreau, C. Paulot, J. Pouthas, B. Gatty, D. Jacquet, E. Piasecki A. Kordyasz, J. Jastrzebski, L. Pienkowski, W. Skulski, B. Lott, R. Bougault, J. Colin, A. Genoux-Lubain, D. Horn, C. LeBrun, B. Quednau, W.U. Schröder, J. Töke, U. Jahnke, Formation and Decay of Hot and Heavy Systems Studied with a 4π Neutron Detector, Proceedings of the XI Workshop on Nuclear Dynamics, Key West, 1991, World Scientific, in press.

D. Jacquet, S. Bresson, R. Bougault, J. Colin, B. Cramer, E. Crema, J. Galin, B. Gatty, A. Genoux-Lubain, D. Guerreau, D. Horn, U. Jahnke, J. Jastrzebski, A. Kordyasz, C. LeBrun, J.F. LeColley, B. Lott, M. Louvel, M. Morjean, C. Paulot, E. Piasecki, L. Pienkowski, J. Pouthas, B. Quednau, F. Saint-Laurent, W.U. Schröder, E. Schwinn, W. Skulski, A. Sokolov, J. Töke, X.M. Wang, Neutron Multiplicity Measurements as a Test of the Character of the Collision, Proceedings of the XXIX International Winter Meeting on Nuclear Physics, Bormio, Italy, 1991 in press.

B. Invited Lectures

"Influence of Rotation-Induced Nuclear Deformation of the Decay of Hot Nuclei", Colloquium, Michigan State University Cyclotron Laboratory, October 9, 1990 (J.R. Huizenga)

"Cold Fusion Research", University Forum Lecture, University of Rochester, October 16, 1990 (J.R. Huizenga)

"Cold Fusion", Nuclear Structure Research Laboratory Seminar, November 8, 1990. (J.R. Huizenga)

"Neutron Calorimetry for Heavy-Ion Reactions" Seminar, Department of Chemistry, Washington University, St. Louis, November 8, 1990. (W.U. Schröder)

"The Decay of ^{156}Er " Seminar, Nuclear Structure Research Laboratory, University of Rochester, November 15, 1990 (B. Szabo)

"The Decay of ^{156}Er Compound Nucleus" Seminar, Chemistry Department, University of Rochester, November 19, 1990 (B. Szabo)

"Cold Fusion - The Scientific Fiasco of the Century", Ithaca College, February 19, 1991 (J.R. Huizenga)

"The Status of Cold Fusion Claims", The Fourteenth Leroy Randle Grumman Lecture, The Grumman Corporation, March 6, 1991 (J.R. Huizenga)

"Cold Fusion: Fact or Fiction", Roberts Wesleyan College, March 15, 1991 (J.R. Huizenga).

"Dissipative Dynamics of Heavy Ion Reactions between 6 and 30 MeV/nucleon", International Spring School in Nuclear Physics, Holzhau-Dresden, Germany, April 8, 1991 (W.U. Schröder)

"The Cold Fusion Fiasco", The 201st ACS National Meeting in Atlanta, GA, April 16, 1991 (J.R. Huizenga)

"From Binary Collisions to Nuclear Disassembly-Heavy-Ion Reactions in the Fermi Energy Domain", Seminar, Departments of Physics and Chemistry, University of Washington, Seattle, May 9, 1991 (W.U. Schröder)

"From Binary Collisions to Nuclear Disassembly-Heavy-Ion Reactions in the Fermi Energy Domain", Seminar, Departments of Physics and Chemistry, Oregon State University, Corvallis, May 10, 1991 (W.U. Schröder)

"Frictional Processes and Nuclear Disassembly in Very-Heavy-Ion Collisions in the Fermi Energy Regime", Invited talk at the IVth International Conference on Nucleus-Nucleus Collisions, Kanazawa, Japan, June 10-14, 1991 (W.U. Schröder),

"Dissipative Heavy-Ion Reactions at Fermi Energies", Seminar, Hahn-Meitner-Institut Berlin, June 26, 1991 (W.U. Schröder)

C. Contributed Papers at Professional Meetings

Search for Cold Donor-Fragment Production in the Near-Barrier Heavy-ion Reaction $^{58}\text{Ni} + ^{208}\text{Pb}$, M.B. Chatterjee, S. Baldwin, J.R. Huizenga, D. Pade, B. Quednau, W. U. Schröder, R.T. deSouza, B. Szabo, J. Töke, and J.L. Wile, *Bull. Am. Phys. Soc.* **36** 1243 (1991).

Search for Anomalies in the Neutron Decay of Gd Composite Nuclei Formed in $^{118,124}\text{Sn} + \text{Si}$ Fusion, B. Szabo, S. Baldwin, S.S. Datta, J.R. Huizenga, B.M. Quednau, W.U. Schröder, R.T. deSouza, J. Töke, and J.L. Wile *Bull. Am. Phys. Soc.* **36** 1244 (1991).

Energy Dissipation and Neutron Emission in the Reaction $^{197}\text{Au} + (6 \text{ GeV}) ^{208}\text{Pb}$, B.M. Quednau, S.P. Baldwin, M.B. Chatterjee, J.R. Huizenga, W.U. Schröder, B.M. Szabo, J. Töke, U. Jahnke, D. Hilscher, H. Rossner, B. Lott, S. Bresson, J. Galin, D. Guerreau, M. Morjean, and D. Jacquet, *Bull. Am. Phys. Soc.* **36** 1244 (1991).

D. Professional Activities**W. Udo Schröder**

Member of the American Physical Society, Division of Nuclear Physics, 1977- .

Member of the American Chemical Society, Division of Nuclear Chemistry and Technology.

Session Chair at the Symposium entitled "Towards a Unified Picture on Nuclear Dynamics", in Nikko, Japan, June 6-8, 1991

Session Chairman, 7th Winter Workshop on Nuclear Dynamics, Key West, January 26-February 2, 1991.

Referee for Journal Articles and Proposals to Funding Agencies.

Member or Chair of several ad hoc and search committees, University of Rochester.

Chairman and/or member of Ph.D. examining committees, University of Rochester, 1984 - .

Member (1990-91) of the Graduate Recruiting Committee, University of Rochester, Department of Chemistry.

Member of Nuclear Structure Research Laboratory Computing Committee 1991

Member of Nuclear Structure Research Laboratory Steering Committee, University of Rochester, 1979-.

Member of Services and Space Committee, Department of Chemistry.

Member of University Computing VMS Committee, 1986 -.

Member of University of Rochester Academic Computing Study Group, 1991.

John R. Huizenga

Chairman, NAS-NRC Committee on Nuclear and Radiochemistry

Member of the Chemistry Review Committee, Lawrence Livermore National Laboratory

Member of Oak Ridge National Laboratory Physics Advisory Committee

Member of AUI Visiting Committee for the Brookhaven National Laboratory Chemistry Department

Member of Advisory Board of NSF Center for Photoinduced Charge Transfer

Chair, Faculty Recruiting Committee of Department of Chemistry

Member of Research Grants and Contracts Committee of Department of Chemistry

Leroy Randle Grumman Medal for Outstanding Scientific Achievement, March 6, 1991

Member of Advisory Council of the Glenn T. Seaborg Institute for Transactinium Science, Lawrence Livermore National Laboratory

Referee of Journal Articles and Agency Proposals

V. **PERSONNEL**

Mr. S. Baldwin, Graduate Student, Department of Chemistry

Dr. M. Chatterjee, Postdoctoral Fellow

Dr. J.R. Huizenga, Tracy H. Harris Professor of Chemistry and Physics

Mr. X. Jiao*, Graduate Student, Department of Chemistry

Dr. B. Lott**, Research Associate

Mr. B. Quednau, Graduate Student, Department of Chemistry

Dr. W.U. Schröder, Professor of Chemistry

Dr. W. Skulski, Visiting Scientist

Mr. B. Szabo, Graduate Student, Department of Chemistry

Dr. J. Töke, Senior Research Associate

*Fall semester

**On leave from CRN Strasbourg, France

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