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STUDIES OF NUCLEAR FISSION, LOW-ENERGY NUCLEAR
REACTIONS AND TRANSURANIC NUCLEI

John R. Huizenga
Principal Investigator

June 1, 1971 - June 1, 1972

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University of Rochester
Department of Chemistry

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Studies of Nuclear Fission, Low-Energy Nuclear
Reactions and Transuranic Nuclei

Supported by the U. S. Atomic Energy Commission
under Contract AT(11-1)3496

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I. GENERAL

A. Introduction

The research group supported under the United States Atomic Energy Commission contract AT(11-1)3496 is in large part located at the Nuclear Structure Research Laboratory. Two members of the group are located in the Chemistry building. In the summer of 1972 we plan to move into new laboratory and office space in Hutchison Hall, the new Chemistry-Biology building.

The Nuclear Structure Research Laboratory is supported by a grant from the National Science Foundation. The major fraction of our experimental program is carried out with the Emperor tandem Van de Graaff in this laboratory. We plan to participate in collaborative programs in the future on the Superhilac at Berkeley and the Meson Factory at Los Alamos.

We wish to acknowledge the direct support of our research programs by the U. S. Atomic Energy Commission and the New York State Science and Technology Foundation. In addition, we are grateful to the National Science Foundation for providing a large amount of indirect support through the use of the facilities at the Nuclear Structure Research Laboratory.

B. Personnel

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* Appointed April 1, 1972. Supported by U.S.A.E.C. and Scientific Ministry of West Germany. Supported jointly with Dr. M. Blann.

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Dr. C. C. Lu - Postdoctoral Research Associate

Dr. H. K. Vonach^{****}

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Mr. W. Hensley[†] - Graduate Student, Department of Chemistry

Mr. M. Kildir[†] - Graduate Student, Department of Chemistry

Mr. G. T. Rizzo - Graduate Student, Department of Chemistry

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Miss E. Bailey - Undergraduate Student, Department of Chemistry

^{**} Supported one-half time by U.S.AEC

^{***} Appointed February 1, 1972. Supported by U.S.AEC and New York State Science and Technology Foundation

^{****}For period of one month, September 1 to September 30, 1971 - Supported by New York State Science and Technology Foundation. Permanent address: Technische Universität München, Germany

[†] Supported during Academic Year by a Fellowship through the Department of Chemistry

C. Publications and Activities

1. Articles

C. C. Lu, J. R. Huizenga, C. J. Stephan and A. J. Gorski, EFFECTS OF ISOSPIN ON STATISTICAL NUCLEAR DECAY, Nuclear Physics A164, 225-245 (1971).

G. Yuen, G. T. Rizzo, A. N. Behkami and J. R. Huizenga, FRAGMENT ANGULAR DISTRIBUTIONS OF NEUTRON-INDUCED FISSION OF ^{230}Th , Nucl. Phys. A171, 614 (1971).

C. K. Cline, REACTION MECHANISMS AND SHELL STRUCTURE EFFECTS ON $^{54}\text{Fe}+^{6}\text{Li}$ AND $^{58}\text{Ni}+d$ REACTIONS AT MEDIUM ENERGIES, Nucl. Phys. A174, 73 (1971).

L. C. Vaz, C. C. Lu and J. R. Huizenga, ISOSPIN AND THE BOHR INDEPENDENCE HYPOTHESIS, Phys. Rev. C5, 463 (1972).

J. R. Huizenga, EXPERIMENTAL AND THEORETICAL NUCLEAR LEVEL DENSITIES, Chapter in Statistical Properties of Nuclei, Edited by J. B. Garg, Plenum Press (New York) p. 425.

J. R. Huizenga, NEAR BARRIER FISSION INDUCED WITH PHOTONS, Nuclear Technology 13, 20 (1972).

F. C. Williams, Jr., G. Chan and J. R. Huizenga, THE SIGNIFICANCE OF SHELL CORRECTIONS IN THE PARAMETERIZATION OF NUMERICAL STATE DENSITY CALCULATIONS, Nucl. Phys., in press.

Th. W. Elze and J. R. Huizenga, COLLECTIVE STATES OF ^{232}Th , ^{238}U and ^{242}Pu , Nucl. Phys., in press.

Th. W. Elze, J. S. Boyno and J. R. Huizenga, COLLECTIVE STATES OF Gd ISOTOPES FROM (p,t) REACTIONS, Nucl. Phys., in press.

C. C. Lu, L. C. Vaz and J. R. Huizenga, LEVEL DENSITIES FROM SPECTRA OF DIFFERENT REACTIONS POPULATING THE SAME NUCLEUS, Nucl. Phys., in press.

C. K. Cline, W. P. Alford, H. E. Gove and R. W. Tickle, MULTIPLET STRUCTURE OF ^{210}Bi FROM THE $^{209}\text{Bi}(d,p)$ AND $^{209}\text{Bi}(\alpha, ^3\text{He})$ REACTIONS, Nucl. Phys., A186, 273 (1972).

2. Contributed papers at professional meetings

C. K. Cline, COMPLEX PARTICLE EMISSION IN THE PREEQUILIBRIUM STATISTICAL MODEL, Bull. Am. Phys. Soc. 16, 1159 (1971).

C. C. Lu, L. C. Vaz and J. R. Huizenga, POPULATION OF NUCLEAR LEVELS BY DIFFERENT COMPOUND NUCLEAR REACTIONS, Bull. Am. Phys. Soc. 16, 1164 (1971).

F. C. Williams, Jr., G. Chan and J. R. Huizenga, NUCLEAR STATE DENSITY CALCULATIONS FOR A NON-INTERACTING FERMION SYSTEM, Bull. Am. Phys. Soc. 16, 1181 (1971).

C. K. Cline, COMPLEX PARTICLE EMISSION IN THE PRE-EQUILIBRIUM STATISTICAL MODEL, International Conference on Statistical Properties of Nuclei, August 23-27, 1971, SUNY at Albany, New York.

C. K. Cline, J. R. Huizenga and H. K. Vonach, MECHANISMS OF (p,p') REACTIONS ON TIN ISOTOPES, Bull. Am. Phys. Soc. 17, 51 (1972).

J. S. Boyno, Th. W. Elze, J. R. Huizenga, and C. E. Bemis, Jr., COLLECTIVE STATES EXCITED IN THE $^{236}\text{U}(d,d')$ REACTION, Bull. Am. Phys. Soc. 17, 463 (1972).

J. S. Boyno and J. R. Huizenga, EXCITED STATES OF $^{155,157,159,161}\text{Tb}$ by (α,t) REACTIONS, Bull. Am. Phys. Soc. 17, 558 (1972).

L. C. Vaz, C. C. Lu and J. R. Huizenga, DETERMINATION OF THE SPIN DEPENDENCE OF THE NUCLEAR LEVEL DENSITY NEAR $A = 60$, Bull. Am. Phys. Soc. 17, 606 (1972).

3. Ph.D. Theses Completed

"Effect of Isospin on Compound Nucleus Decay and a Study of Statistical Properties of Nuclei" by Louis C. Vaz.

"Levels of $^{155,157,159,161}\text{Tb}$ Excited in Helium Induced Single Proton Transfer Reactions" by John S. Boyno.

4. Invited Lectures at Professional Meetings

"Single Nucleon Transfer in Actinide Elements," July 26-30, 1971, Nuclear Structure Physics Gordon Conference, Andover, New Hampshire (Thomas W. Elze).

"Experimental and Theoretical Nuclear Level Densities," August 23-27, 1971, International Conference on Statistical Properties of Nuclei, SUNY at Albany, New York (J. R. Huizenga).

5. Invited Lectures at Other Institutions

"Theoretical and Experimental Nuclear Level Densities," November 17, 1971, Department of Physics and Astronomy Nuclear Structure Seminar, University of Rochester, Rochester, New York (J. R. Huizenga).

"Influence of Shell Structure on the Nuclear Properties of Heavy and Superheavy Elements," March 10, 1972, Herbert S. Harned Symposia in Chemistry, Yale University, New Haven, Connecticut (J. R. Huizenga).

"The Griffin Model: A Closer Look at the Mythology of Nuclear Reactions," September 28, 1971, Chemistry Department Seminar, Yale University; November 1, 1971, T-9 Division Seminar, Los Alamos Scientific Laboratory; November 8, 1971, Physics Division, Oak Ridge National Laboratory; December 8, 1971, Department of Physics and Astronomy Nuclear Structure Seminar,

University of Rochester; April 19, 1972, Cyclotron Institute, Texas A&M University (C. K. Cline).

"Transfer Reactions on Deformed Nuclei," April 3, 1972, Nuclear Physics Seminar, Yale University (J. S. Boyno).

"Zero-, One- and Two-Nucleon Transfer Reactions," May 18, 1972, Seminar at Michigan State University (J. S. Boyno)

6. Professional Activities

Member of Editorial Board of the Journal of Physical Chemistry

Member of Advisory Council of Princeton University's Chemistry Department

Member of Executive Committee of Super-Hilac Users Association

Member of Ad-Hoc Panel on Nuclear Data Compilation, NAS-NRC

Chairman of Division of Nuclear Chemistry and Technology of American Chemical Society

Organizer of programs for national meetings of Division of Nuclear Chemistry and Technology

II. RESEARCH PROGRAM

A. Statistical Nuclear Decay

In this section we discuss the statistical aspects of nuclear reactions. For convenience in later discussion, the terms "composite system" and "compound nucleus" will be used. Traditionally the term compound nucleus is used for an excited nucleus which lives sufficiently long so that all memory of the incident channels has been lost and one has complete independence of the decay mode from the mode of formation. The term composite system is defined as an excited system composed of a strongly interacting group of nucleons. Except for direct reactions, like transfer reactions, the remaining reactions are classified in terms of composite systems. Included in this group of reactions are precompound and compound nucleus reactions. When, for example, a composite system is formed in the region of overlapping levels, the incident channel sets the phases of the overlapping levels. If decay occurs before the composite system has forgotten the initial phases, then such a reaction is classified as a precompound reaction. On the other hand, if sufficient time elapses for the composite system to have forgotten the properties (except for constants of motion, such as J and π) of the entrance channel, then the Bohr independence hypothesis is valid and such a reaction is classed as a compound nuclear reaction.

Several aspects of statistical nuclear decay are under study. Experiments to evaluate the role of isospin in statistical reactions are continuing. The present indication is that the

(p,p') reaction cross sections are enhanced for selected systems due to partial isospin conservation. However, this is a new field and much additional work needs to be done. Recently, experiments have been extended to systems where statistical theory predicts that the T_{α} states decay almost entirely by neutron emission.

Although an accurate determination of the energy dependence of the nuclear level density is difficult to obtain, such data are of great importance for direct comparison with theory. (The recent development of the "Distribution Theory of Nuclear Level Densities" by French and collaborators has given a new impetus for high quality experimental level density data.) The level densities of a few nuclei each populated by several evaporation reactions have been investigated in some detail to study the effect of various parameters on the final results. The spin dependence of the nuclear level density is also of considerable theoretical interest and new determinations of this quantity have been made by measurements of (α, α') angular distributions.

The preequilibrium model continues to be of great interest both from a theoretical and experimental point of view. Recently the preequilibrium statistical model has been extended to calculate complex particle emission and the results of the theory have been compared to experimental data.

The nuclear state densities of non-interacting Fermion systems have been calculated directly from single particle Nilsson levels both as a function of excitation energy and nuclear deformation. These calculations eliminate the

unjustifiable assumption of the conventional theory of level densities that the single particle scheme can be represented by a continuous distribution. Comparisons of the results of this theory with experiments and with the Distribution Theory are topics of great interest to us and part of our continuing program on level densities.

- ✓ 1. Statistical Decay of Compound Nucleus - L. C. Vaz, C. C. Lu, and J. R. Huizenga

The study of the effects of isobaric spin conservation on the statistical decay of the compound nucleus has been extended to the other composite systems ^{66}Zn and ^{64}Zn by measurement of cross sections and the energy spectra of protons and alpha particles emitted from these composite systems. The cross section estimates are based only on measurements at angles between 90° and 180° to emphasize the compound nuclear reaction. The composite system ^{66}Zn was formed at an excitation energy of 19.7 MeV in the $^{65}\text{Cu} + p$ and $^{62}\text{Ni} + \alpha$ reactions, while the composite system ^{64}Zn was formed by the $^{63}\text{Cu} + p$ and $^{60}\text{Ni} + \alpha$ reactions at an excitation energy of 19.5 MeV. The experimental values of the cross section ratio $\sigma(\alpha, \alpha')\sigma(p, p')/\sigma(p, \alpha)\sigma(\alpha, p)$ were 2.2 ± 0.2 and 1.3 ± 0.1 after subtracting the average non-equilibrium contribution¹⁾ of 16 and 11% from the proton cross section in the composite systems ^{66}Zn and ^{64}Zn , respectively.

To account for the deviation of these experimental cross section ratios from the approximate values of unity as predicted by the Bohr independence hypothesis and the statistical model of compound nuclear decay including angular momentum²⁾, we

assume that two isobaric spins $T_>$ and $T_<$ can be formed in a composite system with protons as projectiles. With alpha particle projectiles only one isobaric spin $T_<$ is formed in a composite system. The isobaric level schemes for the two composite systems ^{66}Zn and ^{68}Zn are shown in fig. 1. We also assume that the $T_>$ and $T_<$ states of a composite system formed at a high excitation energy decay independently of each other. If it is further assumed that a fraction³⁾, μ , of the $T_>$ states is mixed with $T_<$ states of a composite system and that this fraction decays just like the $T_<$ states, then it can be shown that the experimental cross section ratio R is given by

$$R = R_< \left[1 + \frac{1-\mu}{2T+\mu} \frac{F_>(p,p')}{F_<(p,p')} \right] \quad (1)$$

where $R_<$ is the theoretical value of the cross section ratio predicted by the statistical theory of nuclear reactions including only angular momentum, T is the ground state isobaric spin of the target nucleus bombarded with protons; $F_<(p,p')$ is the fraction of $T_<$ states that decay by proton emission, and $F_>(p,p')$ is the fraction of the $T_>$ states that decay by proton emission.

Statistical model calculations of the appropriate cross sections incorporating isobaric spin were performed and the theoretical fits to the experimental spectra are shown in fig. 2 for both composite systems. In these fits the level density parameters are treated as adjustable such that the theoretical and experimental spectra agree in both shape and magnitude.

The deviation of the cross section ratios from unity is ascribed to the isobaric selection rule acting on the $T_>$ states of a composite system. This selection rule causes the $T_>$ states of a composite system to decay preferentially by proton emission. The quantity μ in eq. 1 gives a measure of the extent of the isospin mixing in a composite system. The experimental values of $(1-\mu)$ are 0.6 ± 0.1 and 0.5 ± 0.1 for the composite systems ^{66}Zn and ^{64}Zn , respectively. The dynamic criterion for the validity of the isobaric spin selection rule ⁴⁾ in a highly excited system is that $\langle H_C \rangle \ll \langle \Gamma_{J,\pi} \rangle$ where $\langle H_C \rangle$ is the average Coulomb matrix element that causes isobaric spin mixing and $\langle \Gamma_{J,\pi} \rangle$ is the average width of levels of the same spin and parity. It is not possible to get an exact estimate of the Coulomb matrix element at the high excitation energy employed in these experiments. The values of μ indicate that an appreciable fraction of the $T_>$ states in composite systems ^{66}Zn and ^{64}Zn decay preferentially by proton emission before Coulomb forces cause the $T_>$ and $T_<$ states to mix considerably. However, from the fluctuation experiments ⁵⁾ that have been performed on composite systems around our mass region, we estimate that the Coulomb matrix element is of the order of or less than 5 keV.

- 1) J. J. Griffin, Phys. Rev. Letts. 17, 478 (1966); M. Blann, Phys. Rev. Letts. 21, 1357 (1968); G. D. Harp, J. M. Miller and B. J. Berne, Phys. Rev. 165, 1166 (1968); C. K. Cline and M. Blann, Nucl. Phys. A172, 225 (1971).
- 2) A. M. Lane and R. G. Thomas, Rev. Mod. Phys. 30, 257 (1958); A. C. Douglas and N. MacDonald, Nucl. Phys. 13, 462 (1959).
- 3) S. M. Grimes, J. D. Anderson, A. K. Kerman, C. Wong, Role of Isospin in Statistical Processes, Phys. Rev. C5 85 (1972).

- 4) H. Morinaga, 'Phys. Rev. 97, 444 (1955); D. H. Wilkinson, Phil. Mag. 1, 379 (1956).
- 5) M. G. Braga-Marcazzan and L. Milazzo-Colli, in Progress in Nucl. Phys, edited by D. M. Brink and J. M. Mulvey (Pergamon Press, New York, (1970), Vol. II; T. Ericson and T. Mayer-Kuckuk, Ann. Rev. Nucl. Sci. 16, 183 (1966).

Fig. 1 Isobaric level schemes for the composite systems ${}^6\text{LiZn}$ and ${}^6\text{HeZn}$ and the corresponding residual nuclei investigated. Each horizontal line represents a level. The number beside the level gives the energy of a level in MeV relative to the lowest energy of a particular configuration. The lines with the arrow pointing upwards indicate the isobaric spin states of the composite systems. The arrows pointing downwards show the decay of these states. The number along each of these lines is the square of the Clebsch-Gordan coefficient for the coupling of (T, T_z) of the target (or residual nucleus) and (t, t_z) of the incident particle (or emitted particle) to that of the states of the composite system.

Fig. 2 Theoretical fits to experimental spectra at 90° for the two composite systems ^{64}Zn and ^{66}Zn . The theoretical spectra are generated including the isobaric spin in the statistical theory. A Fermi-gas level density and a rigid-body moment of inertia are employed in the calculations. These calculations serve to illustrate that the statistical model reproduces the magnitude and the general shape of spectra.

DIFFERENTIAL CROSS SECTION (mb/sr/MeV)

ENERGY OF OUTGOING PARTICLES IN MeV_{cm}.

2. Determination of Nuclear Level Densities from Evaporation Spectra of Different Reactions Populating the Same Residual Nucleus -- C. C. Lu, L. C. Vaz and J. R. Huizenga

Evaporation spectra from different compound nuclear reactions which excite levels in the same residual nucleus can be used to obtain information about the excitation energy dependence of the nuclear level density of this nucleus. The evaporation spectra are analyzed with an exact statistical theory¹⁾ of compound nuclear reactions which gives the angular and energy dependent differential cross sections. The theory requires an angular momentum dependent level density which is varied to give agreement with experiment. Since the level density of a particular residual nucleus is a fixed quantity, the constancy of the level density parameters obtained from analyses of the spectra of different reactions populating the same residual nucleus provides a more stringent test of the validity of the statistical description of the various reactions.

Six residual nuclei, ^{56}Fe , ^{59}Co , ^{60}Ni , ^{62}Ni , ^{63}Cu and ^{65}Cu , were studied by this method. Experimental spectra were studied for the following reactions and bombarding energies:

$^{56}\text{Fe}(\alpha, \alpha')^{56}\text{Fe}$, 17.2 MeV; $^{59}\text{Co}(p, \alpha)^{56}\text{Fe}$, 13 MeV; $^{59}\text{Co}(p, p')^{59}\text{Co}$, 13 MeV; $^{56}\text{Fe}(\alpha, p)^{59}\text{Co}$, 17.2 MeV; $^{59}\text{Co}(\alpha, \alpha')^{59}\text{Co}$, 14.1 MeV and 17 MeV; $^{62}\text{Ni}(p, \alpha)^{59}\text{Co}$, 13 MeV; $^{60}\text{Ni}(\alpha, \alpha')^{60}\text{Ni}$, 16.6 and 17 MeV; $^{65}\text{Cu}(p, \alpha)^{62}\text{Ni}$, 12 MeV; $^{62}\text{Ni}(p, p')^{62}\text{Ni}$, 13 MeV; $^{59}\text{Co}(\alpha, p)^{62}\text{Ni}$, 14.1 MeV; $^{62}\text{Ni}(\alpha, \alpha')^{62}\text{Ni}$, 16.2 and 17 MeV; $^{65}\text{Cu}(p, \alpha)^{62}\text{Ni}$, 11 MeV; $^{63}\text{Cu}(p, p')^{63}\text{Cu}$, 12 MeV; $^{60}\text{Ni}(\alpha, p)^{63}\text{Cu}$, 16.6 MeV; $^{63}\text{Cu}(\alpha, \alpha')^{63}\text{Cu}$, 17 MeV; $^{65}\text{Cu}(p, p')^{65}\text{Cu}$, 11 MeV; $^{62}\text{Ni}(\alpha, p)^{65}\text{Cu}$, 16.2 MeV; and

$^{65}\text{Cu}(\alpha, \alpha')^{65}\text{Cu}$, 17 MeV. The Fermi gas level density parameters determined by analyses of these spectra with the exact theory of compound nucleus reactions are: ^{56}Fe , $a=5.7 \text{ MeV}^{-1}$, $\Delta=0.7 \text{ MeV}$; ^{59}Co , $a=6.2 \text{ MeV}^{-1}$, $\Delta=-0.8 \text{ MeV}$; ^{60}Ni , $a=6.4 \text{ MeV}^{-1}$, $\Delta=1.3 \text{ MeV}$; ^{62}Ni , $a=6.4 \text{ MeV}^{-1}$, $\Delta=0.5 \text{ MeV}$; ^{63}Cu , $a=6.8 \text{ MeV}^{-1}$, $\Delta=-0.5 \text{ MeV}$; and ^{65}Cu , $a=6.6 \text{ MeV}^{-1}$ and $\Delta=-0.5 \text{ MeV}$. A plot of the experimental level density of ^{63}Cu determined by the above method is shown in fig. 3. Experimental information from other sources is included in fig. 3.

All of the above spectra were analyzed also with the conventional slope technique which utilizes the Weisskopf expression for the differential cross sections; namely,

$$I(\epsilon_b) d\epsilon_b = \text{Const. } \epsilon_b \sigma(\epsilon_b) W(U) d\epsilon_b \quad (1)$$

where $I(\epsilon_b)$ is the spectral intensity at channel energy ϵ_b , $\sigma(\epsilon_b)$ is the inverse cross section and $W(U)$ is the state density of the residual nucleus at excitation energy U . Eq. (1) is an angle integrated expression and can be derived from the exact theory with the assumption that the spin dependent level density has the form $\rho(U, I) = (2I+1)\rho(U, I=0)$. In the application of eq. (1) with the Fermi gas level density, the quantity $\ln\{I(\epsilon_b) (U+t-\Delta)^n / \epsilon_b \sigma(\epsilon_b)\}$ is plotted as a function of $(U-\Delta)^{1/2}$ giving a straight line with a slope equal to $2a^{1/2}$. Experimenters have used values of n ranging from 0 to 2. In fig. 4 we illustrate the sensitivity of the extracted level density parameter a to the choice of n . Theoretical spectra are calculated by the exact theory and analyzed with the slope technique. For the

Fig. 3 Plot of the experimental level density of ^{63}Cu as a function of excitation energy.

025/2628

Fig. 3

Fig. 4 Dependence of the Fermi gas level density parameter $\underline{a}$ deduced from the conventional approximate theory on the parameter $\underline{n}$.

Fig. 4

(p,p') reaction, $\underline{a} = 6.8 \text{ MeV}^{-1}$ was used in the exact theory. For the (α, α') reaction, $\underline{a} = 5.8 \text{ MeV}^{-1}$ was used in the exact theory calculation. The wide range in $\underline{a}$ values deduced from the slope technique for different values of n gives an estimate of the uncertainty in $\underline{a}$ determined by the approximate eq. (1).

- 1) A. M. Lane and R. G. Thomas, Rev. of Mod. Phys. 30, 257 (1958); A. C. Douglas and N. MacDonald, Nucl. Phys. 13, 382 (1959).

3. Measurement of the Spin Cutoff Factor for Some Medium Mass Nuclei -- C. C. Lu, L. C. Vaz and J. R. Huizenga

Although the spin cutoff factor, $\underline{g}$, is an important parameter in the spin-dependent level density expression, very few reliable measurements of this quantity have been made. One way to determine $\underline{g}$ is from angular distribution measurements of evaporated particles for which statistical compound nucleus theory gives a good description of the evaporation spectrum. The anisotropy for each energy bin of a particle spectrum depends in large part on the spin cutoff factor $\underline{g}$.

The (α, α') reactions were studied with 17 MeV alpha particle projectiles on targets of ^{56}Fe , ^{59}Co , ^{60}Ni , ^{62}Ni and ^{63}Cu at laboratory angles of 87° , 112° , 142° and 167° . The $^{63}\text{Cu}(p, \alpha)^{60}\text{Ni}$ and $^{65}\text{Cu}(p, \alpha)^{62}\text{Ni}$ reactions were studied with 12 and 11 MeV proton projectiles, respectively. In addition, the $^{60}\text{Ni}(\alpha, p)^{63}\text{Cu}$ and $^{62}\text{Ni}(\alpha, p)^{65}\text{Cu}$ reactions were studied with 16.6 and 16.2 MeV alpha particle projectiles, respectively.

Typical experimental and theoretical spectra at laboratory angles of 87° and 167° are shown in fig. 5. The theoretical

Fig. 5 Comparison of experimental and theoretical spectra
at laboratory angles of 87° and 167° .

Fig. 5

spectra are based on the exact theory¹⁾ of statistical nuclear decay which gives the angular and energy dependent differential cross sections for compound nucleus reactions including explicitly the angular momentum. The anisotropy of the evaporated alpha particles as a function of energy is shown in fig. 6 for several (α, α') reactions. The theory based on a spin cutoff factor of the form

$$\sigma^2 = \mathcal{J} t / \hbar^2$$

where $\mathcal{J}$ is the rigid-body moment of inertia based on a nuclear radius of $1.2A^{1/3}F$ and t is the thermodynamical temperature, gives good agreement with the experimental results. As can be seen in fig. 6, reducing the moment of inertia to one-half the rigid-body value, leads to a very large discrepancy between theory and experiment. The (p, α) and (α, p) reactions give anisotropies which are smaller than the values for the (α, α') reaction in agreement with theory. We conclude that the spin cutoff factors for nuclei near $A=60$ are consistent with the values calculated from eq. (1) when the rigid-body moment of inertia is used.

- 1) W. Hauser and H. Feshbach, Phys. Rev. 87, 366 (1952);
A. C. Douglas and N. MacDonald, Nucl. Phys. 13, 382 (1959).

4. Complex Particle Emission in the Preequilibrium Statistical Model -- C. K. Cline

A study has been undertaken to see if the preequilibrium statistical model for nuclear reactions¹⁻³⁾ can simultaneously reproduce the energy spectra of protons and of heavier particles emitted from the same reaction system. In order to be able to

Fig. 6 Comparison of the dependence of experimental and theoretical anisotropy on the energy of exit alpha particles.

account for the relative abundances of different types of emitted particles, it was necessary to abandon a strict particle-hole formalism and take account of the fact that excited particles consist of both protons and neutrons. This was done by modifying the rate expression for the emission of particles of a given type from a state with p particles and h holes. In addition, the master equations which describe the equilibration of the compound nucleus have been extended to allow for the competition of particle emission with particle-hole pair creation and destruction. This becomes an important consideration at the higher excitation energies encountered in this work, but has been found to have only a small effect on the calculations for systems below about 30 MeV of excitation. Finally, an empirical factor equal to the factorial of the mass number of the emitted particle has been included in the model to account for the relative yields of different mass particles.

Bertrand and Peele have simultaneously measured the energy spectra of protons, deuterons, tritons, and He ions emitted in proton induced reactions⁴⁾. Their angle integrated data for a variety of targets from Fe to Bi and for bombarding energies between 29 and 62 MeV have been analyzed with only the elastically scattered protons removed from consideration. For each reaction system, the two free model parameters are adjusted to reproduce the proton spectrum. The resulting values are then used to calculate the corresponding complex particle spectra with no adjustable parameters. Figure 7 shows the results of the analysis for the $^{54}\text{Fe} + p$ reaction system at 3 bombarding energies.

Fig. 7 Experimental and Calculated Charged Particle
Spectra for protons incident on ^{54}Fe

Fig. 7-

In general, the model has proved to be extremely successful at reproducing the relative yields of the different particle types once the universal empirical factor is included, and the results indicate that almost all the mass 2 and 3 particles are emitted during equilibration. The model also does fairly well at reproducing the spectral shapes for complex particles formed with 30 MeV incident protons, but at higher energies the data show more than the predicted number of high energy particles. These extra particles may be produced in direct one-step pickup processes which are generally not accounted for in the model. In addition, for systems in the lead region, the data show a strong enhancement for triton emission relative to the calculations. The reason for this discrepancy may be related to a neutron skin on the target nuclei or to shell effects, but is not understood at the present time.

The analyses indicate the increasing importance of preequilibrium particle emission with increasing excitation energy and they consistently lead to an initial exciton number of two. This is to be compared with the average value of three which is found³⁾ from previous analyses of proton and neutron spectra from nucleon induced reactions. When proton groups corresponding to the excitation of strong collective states are removed from the present (p,p') spectra prior to analysis, this discrepancy disappears. In addition the fit to the deuteron spectrum is somewhat improved while the results for the heavier particles are not significantly altered. Since the preequilibrium model considers only sequential two-body interactions, it is not surprising that

removing collective effects from the data leads to a more consistent picture of nuclear reactions.

The present work is currently being extended to the study of complex particle emission in alpha particle induced reactions:

- 1) J. J. Griffin, Phys. Rev. Lett. 17, 478 (1966)
- 2) M. Blann, Phys. Rev. Lett. 21, 1357 (1968)
- 3) C. K. Cline and M. Blann, Nucl. Phys. A172, 225 (1971)
- 4) F. E. Bertrand and R. W. Peele, Oak Ridge National Laboratory Reports, ORNL-4450 (1969), ORNL-4460 (1969), ORNL-4469 (1970), ORNL-4471 (1970) and ORNL-4638 (1971).
- ✓ 5) The Significance of Shell Corrections in the Parameterization of Numerical State Density Calculations -- F. C. Williams, Jr.*,
G. Chan and J. R. Huizenga

The nuclear state density of a non-interacting Fermion system has been calculated directly from a set of single particle Nilsson levels both as a function of energy and deformation by two numerical methods. The first method is a combinatorial calculation and is based on the repetitive use of recursion relations to expand the grand partition function. The second is based also on the grand partition function; however, in this method one uses the saddle point approximation to deduce the relevant thermodynamical quantities. Both methods eliminate the unjustifiable assumption of the conventional theory of level densities that the single particle level scheme can be represented by a continuous distribution.

In fig. 8 is shown a plot of the square of the entropy as a function of excitation energy for ^{242}Pu at three deformations. In the 40 to 60 MeV excitation energy region the parameters $a(U)$ and $\Delta(U)$ are changing only slowly with energy, and an extrapolation of this energy region to zero excitation energy gives the values of a and Δ listed in fig. 8. The values of a and Δ continue to change slightly with the temperature due to the fact that the Fermi energy is a function of temperature for a set of Nilsson levels. In this sense, the Nilsson model (and other models such as the Woods-Saxon model) differs from the conventional equidistant or periodic spacing models in that no true asymptotic values of Δ and a are attained at high temperature. The variations in the neutron (μ_N) and (μ_p) chemical potentials with excitation energy for ^{208}Pb ($\epsilon=0$) and ^{242}Pu ($\epsilon=0.21$) are shown in Figs. 9 and 10 for a Nilsson model. The corresponding changes in the level density parameters $a(U)$ [$S^2 = 4a(U)[U - \Delta(U)]$] and the state density entropy intercept $\Delta(U)$ with excitation energy are plotted in figs. 11 and 12. A relationship between the Strutinsky shell correction and the effective zero of excitation energy extrapolated from the nuclear entropy in the region of high temperature has been demonstrated both algebraically and numerically. The results of the numerical calculations for excitation energies between 40 and 60 MeV for a large number of nuclei ranging from $A=20$ to 242 are shown in fig. 13. It can be seen from this plot that the shell correction determined from the entropy intercept is correlated with the Strutinsky

Fig. 8 Plot of the entropy squared versus excitation energy for ^{242}Pu at three deformations. The calculations included single particle (Nilsson) levels up to $N=12$ for $\epsilon=0$ and $N=17$ for $\epsilon=0.21$ and 0.41 .

008/2807

Fig. 8

Fig. 9 Dependence of the neutron (μ_N) and proton (μ_p) chemical potentials on excitation energy for a set of Nilsson levels for ^{208}Pb with zero deformation. Single particle levels to $N=12$ were included in the calculation.

007/2985

Fig. 9

Fig. 10 Dependence of the neutron (μ_N) and proton (μ_P) chemical potentials on excitation energy for a set of Nilsson levels for ^{242}Pu with deformation $\epsilon=0.21$. Single particle levels with $N=17$ were included in the calculation.

007/2984

Fig. 10

Fig. 11 Plots of the level density parameter $\underline{a}(U)$
and the state density entropy intercept
 $\Delta(U)$ as a function of excitation energy
for ^{200}Pb ($\epsilon=0$).

007/2983

Fig. 11

Fig. 12 Plots of the level density parameter $a(U)$ and the state density entropy intercept $\Delta(U)$ as a function of excitation energy for ^{242}Pu ($\epsilon=0.21$).

007/2982

Fig. 12

Fig. 13 Plot of the state density intercept as determined from the statistical method by a direct calculation of the entropy versus the Strutinsky shell correction calculated with the sixth order Hermite polynomial.

shell correction. However, it should be made clear that there is not a one-to-one correspondence between the two quantities and one cannot use the entropy intercept as a substitute for the Strutinsky shell correction.

The results of the calculations show also that with a realistic set of single particle orbitals, one can account qualitatively, and in some cases quantitatively, for the parameters found necessary to fit experimental data. Calculations reproduce qualitatively the observed values of a_f/a_n found in measurements of the ratio of the fission width to neutron emission width and predict also the important role of the liquid drop fission saddle point deformation in the interpretation of medium energy fission fragment angular distributions.

The calculated state density as a function of energy for ^{208}Pb exhibits some interesting correspondence with experimental results which are at variance with the simple Fermi gas theory. For example, the experimental state density of nuclei at or near a closed shell is known to be well approximated by a constant temperature model for the first 10 MeV or so of excitation energy. The theoretical state density for ^{208}Pb for this energy range is shown in fig. 14 and is well represented by a constant temperature model.

- ✓ 6. Mechanisms of (p,p') Reactions on Tin Isotopes -- C. K. Cline, J. R. Huizenga and H. K. Vonach*

Energy spectra for inelastic proton scattering on ^{112}Sn , ^{116}Sn ,

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Fig. 14 Plot of the theoretical state density versus energy for ^{200}Pb at zero deformation. The straight line is an approximation of the state density calculated with a constant temperature model.

007/2805

Fig. 14

^{120}Sn and ^{124}Sn have been measured at laboratory angles of 60° , 90° , 135° and 150° for incident energies of 14 and 17.8 MeV. A 150° spectrum for (p,p') reactions on ^{118}Sn was measured with 10 MeV incident protons, but further experiments at this bombarding energy were abandoned because of the high cross section for elastic scattering. The spectra were measured using a two element counter telescope in the 21" scattering chamber. Both detectors were of the silicon surface barrier type. Sample spectra for the $^{118}\text{Sn}(p,p')$ reaction at 14 MeV are shown in fig. 15.

In the absence of isospin selection rules, the measured proton spectra from $^{118},^{120},^{124}\text{Sn}$ should consist almost entirely of particles coming from non-compound nucleus processes, and spectra similar to the present ones have been used¹⁾ to estimate the direct reaction components in (p,p') spectra for the lighter tin isotopes. However, any T_1 states in the composite nucleus which have not undergone isospin mixing should decay by proton emission. In fact it is found that the angular distributions and spectral shapes of the present data indicate the presence of a low energy, isotropic component which is thought to be due to proton emission from the T_1 states. Despite its evaporation-like appearance, this component peaks at too high a particle energy relative to the peak in the ^{112}Sn spectra to be due to compound nucleus emission, and, at present, the most consistent interpretation of the heavy isotope data seems to be in terms of a T_1 and a T_2 preequilibrium component.

Preequilibrium particle emission is predicted to be very

Fig. 15 Energy spectra from the scattering of 14 MeV protons on ^{116}Sn . The laboratory angle for each curve is shown in the figure.

Fig. 15

much more important for the T_2 states than for the T_1 ones, and virtually none of the T_2 strength is expected to reach equilibrium. Furthermore, most of the T_2 preequilibrium particles should be emitted fairly late in the equilibration process; a prediction which is in agreement with the observed isotropic angular distributions. By analyzing the heavy isotope data in terms of two preequilibrium components, it is estimated that 40 to 80% of the T_2 states decay before isospin mixing occurs.

- 1) B. L. Cohen, G. R. Ras, C. L. Fink, J. C. Van der Weerd and J. A. Penkrot, Phys. Rev. Lett. 25, 306 (1970)

✓ 7. The Exclusion Principle and Preequilibrium Decay--C.K. Cline

The preequilibrium statistical model first proposed by Griffin has not previously included the effects of the Pauli exclusion principle, while other non-equilibrium models such as the Harp-Miller model^{1,2)} and Blann's^{3,4)} hybrid model have taken the Pauli principle into account. However, no information has been available on the importance of the exclusion principle to preequilibrium particle emission.

The preequilibrium model has been modified from its most recent form⁵⁾ by replacing the usual Ericson particle-hole state density with the Williams state density⁶⁾ which takes account of the exclusion principle. A set of rate expressions for the residual interactions (particle-hole pair creation and destruction) has been derived which also takes this effect into account. Lifetimes calculated from these rate expressions are shown in fig. 16. When these rate expressions are used in the model's master equations, the resulting equilibrium configuration for the system is close

Fig. 16 Effects of the Pauli exclusion principle on calculated lifetimes for various particle-hole configurations against residual two-body interactions.

Fig. 16

to the one predicted using Williams' state densities. This demonstrates the consistency between the new rate expressions and Williams' state density formula. The most probable exciton number at equilibrium in the present case is significantly lower than that obtained in earlier calculations made with Ericson's formula.

It has been found that the shapes of the calculated particle energy spectra are generally not seriously altered by putting the exclusion principle into the model. The only significant changes are found in the low energy portions of the spectra, particularly the α -particle spectra, from fairly light mass systems and at low excitation energies. Complex particle spectra are most seriously affected because of the greater importance of particles emitted from states with relatively high particle-hole numbers. The predicted relative yields of different particle types are not seriously altered in the Pauli-corrected results although in one extreme case an enhancement of about 40% was noted in the calculated $\alpha:p$ intensity ratio. Finally, there does not seem to be any significant change in the predicted absolute yields of high energy nucleons.

At the present time, it seems that for virtually all cases previously treated with the preequilibrium model, no essential change in the conclusions would result from repeating the analyses with the exclusion principle taken into account. However, for the heavy isotope $\text{Sn}(p,p')$ reactions described in the previous section, it was necessary to include the Pauli principle in the analysis because of the very low effective excitation energies for the T_1 states. Finally, it is interesting to note that in the cases where

the exclusion principle becomes important, namely where particle emission from states with fairly large exciton numbers is significant, it is also important to carry out the solution of the time-dependent master equations in preference to using the slightly simpler closed form expressions for the particle spectra.

- 1) G. D. Harp, J. M. Miller and B. J. Berne, Phys. Rev. 165 (1968) 1166
- 2) G. D. Harp and J. M. Miller
- 3) M. Blann, Phys. Rev. Lett. 27 (1971) 337
- 4) M. Blann and A. Mignerey, report COO-3494-1 and Nucl. Phys. to be published
- 5) C. K. Cline, Univ. of Rochester Report UR-NSRL-49 (1972)
- 6) F. C. Williams, Jr., Nucl. Phys. A166 (1971) 231

✓ 8. Effective Two-Body Matrix Elements in the Preequilibrium Model-
C. K. Cline

One of the shortcomings of the preequilibrium model first proposed by Griffin has been that it contains an unknown average matrix element for the residual two-body interactions. Thus all its time scale and cross section predictions have been only relative. Because these matrix elements are for residual interactions (most of the two-body interaction having presumably gone into the potential well responsible for the nuclear states) and because they are averaged over states with different exciton numbers as well as over the energies of the interacting particles, it is difficult to calculate them from first principles. A project is thus currently under way to evaluate these matrix elements empirically

✓

using existing comparisons between calculated and experimental particle energy spectra. If the variation of the matrix element with excitation energy and mass number can be determined in this way, it should be possible to put the model on a more absolute footing.

Preliminary results based on 8 experimental reaction systems yield matrix elements of the order of 0.6 to 8 keV. These values are, as expected, significantly smaller than the average full two-body matrix elements (10 to 1000 keV) determined from two-particle multiplets in near closed shell nuclei. The variation of the matrix element with excitation energy E and the mass number A of the system is consistent with the relation $M^2 \propto A^{-3} E^{-1}$. These are the dependences predicted by comparing the model rate expressions with total two-body interaction rates based on nuclear matter calculations and used in the hybrid model. There also seems to be some dependence of the matrix element on the mass number of the projectile.

B. Direct Reaction Studies on Heavy Deformed Nuclei

The high intensity α and ^3He beams, plus the Enge spectrograph available here, have provided unique capabilities for the study of Nilsson states for protons in rare-earth and actinide nuclei. Such studies are continuing and are limited mainly by the time required for scanning and detailed analysis of the results. Inelastic scattering provides an excellent probe for the study of collective states, and additional work along these lines is anticipated.

1. The Single Proton Levels of $^{155,157,159,161}\text{Tb}$ Excited by the $(^3\text{He},d)$ and (α,t) Reactions -- J. S. Boyno and J. R. Huizenga

The deformed, odd-A isotopes of Tb are an especially fertile field for study by charged particle reaction spectroscopy. The availability of stable Gd targets[†] of mass 154, 156, 158 and 160 allows one to follow the effects of changing neutron number as N varies from N=90 to N=96. Since N=90 marks the onset of deformation, we see marked changes in the deformation with increasing mass.

The $(^3\text{He},d)$ and (α,t) reactions on $^{154,156,158,160}\text{Gd}$ were run with 25.5 ^3He and 27.0 MeV ^3He particles, respectively. The $(^3\text{He},d)$ reactions on the three heavier mass targets were performed at $\theta=60^\circ$, while the $(^3\text{He},d)$ reaction on ^{154}Gd was run at 80° because our calculations indicated that lighter mass impurities might be present at 60° . The (α,t) experiments were run at 60° and 90° , although the $^{154}\text{Gd}(\alpha,t)$ exposure at 90° was not used since it was strongly contaminated by scattering due to misaligned entrance slits. The exiting deuterons and tritons were analyzed in an Enge type spectrograph and recorded on Kodak nuclear emulsion plates, type NTB50, which were covered with thin aluminum absorbers. A typical spectrum is shown in fig. 17.

DWBA analysis was used to interpret the reaction results, and the spectroscopic information obtained was compared to the theoretical predictions of the Nilsson¹⁾ model, expanded to include tetroidal deformation²⁾. Corrective terms added to the simple model included calculation of the Coriolis interaction, and an

[†] We are grateful to J. L. Lerner for preparing the targets with the isotope separator at the Argonne National Laboratory

Fig. 17 Deuteron Spectrum recorded from the ^{158}Gd
 $(^3\text{He}, d)$ reaction at $\theta_L = 60^\circ$.

056/2894

Fig. 17

estimation of the effect of the pairing interaction on the excitation energies and intensities of the observed states. Qualitative comparisons of experiment to the theoretical predictions of Soloviev³⁾, which deal with the problem of single particle-vibrational coupling, were also performed.

Level identifications were based on previous work done on these nuclei⁴⁾, comparison of rotational band intensity "fingerprints" and energy systematics, and on the ℓ value discrimination available from the cross section ratios $d\sigma(^3\text{He},d)/d\sigma(\alpha,t)^{60^\circ}$, $d\sigma(^3\text{He},d)/d\sigma(\alpha,t)^{90^\circ}$ and $d\sigma(^3\text{He},d)/\frac{d\sigma(\alpha,t)^{60^\circ}}{d\sigma(\alpha,t)^{90^\circ}}$, all of which are predicted to be ℓ dependent. These ratios provided useful ℓ value information for the majority of the lines observed.

Bands observed are: ^{155}Tb , {411+} (g.s.), {413+}, {532+}, ({402+}), ({411+}), ({411+} \gamma), ({514+}); ^{157}Tb , {411+} (g.s.), {413+}, {532+}, {411+} \gamma, {404+}, {402+}, {411+}, ({541+}); ^{159}Tb , {411+} (g.s.), {413+}, {532+}, {411+} \gamma, {404+}, ({523+}), ({541+}), {411+}, {402+}; ^{161}Tb , {411+} (g.s.), {413+}, {523+}, ({532+}), {404+}, {411+}, ({541+}), {402+}.

The parentheses indicate uncertain assignments. The energy systematics of the observed bands are given in table 1.

- 1) S. G. Nilsson, Kgl. Danske Videnskab. Mat. fys. Medd. 29 No. 16 (1955)
- 2) B. Nilsson, Nucl. Phys. A129, 445 (1969)
- 3) V. G. Soloviev and S. I. Fedotov, Nonrotational States of Odd Z Deformed Nuclei in the Region $153 < A < 177$, preprint, Joint Institute for Nuclear Research, Dubna, 1971
- 4) M. E. Bunker and C. W. Reich, Rev. Mod. Phys. 43, 348 (1971)

Table 1

Bandhead Energy of Observed Bands^{a)} in keV

$K^\pi (Nn_z A)$	^{155}Tb	^{157}Tb	^{159}Tb	^{161}Tb
$\frac{3}{2}^+ (411+)$	0±4	0±3	0±3	0±2
$\frac{5}{2}^+ (413+)$	275±4	326±3	348	307±6
$\frac{5}{2}^- (532+)$	227	326±3	364	480
$\frac{7}{2}^- (523+)$			(513 [†])	411±6
$\frac{1}{2}^+ (411+) \gamma$	(768±10)	595±5	580±3	
$\frac{7}{2}^+ (404+)$		657±4	777±3	944±4
$\frac{5}{2}^+ (402+)$	(494±3)	837±3	1020±4	1245±5
$\frac{1}{2}^+ (411+)$	(750±3)	923±3	974±3	990±5
$\frac{1}{2}^- (541+)$		(965±3)	(856±3)	(1052±4)
$\frac{9}{2}^- (514+)$	(887 [†])			

a) If bandhead was not observed, previously known energy is listed; if bandhead energy is unknown, position estimated and marked with dagger. Energies in parentheses are those of uncertain assignments.

2. Study of the (p,t) Reactions on Even Gd Isotopes -- Th. W. Elze*, J. S. Boyno and J. R. Huizenga

The $A+2\text{Gd}(p,t)^A\text{Gd}$ reactions have been studied with 18 MeV protons incident on isotope separated targets[†] of ^{152}Gd , ^{154}Gd , ^{156}Gd , ^{158}Gd and ^{160}Gd . Angular distributions of the emergent tritons were measured at 8 angles between 10° and 60° with a position-sensitive wire counter¹⁾ located in the focal plane of an Enge split-pole magnetic spectrograph. The use of a proportional counter in the present experiment was advantageous because it enabled us to discriminate between different types of particles. In addition to the measurements with the wire counter, emulsion plates were exposed at $\theta_L = 23^\circ$ with each of the Gd targets in order to obtain accurate excitation energies. Thus, the need for an energy calibration of the wire counter setup was eliminated. The plate exposures served also as an additional check on the normalization of the individual angular distributions relative to each other.

Typical triton spectra measured with the wire counter are shown in fig. 18. The energy resolution is approximately 20 keV. Angular distributions for the stronger groups, i.e. 0^+ and 2^+ states, are shown in fig. 19 while excitation energies and relative differential cross sections measured at 23° are collected in table 2, together with the spin assignments. All of the spin assignments deduced from the present angular distributions agree with those published in the existing literature.

[†] We are grateful to J. L. Lerner for preparing the targets with the isotope separator at the Argonne National Laboratory

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Fig. 18 Typical triton spectra measured with the position-sensitive proportional counter in the focal plane of the Enge spectrograph. The impurity lines are caused by deuteron pulses leaking from the deuteron buffer into the triton buffer.

Fig. 18

Fig. 19 Angular distributions of triton groups measured in the $A+2\text{Gd}(p,t)^A\text{Gd}$ reactions ($150 \leq A \leq 158$). The higher 2^+ states are grouped according to their previous classification as beta vibrations (second display from the right) and gamma vibrations (right-most display). The 1111 keV 2^+ state of ^{152}Gd has not been classified previously.

Table 2

Levels of Gd isotopes excited by the (p,t) reaction

Final nucleus and reaction Q value (MeV)	Excitation energy (keV)	$(d\sigma/d\Omega)_{rel}^a)$ at 23°	Assignment
^{158}Gd	0	1.00 ^{b)}	0 ⁺
	79	0.21	2 ⁺
(-4.915)	263	0.08	4 ⁺
	539	≤ 0.01	6 ⁺
	1186	0.05	2 ⁺ , γ
	1454	0.20	0 ⁺ , β
	1520	0.07	(2 ⁺ , β)
^{156}Gd	0	1.09	0 ⁺
	90	0.19	2 ⁺
(-5.817)	290	0.05	4 ⁺
	582	≈ 0.01	6 ⁺
	1050	0.11	0 ⁺ , β
	1131	} 0.11 ^{c)} {	2 ⁺ , β
	1154		2 ⁺ , γ ^{d)}
^{154}Gd	0	1.00	0 ⁺
	121	0.18	2 ⁺
(-6.494)	371	0.04	4 ⁺
	681	0.13	0 ⁺ , β
	823	0.04	2 ⁺ , β
	997	0.05	2 ⁺ , γ
^{152}Gd	0	0.54	0 ⁺
	344	0.12	2 ⁺
(-6.661)	612	0.39	0 ⁺ , β
	757	0.03	4 ⁺
	930	0.06	2 ⁺ , β
	1053	0.11	0 ⁺ , β
	1111	0.03	2 ⁺ , β
^{150}Gd	0	1.00	0 ⁺
	640	0.05	2 ⁺
(-6.624)	1137	≤ 0.01	3 ⁺ f)
	1209	0.15	0 ⁺

Table 1: Cont'd

-
- a) Intensities of $^{156,154,152,150}\text{Gd}$ normalized to ground state of $^{154}\text{Gd} = 1.00$
 - b) Intensities of ^{158}Gd normalized to ground state of $^{158}\text{Gd} = 1.00$
 - c) Unresolved doublet
 - d) From ref.^{11,12)}
 - e) From ref.¹¹⁾
 - f) From ref.¹³⁾

The neutron numbers of our target nuclei vary from $N=88$ to $N=96$, thus spanning the transition region $N=88$ to 90 . Three different situations are evident. The $^{152}\text{Gd} \rightarrow ^{150}\text{Gd}$ reaction connects two spherical nuclei, while the $^{155}\text{Gd} \rightarrow ^{154}\text{Gd}$, $^{150}\text{Gd} \rightarrow ^{156}\text{Gd}$ and $^{160}\text{Gd} \rightarrow ^{158}\text{Gd}$ reactions connect two deformed nuclei. The reaction $^{154}\text{Gd} \rightarrow ^{152}\text{Gd}$ connects a deformed nucleus to a spherical one. With the exception of the $^{154}\text{Gd}(p,t)^{152}\text{Gd}$ reaction, only one excited 0^+ state of each isotope has been found and the cross section of this state is fairly constant with a value of approximately 15% of the cross section for the formation of the ground state. In ^{152}Gd , however, two excited 0^+ states were found. The combined cross section of these two excited 0^+ states is larger than the cross section of the excited 0^+ state in each of the neighboring isotopes (cf. table 2), and the cross section of the ^{152}Gd ground state has dropped to about one-half that of neighboring isotopes. We note, however, that the total 0^+ strength for each of the Gd nuclei stays remarkably constant across the entire range of Gd isotopes. The splitting of the 0^+ strength for the $^{154}\text{Gd}(p,t)^{152}\text{Gd}$ reaction is interpreted in terms of the changing nuclear shapes in the transitional region ($N=90-88$). The apparent strong overlap of the 1053 keV 0^+ state of ^{152}Gd with the ^{154}Gd ground state suggests that this state is a deformed state coexisting in the spherical ^{152}Gd nucleus. This interpretation is supported by the fact that the 1053 keV state has not been observed²⁾ in inelastic deuteron scattering from ^{152}Gd . It would be interesting to see the results of a (t,p) experiment on ^{156}Gd which would afford one a means of corroborating or disproving the present interpretation.

1) We are indebted to H. W. Fulbright, W. A. Lanford and R. Markham for making the wire counter available to us. H. W. Fulbright and J. A. Robbins, Nucl. Instr. 71, 237 (1969)

2) R. Bloch, B. Elbek and P. O. Tjøm, Nucl. Phys. A91, 576 (1967)

3. Collective States of ^{232}Th , ^{238}U and ^{242}Pu Excited by Inelastic Deuteron Scattering -- Th. W. Elze and J. R. Huizenga

As part of a general study of actinide nuclei, we have investigated the inelastic scattering of 16 MeV deuterons from ^{232}Th , ^{238}U and ^{242}Pu targets. The chief objective of this work has been to identify collective excitations in these nuclei and to determine from the observed differential cross sections relative reduced transition probabilities $B(E2)$ and $B(E3)$. Spectra of inelastically scattered deuterons were momentum analyzed at 90° and 125° with NSRL Enge spectrograph and recorded on nuclear emulsion plates. An energy resolution of approximately 8 keV has been achieved. The deuteron spectrum from the $^{238}\text{U}(d,d')$ reaction as measured at 125° is shown in fig. 20. In all the nuclei studied, the ground state rotational bands are excited up to the 8^+ members. The deuteron groups labeled 1^- , 3^- , 5^- at 679, 731 and 825 keV, respectively, belong to the band built on the $K = 0^-$ octupole vibration. Based on the characteristic 1^- , 3^- , 5^- intensity pattern, which is also found in the ^{232}Th and ^{242}Pu spectra, the $K = 0^-$ octupole vibration is identified in the latter two nuclei. Other strongly excited states are identified as $K = 0^+$ β -vibration, $K = 2^+$ γ -vibration and other octupole vibrations.

Based on the proportionality between the inelastic scattering cross section and the reduced transition probability $B(E\lambda)$ for an $E\lambda$ transition, an attempt was made to determine $B(E2)$'s and $B(E3)$'s. Using the average value of the 90° and 125° cross sections,

Fig. 20 Spectrum of deuterons scattered from ^{238}U .

Fig. 20

the reduced relative transition probabilities as shown in tables 3-5 were determined. There is, in general, very good agreement between the present values and those obtained from other experiments.

C. Nuclear Fission

- ✓ 1. Lithium Ion Induced Fission of ^{232}Th and ^{238}U -- G. T. Rizzo,
C. C. Lu and J. R. Huizenga

Targets of natural U and Th were bombarded with ^6Li and ^7Li ions accelerated to energies of 38 MeV in the tandem Van de Graaff. The fission fragment angular distributions and cross sections were measured as a function of projectile energy. Due to the large fission width of heavy nuclei, there is a high probability of fission occurring during the deexcitation of each highly excited compound nucleus. Hence, from the fission cross section it is possible to get a good estimate of the total reaction cross section.

In order to be able to compare the experimental reaction cross sections with theory, one requires a suitable set of optical model parameters. For this purpose, measurements were made at two energies of the ratio of the elastic cross to the Rutherford cross section as a function of angle. The inelastic groups to the low-lying states (eg., the 2^+ and 4^+ states) were resolved from the elastic group with a sonic spark counter* mounted in an Enge split-pole spectrograph. A search for the "best" set of optical model parameters is presently under way.

* We wish to thank Roger Markham for his assistance in these experiments.

Table 3
Reduced Transition Probabilities
First 2^+ States

	E (keV)	$B(E2; 0^+ \rightarrow 2^+)/e^2 \times 10^{-48} \text{ cm}^4$	
		$(d, d')^a_{\text{av.}}$	Coul. Exc. $^b)$
^{232}Th	48	9.1 ± 0.6	9.4 ± 0.2
^{238}U	45	11.7 ± 0.8	11.7 ± 0.2
^{242}Pu	46	16.5 ± 1.4	13.3 ± 0.4

$^a)$ Normalized with the Coulomb excitation value for ^{238}U

$^b)$ From ref. ¹⁴⁾

Table 4

Reduced Transition Probabilities
Gamma-Vibrational States

	E(keV)	$B(E2; 0^+ \rightarrow 2^+)/e^2 \times 10^{-48} \text{ cm}^4$	
		$(d, d')^c_{av}$	Coul. Exc. ^{a)}
^{232}Th	786	0.20 ± 0.03	0.14
^{238}U	1061	0.10 ± 0.01	0.09
^{242}Pu	1102	$0.15 \pm 0.03^b)$	

^{a)} From ref. 2)

^{b)} Assignment uncertain.

^{c)} Normalized with the Coulomb excitation value for the 45 keV level of ^{238}U from table 5.

Table 6
Reduced Transition Probabilities
Octupole States

E (keV)		$B(E3; 0^+ \rightarrow 3^-) / e^2 \times 10^{-72} \text{ cm}^6$				
		$(d, d')_{90^\circ}$	$(d, d')_{125^\circ}$	$(d, d')_{\text{av.}}^d$	Theory	Other Exp. ^{a)} Coul. Exc. ^{b)}
^{232}Th	776	0.71	0.59	0.65 ± 0.06	0.59	0.50
	1107	0.44	0.45	0.45 ± 0.05	0.26	0.30 ± 0.10
^{238}U	731	0.57	0.51	0.54 ± 0.07	0.44	0.50 ± 0.06 0.54 ± 0.04
	998	0.20	0.23	0.22 ± 0.03	0.18	0.22 ± 0.05 0.23 ± 0.02
	1169	0.24	0.34	0.29 ± 0.05	0.11	0.20 ± 0.10 0.13 ± 0.02
^{242}Pu	833	0.85	0.57	0.71 ± 0.09	0.41	
	1020	0.67	0.81	0.74 ± 0.11	0.12	
	1650	0.29	0.46	$0.38 \pm 0.06^c)$	0.09	

a) From ref. ¹⁵⁾

b) Taken from ref. ⁶⁾ assuming $1B(E3)_{\text{spu}} = 2.35 \times 10^{-74} e^2 \text{ cm}^6$

c) Assignment uncertain

d) Normalized with the value for the 731 keV level of ^{238}U ⁶⁾

D. Nuclear Methods in Chemical Structure Studies

1. Effect of Pressure and Chemical Environment on the Radioactive Decay Constant of ^7Be -- W. K. Hensley, E. Bailey, and J. R. Huizenga

Samples of BeO containing radioactive ^7Be have been placed under static high pressures up to 300 kbar and the electron capture decay constant measured in situ. In order to attain maximum pressure with simple equipment, we chose to use presses similar to the "squeezer" design pioneered by Bridgman.

A press using diamond anvils driven by a simple piston and screw device, developed by Bassett et al.⁽¹⁾ was utilized in the present experiment. With this press, samples in polycrystalline form are placed between two opposing flat diamond anvil faces. As the anvils are driven together, the sample extrudes until friction prevents further extrusion. This results in a pressure distribution with maximum pressure at the center and essentially atmospheric pressure at the perimeter. A schematic diagram of the press is shown in Fig. 21. The diamond anvils "A" are 30 mg., brilliant cut, single crystals which have had their culet faces enlarged. One anvil has a face that is approximately 0.5 mm in diameter, and the other has a smaller face (0.3 mm in diameter has been used in this work). A maximum of 300 kbar can be achieved with a face of 0.3 mm in diameter and 125 kbar with a face 0.5 mm in diameter. The larger the diameter of the anvil face, the thicker the resulting sample.

The diamond anvils are fastened to rockers which are

Fig. 21 A schematic diagram of the high pressure press
and its components.

SCALE = 2:1

mounted in troughs at the ends of two pistons. These rockers are arranged in such a way as to permit both angular and translational adjustment so that the anvil faces can be matched and made parallel to each other. Both pistons slide inside a cylindrical hole in the body of the press and are keyed in order to prevent rotation. The two pistons are driven together by driving screws "D."

Passage of light for anvil alignment and sample observation is provided by axial holes in parts B, C and D. Alignment is necessary because uniform pressure distribution and long life of the anvils depends largely on the anvil faces being strictly parallel. The alignment of the anvil faces is affected by a pair of rockers that have their axes of rotation at right angles to each other. The alignment is tested in two ways, interference (Newton) rings which are formed between the two polished faces at very small separation distances, and centering of high pressure phases in a sample such as silver iodide which undergoes several phase changes. The latter is by far the most sensitive method. A photograph of the assembled press is shown in Fig. 22.

The pressure to which a sample is subjected is measured by means of a sodium chloride internal standard. The X-ray diffraction pattern of an intimate mixture of the sample with sodium chloride normally only shows lines attributable to the NaCl. This results from the low atomic scattering factors for Be and O using Mo and Cu K_α radiation. The lattice parameters calculated from the sodium chloride lines can then be used to determine the pressure using the isothermal compressibility of sodium chloride. For this purpose, Weaver's

Fig. 22 Photograph of the assembled high pressure press.

Fig. 22

equation of state for sodium chloride is used. Weaver's equation is in agreement, within experimental uncertainties, with the fixed points on the absolute pressure scale and those determined by other workers up to 300 kbar.

Measurements of the effect of pressure on the decay rate of ^7BeO are presently being taken for samples at approximately 120 and 280 kbar pressure. A measurement has already been completed for a ^7BeO sample at ~210 kbar pressure. The preliminary results of the latter two samples are in agreement with the trend predicted from the results of the 210 kbar sample. ^7Be decay constants are measured by monitoring the activity of the 477 keV gamma-ray from the daughter ^7Li . The measurements are made with high resolution Ge(Li) detectors and standard pulse height analyzers. Computerized data handling allows multiple analyses of the data. Principally, two methods are used, namely, direct calculation and comparison of the decay constants obtained from least-square fits of the exponential decay data and by the use of the differential method which yields the difference between two decay constants. Further data analyses are in progress to determine quantitatively the effect of pressure on the decay constant of ^7BeO .

In addition to the measurements of the effect of pressure on electron capture decay rates, the procedures developed for gamma ray counting and computerized analysis have been used for new measurements of the effect of the chemical environment on the decay constant of ^7Be . Samples of Be, BeO , $\text{Be}(\text{OH}_2)_4^{++}$ and BeF_2 in two different structures are

presently being studied. With the possible exception of the $\text{Be}(\text{OH}_2)_4^{++}$ case, the present results agree qualitatively with earlier work done with ionization chambers.

(1) W. Bassett, et al. Rev. Sci. Instr. 38, 37 (1967).