A PROGRAM IN NUCLEAR SPECTROSCOPY

Final Report

John W. Mihelich

University of Notre Dame
Notre Dame, Indiana

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ABSTRACT

This project has been concerned with detailed investigations of the properties of nuclear levels, primarily in the rare-earth region, beginning at a time when extremely little was known about them. Scintillation spectrometers, beta spectrometers, and high-resolution Ge(Li) and Si(Li) detectors have been employed in a number of configurations to do singles and coincidence measurements and make determination of very short nuclear level lifetimes, using radioactive sources. In recent years, the research has been broadened to make use of the FN accelerator, including Coulomb excitation and other in-beam experiments. Data have been obtained on energies, spins, and parities of levels, internal conversion coefficients, multipole mixing in gamma-transitions, level half-lives and retardation factors, systematics, electromagnetic transition probabilities, and band mixing.

FINAL REPORT

I. INTRODUCTION

This report covers the period, December 1, 1956 through November 30, 1971, and describes some of the contributions this project made during this very active period in nuclear structure physics.

This project was first funded during the period when a strong collaborative effort was being initiated between the writer and B. Harmatz of the Electro-nuclear Division of the Oak Ridge National Laboratory. This collaborative effort which was maintained for several years turned out to be a most fruitful and valuable program as it helped to "open up" the vast and complicated area of the systems of nuclear excitations in deformed rare-earth nuclei. The 86" proton cyclotron was then part of that division and a great deal of beam time was used in the obtaining of excitation functions (i.e., p, n ; $p, 2n$; or $p, 3n$) on targets of varying degrees of enrichment. Many elements had not yet been enriched by the Stable Isotopes division. A technique was developed by us to obtain intense, thin sources for use in 180° flat-field magnetic spectrographs, which had the invaluable property of photographic recording of the entire spectrum at moderately high resolutions. This investigation was concerned primarily with the internal conversion electron spectra which permitted the determination of multipolarities from L and M subshell ratios. The approach was very similar to that previously employed in the study of the chain of Hg isomers by Mihelich, deShalit et al. At that time, the "modern" internal conversion coefficients of M. E. Rose et al. were just becoming available, and in many cases, one had to rely on empirical knowledge of the conversion patterns of various multipolarities. Untold thousands of conversion lines were studied, looking at their energies, intensities, excitation functions, and decay rates. A series of important papers were produced by us in that period, papers which are still widely quoted in the literature.

This was also a period when the theory was making rapid strides. The seemingly impenetrable maze of low lying levels exhibited by these rare earths became enormously clearer with the introduction of models involving rotational levels superimposed on ground states, intrinsic states, and vibrations.

Meanwhile, a program was being started at Notre Dame (initially funded by the University) to make more definitive studies of the level structure using magnetic beta-spectrometers, scintillation spectrometers, directional correlation, coincidence measurements, and determination of level half-lives. Ge(Li) detectors were used by us very early in their development. Professor E. G. Funk came to Notre Dame in 1958 and has been heavily involved in these experiments since that time. The project group has consisted of two faculty members, varying numbers of graduate students, and one postdoctoral research associate.

During this time sources were obtained from Oak Ridge or the reactor or cyclotron at Argonne National Laboratory. In later years, the cooperation of the Argonne cyclotron facility was invaluable. When the Notre Dame FN Tandem accelerator was installed in 1968, we began to integrate the use of this machine with our experiments on radioactive sources. We have made short-lived activities with proton or deuteron beams, have done Coulomb excitation experiments with ^{16}O or ^4He beams, and are engaged in some in-beam gamma-ray studies. The accelerator project was funded from the beginning by the NSF and our project contributed some funds toward operating costs. Our AEC support terminated November 30, 1971, and we were supported by an NSF grant beginning January 1, 1972. As of February 1, 1973, our project has been consolidated with the accelerator project under a single NSF grant.

Our efforts over the years have encompassed a wide variety of techniques and we have tried to attack a problem in as many ways as possible. During the fifteen years of AEC support, twenty-four Ph.D. theses were completed or were well on the way to completion. These are listed in an appendix. Thirty-seven papers were published in this period, not counting abstracts at professional meetings. A considerable number of investigations were initiated in that period and are being prepared for publication. The publication list is given in an appendix.

II. RESEARCH PROGRAM

A. Research Conducted During Period of AEC Support

A brief resume of the variety of experiments we have carried out follows.

1. Measurements of Level Half-lives and Coincidence Techniques

Coincidence techniques have been used constantly beginning originally with a fractional-microsecond unit and progressing with the state of the art. The lifetime measurements are discussed primarily in the theses of C. Schwerdtfeger, H. J. Prask, H. Kugel, R. Belt, and Sr. C. Madden. In this period papers were published on the half-lives of the 2^+ and 4^+ rotational states of doubly even rare-earth nuclei, numbers which were important at that time for checking the theory and which were useful to people doing other types of experiments. We published one paper on life-times of positrons annihilating in Au, clearing up a point of confusion. Most recently, the half-life of a state in ^{173}Lu which is depopulated only by a 4.65-keV transition was measured, detecting the M conversion electrons with a Bendix Spiraltron. This half-life, when corrected for the internal conversion coefficient of several million, gives good agreement with the theoretically expected value. In the same dissertation research, the half-life of a 1318-keV state in ^{174}Yb was measured to be 0.51 ± 0.03 nsec. Here, the state is populated only by L-electron capture so that L X-rays must be used as the preceding radiation. A tin-loaded plastic scintillator

was used in this case.

Other experiments have been done to ascertain the available energy for electron capture by measuring the L/K capture ratio by obtaining the L- and K- X-ray intensities in a suitable coincidence arrangement. Of course, no level scheme can be constructed until coincidence experiments have been done. We have elucidated a number of complex level schemes in this way. A well-done experiment will also permit the indirect "resolution" of gamma rays too close together to be directly resolved by detectors available at that time. These indirect breakaparts have been confirmed in later years when better detectors became available.

2. Directional Correlation Measurements

The early directional correlation measurements were made with two NaI detectors using ordinary single-channel analyzers and a coincidence circuit with a resolving time of 0.1 μ sec. Some of these measurements were concerned with establishing the nature of the so-called gamma vibrational bands. Despite the complexity of the gamma-ray spectra, meaningful results could be obtained since we had a great deal of internal conversion electron data, taken both here and at Oak Ridge. As larger scintillators and modern multichannel analyzers became available (and affordable), more sophisticated measurements could be attempted. A number of theses and papers in this field were completed. With the advent (1964) of high-resolution semiconductor detectors the number of cases which could be investigated was greatly increased. The narrow peaks produced by these detectors precluded use of the single-channel analyzers generally available then. Accordingly, a digital gate was designed and constructed. This device was described in the publication by Chagnon and Jaklevic. Of current interest has been the determination of triple multipolarity admixtures in certain cases. Here, in order to establish, say, an $E1 + M2 + E3$ admixture, other data beside the directional correlation data are needed, for example, the internal conversion coefficients.

3. Determination of Level Schemes

In establishing level schemes, a variety of techniques must be used. Single and coincidence spectra, beta-spectra, directional correlations, and level half-life measurements must be used as much as possible, as well as information obtained in other experiments, such as capture gamma rays, reaction studies, etc. The usefulness of high-resolution gamma-ray detectors is obvious; Si(Li) detectors designed for conversion electron studies have made possible the obtaining of intensities of very weak conversion lines. An example is in the case of establishing triple admixtures discussed in the last section. Of interest has been the establishing of $E0$ admixtures in certain transitions between $K = 1/2$ bands in an odd-mass nucleus (e.g., ^{173}Lu). The resolution for low-energy photons currently available has allowed us to start some interesting studies of low lying states in odd-odd

nuclei and the measurement of internal conversion coefficients for transitions with energies just above the K-shell binding energy (i.e., near threshold).

Some of the more recent level scheme experiments have led rather naturally into in-beam studies on the accelerator. For example, in a lengthy series of experiments conducted by us, it has been established that ^{154}Tb has isomeric states (in ascending order) designated as 0^+ (21.7h), 3^+ (9.0h), and 7^- (22.5h). The parities are the most reasonable choices, although not necessarily certain. Although there is no direct evidence for transitions proceeding between these states, it is clear that such transitions do proceed since the decay curves for the two lower states do exhibit growth-decay characteristics. We are currently continuing the problem using high-resolution detectors on sources and also by doing in-beam experiments to ascertain the levels in ^{154}Tb .

It has been clear over the years that the information obtained from well-studied level schemes is invaluable and very frequently complements the data obtained in other ways, such as Coulomb excitation, particle-transfer reactions, inelastic scattering, etc.

In some of these problems, data on the β^- or β^+ spectra were needed to help determine the spins and parities of the levels involved. Here, information on the intensities, shapes, and log ft's are quite useful. Very early in our history, we constructed an intermediate-image spectrometer for use in such experiments. A magnetic device of this type is essential in cases where a very weak conversion line is masked by a background of positrons. Before the advent of high-resolution semiconductor detectors, magnetic analysis was essentially the only way to investigate conversion lines. A number of 180° flat field instruments were used, but are practical only when intense sources are available.

During the time when the Notre Dame Chemistry Department was involved in radioactivity, a close cooperation with that group was maintained. They were a great help in the setting up of our radiochemical procedures. We have also cooperated with scientists from nearby schools; J. R. Van Hise from Andrews University and Tri-State College, and A. E. Rainis from Tri-State College while he was there.

4. Program on the Tandem Accelerator

With the installation of the FN accelerator in 1968, we began to orient our research program toward the incorporation of this facility into our ongoing program with radioactive sources. The accelerator has been used to produce these relatively short-lived activities which were feasible with the energies and currents available. Sources are still produced in the reactor or cyclotron at Argonne National Laboratory. We also began a program of

Coulomb excitation experiments on a number of rare-earth nuclei, ones which we had studied previously in other ways.

In particular, a series of experiments has been done on the even-mass isotopes of Yb ($A = 168$ through 176) and Dy ($A = 160$ through 164) using oxygen and helium beams. Most of these experiments have been done measuring the gamma-ray spectrum coincident with the backscattered ions, although some experiments have been done by measuring the spectrum of inelastically scattered alpha particles using a broad-range spectrograph. The experiments on the Yb nuclei have been concerned with the ground-state band, comparing the experimental and theoretical ratios of the excitation of the 8^+ and 6^+ members of the ground-state band. Also of interest were the excitation probabilities for various states in the β and γ vibrational bands. These results are being written up for publication. The Yb nuclei are quite interesting since a number of excited 0^+ levels are present. The degree of collectivity of these 0^+ states is an important question. It appears to vary with neutron number, and furthermore, within the same nucleus, there are large differences in the $B(E2)$ values for exciting these states.

In the case of the Dy nuclei, experiments were carried out to measure the $B(E3)$ values to members of the $K = 0^-$ and 1^- bands. We have also studied the ground-state bands, where a number of factors must be taken into consideration, such as the size of β_4 , quantum mechanical effects, as well as the experimental effects such as target thickness, etc.

It is worth noting that we have made extensive studies of the Yb and Dy nuclei using radioactive sources. Both kinds of data are necessary for proper interpretation of the results.

B. Future Research

During the period of AEC support, this project was able to do a considerable amount of worthwhile research, primarily with radioactive sources. The accomplishments of that period permitted us to acquire NSF support, and we plan to continue our program, using both on-line experiments and radioactivity studies to further examine the properties of nuclear levels.

APPENDIX A

Titles of Ph. D. Dissertations on Research Sponsored by Project

<u>Date Submitted</u>	<u>Author</u>	<u>Title</u>
August, 1957	Thomas J. Ward	Investigation of the Properties of Low Lying Levels in Gd ¹⁵⁵ and Hf ¹⁷³
August, 1958	K. Paul Jacob	Electron Capture Decay of Tm ¹⁶⁸ , Tm ¹⁶⁶ and Lu ¹⁷²
June, 1960	John W. Bichard	The Electron Capture Decay of ⁷¹ Lu ¹⁷³ to Low Lying Levels in ⁷⁰ Yb ¹⁷³
June, 1961	Charles F. Schwerdtfeger	A Study of the Decay of Eu ¹⁴⁸ , Pm ¹⁴⁸ and Pm ^{148m} to Levels in Sm ¹⁴⁸
August, 1962	Brother Mark Guttman	The Decay of Eu ¹⁵⁰ (5 yr.) and Eu ¹⁵⁰ (14 hr.)
October, 1962	Henry J. Prask	The Decay of Gd ¹⁴⁹ to Eu ¹⁴⁹ and Unified Model Calculations; Some Nanosecond Half-life Measurements
March, 1963	James J. Reidy	Directional Correlation Measurements on Cascades in Er ¹⁶⁸ and W ¹⁸²
November, 1963	Francis J. Schima	The Decay of At ²¹⁰ to Po ²¹⁰ and Several Model Calculations
June, 1964	Gerald C. Martin, Jr.	Absolute Determination of Cross Sections for Some Alpha-Particle Induced Reactions of Holmium-165 and of Erbium-164, -166 and -167
May, 1965	Joseph F. McNulty	The Radioactive Decays of Eu ¹⁴⁷ (24 d.), Lu ¹⁷³ (1.4 y.) and Tb ¹⁵⁴ (8 hr., 22 hr.)
October, 1966	Joseph M. Jaklevic, Jr.	Coincidence and Directional Correlation Measurements on the Decays of Gd ¹⁴⁹ and Tb ¹⁶⁰ Employing a Ge-Li Detector
October, 1966	Duane J. Buss	The Decays of Pm ¹⁴⁶ , Eu ¹⁴⁶ and Eu ^{150, 150m}

<u>Date Submitted</u>	<u>Author</u>	<u>Title</u>
March, 1967	Henry W. Kugel	Fast Coincidence Measurements: Halflives of Nuclear Rotational States and Positron Lifetimes in Metals
May, 1967	Patrick F. Kenealy	Coincidence and Directional Correlation Measurements in the Study of Excited States in Gd^{156} and Er^{168} Populated by the Decay of Tb^{156} (5.3 d) and Tm^{168} (87 d)
November, 1968	Joseph J. Sapyta	A Study of the Decay of the Re^{182} Isomers (13 h and 64 h) and Ta^{182} (115 d) to W^{182}
January, 1970	Carl J. Paperiello	A Study of the Decays of Gd^{146} , Eu^{146} , Tb^{158} , and Lu^{170} ; Band-Mixing Calculations for Negative-Parity Bands in Gd^{158}
August, 1970	William W. Seremak	A Study of the Decays of Lu^{172} , Lu^{174} , and Lu^{174m}
September, 1970	Ronald A. Belt	Half-life Measurements in Yb^{172} and the Decays of Eu^{147} (22 d) and Hf^{173} (23.9 h)
January, 1971	Albert E. Rainis	A Study of the Decays of Ho^{162} , Ho^{162m} , and $Ho^{160} + Ho^{160m}$
August, 1971	Dennis R. Zolnowski	A Study of the Decays of ^{152}Tb (17.5 h) and ^{173}Hf (23.9 h) Employing Si(Li) and Ge(Li) Detectors
January, 1972	Sister M. Caecilia Madden	Half-life Measurements of Short-Lived Nuclear States in ^{154}Gd , ^{160}Dy , ^{174}Yb , ^{182}W , ^{173}Lu , and ^{175}Lu
January, 1972	David C. Sousa	Study of the Decay of ^{154}Tb , ^{154m}Tb and $^{154m2}Tb$ Using Ge(Li) and Si(Li) Detectors
May, 1972	Richard N. Oehlberg	A Coulomb Excitation Study of ^{160}Dy , ^{162}Dy , and ^{164}Dy
Fall, 1973	Arthur G. Schmidt	Directional Correlation Studies of ^{182}W and ^{174}Yb

APPENDIX B

Publications Completed or Begun While Under AEC Support

"Nuclear Spectroscopy of Neutron Deficient Rare-Earth Isotopes," Mihelich, Harmatz, and Handley, Phys. Rev. 108, 989 (1957).

"Some New Isomeric Transitions in the Rare-Earth Region," Mihelich and Harmatz, Phys. Rev. 106, 1232 (1957).

"Nuclear Spectroscopy of Odd-Mass (161-173) Nuclides," Harmatz, Handley, and Mihelich, Phys. Rev. 114, 1082 (1959).

"Electron Capture of Lu^{173} ," Bichard, Mihelich, and Harmatz, Phys. Rev. 116, 720 (1969).

"Electron Capture of Tm^{166} and Tm^{168} ," Jacob, Mihelich, Harmatz, and Handley, Phys. Rev. 117, 1102 (1960).

"Radioactive Decay of Pm^{143} , Pm^{144} , and Pm^{146} ," Funk, Mihelich, and Schwerdtfeger, Phys. Rev. 120, 1781 (1960).

"Nuclear Spectroscopy of Neutron Deficient Lu, Ta, and Re Isotopes," Harmatz, Handley, and Mihelich, Phys. Rev. 119, 1345 (1960).

"The Character of the 1315 keV State in Yb^{174} ," Prask, Bichard, Funk, and Mihelich, Nucl. Phys. 29, 100 (1962).

"Nuclear Levels in a Number of Even-Even Rare Earths," Harmatz, Handley, and Mihelich, Phys. Rev. 123, 1758 (1961).

"The Decay of Pm^{148} , Pm^{148m} , and Eu^{148} ," Schwerdtfeger, Funk, and Mihelich, Phys. Rev. 125, 1641 (1962).

"The Electron Capture Decay of Gd^{149} ," Prask, Reidy, Funk, and Mihelich, Nucl. Phys. 36, 441 (1962).

"The Decay of Eu^{147} to Sm^{147} ," Schwerdtfeger, Prask, and Mihelich, Nucl. Phys. 35, 168 (1962).

"The Decay of Eu^{146} to Sm^{146} ," Funk, Schwerdtfeger, and Mihelich, Nucl. Phys. 39, 147 (1962).

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"Lifetimes of the 246 and 46 keV Transitions in Po^{210} ," Funk, Prask, Schima, McNulty, and Mihelich, Phys. Rev. 129, 757 (1963).

"Study of the Decay of Tm^{168} to Er^{168} Using Coincidence and Directional Correlation Techniques," Reidy, Funk, and Mihelich, Phys. Rev. 133, B556 (1964).

"Electron Capture of At^{210} (8.3 h) to Po^{210} ," Schima, Funk, and Mihelich, Phys. Rev. 132, 2650 (1963).

"The Decay of Eu^{150} (13 h) and Eu^{150} (~ 5 y)," Guttman, Funk, and Mihelich, Nucl. Phys. 64, 401 (1965).

"The Decay of Tb^{158} to Gd^{158} and Dy^{158} ," Funk, Schima, and Mihelich, Nucl. Phys. 63, 305 (1965).

"A Reinvestigation of the Decay of Eu^{147} ," McNulty, Funk, and Mihelich, Nucl. Phys. 55, 657 (1964).

"Condition of Separation of Rare-Earth Radioactivities by Ion Exchange," G. C. Martin, J. Inorg. Nucl. Chem. 26, 1621 (1964).

"A Reinvestigation of the Decay of Gd^{149} ," Jaklevic, Funk, and Mihelich, Nucl. Phys. 84, 618 (1966).

"Reinvestigation of the Decays of Eu^{146} and Pm^{146} and the Existence of Two Close-Lying States at ≈ 1381 keV in Sm^{146} ," Buss, Funk, and Mihelich, Phys. Rev. 141, 1193 (1966).

"Half-Lives of the $2+$ Rotational States in Dy^{158} and Gd^{158} and Several Other Half-Life Measurements for Deformed Nuclei," Funk, Prask, and Mihelich, Phys. Rev. 141, 1200 (1966).

"The Decay of Pt^{191} (3.0 d) to Ir^{191} ," Blichert-Toft, Funk, and Mihelich, Nucl. Phys. 77, 513 (1966).

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"The Decay of Tb^{155} and Eu^{155} to Levels in Gd^{155} ," Blichert-Toft, Funk, and Mihelich, Nucl. Phys. A100, 2 (1967).

"Coincidence and Directional Correlation Measurements on the Decay of Tb^{160} Employing a Ge(Li) Detector," Jaklevic, Funk, and Mihelich, Nucl. Phys. A99, 83 (1967).

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"The Decay of Eu^{150} (12.8 h)," Kugel, Buss, Funk, and Mihelich, Nucl. Phys. A115, 2 (1968).

"Coincidence Measurements on the Decay of Tm^{168} (87 d)," Kenealy, Funk, and Mihelich, Nucl. Phys. A110, 3 (1968).

"Decay of Re^{182} Isomers and Ta^{182} to W^{182} ," Sapyta, Funk, and Mihelich, Nucl. Phys. A139, 161 (1969).

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"Half-Life Measurements and Transition Probabilities in Yb^{172} ," Belt, Kugel, Jaklevic, and Funk, Nucl. Phys. A134, 225 (1969).

"Decay of a New Isomer in Tb^{154} to High-Spin Levels in Gd^{154} ," Riedinger, Sousa, Funk, and Mihelich, Phys. Rev. C4, 1352 (1971).

"Half-Life and Angular Correlation Measurements in the Decay of Eu^{147} ," Belt, Funk, and Mihelich, Nucl. Phys. A175, 129 (1971).

"Level Structure in Gd^{152} Studied in the Decay of 17.5 h Tb^{152} ," Zolnowski, Funk, and Mihelich, Nucl. Phys. A177, 513 (1971).

Publications Being Prepared on Research Begun
During Period of AEC Support

"Decay of ^{160}Ho and $^{160\text{m}}\text{Ho}$," Rainis, Riedinger, Funk, and Mihelich.

"Decay of the Three Isomers of ^{154}Tb ," Sousa, Riedinger, Funk, and Mihelich.

"Decay of ^{173}Hf to ^{173}Lu ," Funk, Madden, Belt, and Mihelich.

"Coulomb Excitation of $^{160}, ^{162}, ^{164}\text{Dy}$," Oehlberg, Riedinger, Funk, and Mihelich.

"Coulomb Excitation of Even Mass $^{168-176}\text{Yb}$," Riedinger, Rainis, Funk, and Mihelich.

"Measurements of Half-Lives of Several Negative-Parity States in Deformed Even Nuclei," Madden, Funk, and Mihelich.

"Gamma-Gamma Directional Correlation Measurements in the Decay of ^{182}Ta to ^{182}W ," Schmidt, Funk, and Mihelich.

"Directional Correlation Measurements and $E1 + M2 + E3$ Admixtures in ^{174}Yb ," Schmidt, Funk, and Mihelich.