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EXPERIMENTAL STUDY OF NUCLEAR ISOMERS

Final Report

March 1, 1966 - June 30, 1972

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ABSTRACT

A program of experimental investigations of nuclear isomers was supported by the AEC from March 1, 1966 through August 31, 1971, with no-funds extensions to June 30, 1972. Results can be grouped into three phases: (1) isomers in the 10 ms - 10 sec half-life range studied with a pulsed TRIGA reactor and fast rabbit; (2) multipolarity determination of low-energy highly-converted transitions; and (3) feasibility studies of shape isomer experiments using neutrons. In Phase 1, $\text{In}^{114\text{m}}$, $\text{In}^{116\text{m}}$, $\text{Xe}^{125\text{m}}$, $\text{Xe}^{127\text{m}}$, $\text{Ba}^{136\text{m}}$, $\text{Gd}^{155\text{m}}$, $\text{Dy}^{157\text{m}}$, $\text{Ta}^{182\text{m}}$, and $\text{Ir}^{194\text{m}}$ were investigated along with two new isomers $\text{Xe}^{134\text{m}}$ and $\text{Sm}^{153\text{m}}$. In Phase 2, a new method of determining multipolarity based on relative L x-ray intensities was developed and applied. Extensive tables of theoretical values of atomic fluorescence and radiationless transition probabilities were calculated. In Phase 3, valuable neutron-beam shape isomer investigations were found feasible but only with a new experimental approach. A new instrument, the inner shell vacancy (ISV) detector, was conceived, developed, and tested successfully in bench model form, but contract termination and inadequate funds forestalled completing a model for shape isomer experiments. In one test, the ISV detector enabled measurement of the half-life of the 1.28-keV level of Ag^{110} . Lists of talks, reports, publications, and citations are appended.

TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
1. General Summary of Work	1
1.1 "Millisecond Isomers" (Phase 1)	1
1.2 Isomeric Transitions of Low Energy (Phase 2)	2
1.3 Shape Isomers (Phase 3)	3
2. Resume of Specific Investigations	5
2.1 Spin-metastable "Millisecond" Isomers	6
2.2 Multipolarity Determination by the L X-Ray Pattern Method	7
2.3 Atomic Fluorescence Parameters	8
3. Overall Evaluation of Progress	8
Appendix A Lists of Talks, Reports, and Publications	A1
A.1 Talks	A1
A.2 Reports	A2
A.3 Publications	A4
Appendix B List (Partial) of Citations of Work	B1
Appendix C Personnel	C1

1. GENERAL REVIEW OF WORK

A brief general review of the research activities carried out with AEC support is given in this section. The period covered is from March 1, 1966, through the termination date, June 30, 1972, with some mention of subsequent results that came from a logical continuation of the supported program. Following the general review, a resume of specific investigations is provided in Sect. 2, and an overall evaluation of the progress accomplished under AEC sponsorship is presented in Sect. 3.

The central theme of the research program was the experimental study of nuclear isomers as valuable and sometimes unique clues to an improved understanding of excited states of nuclei. Historically, spin-metastable isomers were important in developing the early shell model, and the Nilsson model benefitted from isomer experiments such as those on K-forbidden isomers. Around 1968, shape isomerism, a newly discovered type, was added to the armamentarium as another powerful probe for nuclear structure studies.

Research under the contract can be subdivided into three temporal phases which reflect the changes with time, both here and elsewhere, in the type of isomerism which the then-current state of knowledge indicated was the most fruitful to study.

1.1 "Millisecond" Isomers (Phase 1)

The initial direction of research was along the lines described in the original research proposal (April, 1965) -- namely, to investigate isomers in the 10 ms - 10 sec half-life range, which was then relatively unexplored for primarily experimental reasons, by exploiting the unique combination of a pulsed TRIGA reactor ($\phi > 2 \times 10^{15}$ n/cm² sec), a fast pneumatic sample-transfer system or "rabbit" (transit times as short as 30 ms), and state-of-art detectors and electronics (high resolution Li-drifted semiconductor detectors and multichannel analyzers and other electronics with high count rate capability).

Topics of contemporaneous interest during this phase were (a) quasi-particle isomers in even-even and in odd-mass nuclides; (b) K-forbidden isomers in deformed nuclides as probes to trace the dependence of the energies and mixing of Nilsson states on N and Z , and hence on deformation; and (c) ratios of isomer production cross sections, especially with two or more metastable states in the same nuclide.

The specific nuclides we investigated have for the most part been reported previously in formal documents with full distribution or in publications; for a resume see Sect. 2.1 below.

1.2 Isomeric Transitions of Low Energy (Phase 2)

Isomeric transitions with energy less than the binding energy of K-shell electrons are usually strongly internally converted and are frequently difficult to characterize as to multipolarity because of the low energy of the radiations (conversion electrons) that must be measured in standard methods of multipolarity determination. When confronted with this situation in the case of Ta^{182m} (0.3 sec), we originated a new method based on observation of solely the pattern of relative intensities of L_α , L_β , and L_γ x rays resulting from L-shell internal conversion. The advantage of this method is that L x-ray intensities are much more readily measured than low energy electron intensities. The ratios $L_\alpha:L_\beta:L_\gamma$ depend on the internal conversion coefficient ratios $\alpha_{L_1}:\alpha_{L_2}:\alpha_{L_3}$, which in turn depend markedly on the multipolarity of the nuclear transition, and to some extent on its energy. The success of the method depends experimentally on the improved x-ray energy resolution that was at that time becoming available with cooled Li-drifted detectors and cooled FET preamplifiers. The method depends also on having theoretical or experimental values for fluorescence yields ($\omega_{L_1}, \omega_{L_2}, \omega_{L_3}$) and Coster-Kronig transition probabilities (f_{12}, f_{13}, f_{23}). Our program was therefore expanded to include measurements of some of these parameters; also, in collaboration with the University of Oregon, extensive calculations of theoretical values were carried out.

The L x-ray pattern was first used on Ta^{182m} (0.3 sec); subsequently, we employed it as a supplementary method in several other cases (see Sect. 2.2

below). Recently the method has been adopted by others (Schmidt-Ott et al.; see Appendix B) to find M1/E2 mixing ratios in Ra^{223} , Np^{239} , and Cm^{245} .

1.3 Shape Isomers (Phase 3)

Fissioning isomers were first seen in 1962 and became recognized in 1968 as a totally unexpected and very important new phenomenon which opened a new avenue to experimental and theoretical study of the fission process (e.g., mass-yield asymmetry) and of highly deformed nuclei (at greater than twice ground state deformation). The relevant theory, due to Strutinsky, has also had a strong influence in theoretical predictions of superheavy elements. Furthermore, there are illuminating partial analogies between highly deformed nuclei and intermediate stages in reactions between heavy ions and heavy targets.

Shape isomers have been actively investigated in Dudna, Copenhagen, Seattle, Los Alamos, Oak Ridge, Heidelberg, Munich, and elsewhere. A great deal has been learned from the experiments to date, most of which have used charged particle beams.

Since late 1969,^{*} the major experimental effort in the Cornell research program has been directed toward investigations of the production and decay of shape isomers using neutron beams. It has often been true in nuclear structure research that neutron reactions provide usefully complementary results to those from charged particle reactions. Some advantages of neutron experiments are a lower background for low energy photons and electrons, fewer competing reactions, higher total cross sections, better knowledge of the energy and spin of the compound nucleus, and feasibility of long running times. Some disadvantages are the smaller number of product nuclides that are accessible with available targets, lower beam intensities, and less precise control and measurement of beam energy. Two types of experiments for which neutrons are especially well suited include observation of the gamma decay of shape isomers

^{*} One of us (D.D.C.) spent his 1968-69 sabbatic year in Copenhagen on a Guggenheim fellowship.

(which has not yet been seen by any method but is important because it can provide exact knowledge of the energy, spin, and parity of the isomer) and observation of transitions in the cascade populating the isomer (which can give important data on excited states "in" the second well of the double-humped barrier).

Detailed feasibility studies of shape isomer experiments with neutrons were carried out. These showed that very useful results could be obtained. However, one conclusion was that no existing type of detector could fulfill the requirements set by certain key experiments. The search for a way out of this situation led to the conception and development of a new type of detector, which we designate by the name "inner shell vacancy" (ISV) detector.

The problem has several aspects. Most shape isomers have half-lives less than one microsecond, and with slow neutrons the usual techniques for isolating such short-lived isomers -- i.e., by using pulsed beams or nuclear recoils -- are not feasible. A different method of timing isomer formation in a steady beam is needed, based in some fashion on the radiation cascade populating the isomer. Also, since the isomeric yield is low ($<10^{-5}$ of the total reaction rate), the method should be highly efficient, sensitive, and selective.

The potential solution that was chosen is to observe the simultaneous multiple emission of electrons that is known to occur in association with an inner shell vacancy, which in this case would be created by internal conversions in the populating cascade (e.g., in rotational band transitions). A simple bench model was built to try out the concept with the use of ISV-producing radioactive sources rather than a more complicated beam-and-target arrangement. Tests with Pm^{145} and Am^{241} were successful and showed the idea was feasible.

Analysis of recent (1973) measurements with $\text{Ag}^{110\text{m}}$ involving both population and decay of the 1.28-keV first excited state of Ag^{110} shows the ISV detector to be sensitive (it responds to transitions with energy as low as 1.28 keV), selective (spurious response to betas via their dE/dx is much less probable than response to processes producing true ISV's), and efficient (up to 30% for some transitions). This value refers to absolute efficiency,

defined as the ratio of the ISV-associated detector signal rate to the absolute ISV production rate. The detector is also fast (results on the 32-ns half-life in Pm^{145} decay clearly show that the potential lower limit of time resolution is less than a few nanoseconds).

An initial attempt to observe the U^{236} fissioning isomer in the $\text{U}^{235}(n,\gamma)$ reaction failed with the bench model because its design happened to give it excessive sensitivity to ambient gamma background. However, there are no apparent inherent obstacles to making an ISV detector that is fully satisfactory for neutron beam use. Models optimized for such use are, at this writing, partially designed and constructed. It should perhaps be mentioned that application of the ISV detector concept in experiments using charged particle beams is not feasible because of the large number of electrons released by each beam particle via its dE/dx .

2. RESUME OF SPECIFIC INVESTIGATIONS

2.1 Spin-metastable "Millisecond" Isomers

Investigations of Ba^{136m} (0.3 s), Xe^{125m} (58 s), Xe^{127m} (74 s), and Xe^{134m} (0.3 s) were reported in detail in the Ph.D. thesis of W. G. Winn (NYO-3664-6). Improved energies and half-life were found for Ba^{136m} . Discrepancies in earlier reports by others on Xe^{125m} were resolved, and a (probable) spin and parity of $9/2^-$ were assigned to the isomeric level, which had previously been thought from systematics would be an $11/2^-$ state. The decay scheme was found to be analogous to that for Xe^{127m} , which was also investigated. The previously unknown isomer Xe^{134m} was discovered. This isomer, whose possible existence had been suggested by L. K. Peker, is a two-quasineutron 7^- state with analogs in its $N = 80$ isotones Ba^{136m} , Ce^{138m} (9 ms) and Nd^{140m} (0.6 ms). A decay scheme, including the E3 character of the isomeric transition, was determined but the reduced half-life for Xe^{134m} was found to be larger by a factor of 6 to 10 than the values for the analogous isomers. Some citations by others of these results are listed in Appendix B.

A possible K-forbidden isomer in Gd^{155} was suggested in 1967 by preliminary data from the Copenhagen group. Its existence, identification, and half-life (31 ms) were confirmed in Gd^{154} (n, γ) studies reported by M. Etzion in his Ph.D. thesis (NYO-3664-10), which also reports his development of a fast buffer memory system. This initial Cornell experiment utilized a NaI detector; shortly after, a Ge(Li) x-ray detector was acquired, and investigations were continued by M. B. Kime. Some collaboration with Copenhagen also occurred, both by mail and by D. D. Clark when he arrived there for his sabbatic. Detailed results on Gd^{155m} , which is a K-forbidden $11/2^-$ [505] isomer, have been reported in M. B. Kime's Ph.D. thesis (NYO-3664-17) and as "private communications" in several Copenhagen publications.

Also studied by Kime were two $N = 91$ isotonic analogs of Gd^{155m} . He re-investigated Dy^{157m} (24 ms), further developed the partial decay scheme proposed for it by the Copenhagen group, and discovered the new isomer Sm^{153m} (11 ms). Essentially complete decay schemes for these isomers were reported in his thesis. All three involve K-forbidden transitions from the $11/2^-$ [505] isomeric level to lower-lying rotational states. For citations by others of this work see Appendix B.

Another isomer re-investigated by Kime was Ir^{194m} (32 ms). Details of this work appear only in Technical Progress Report No. 6 (COO-3160-3). The six observed gamma transitions were fitted into a partial decay scheme, but the isomeric transition itself was not seen, and the isomeric level energy was shown only to lie between 196 and 273 keV.

One new result has been obtained during the tests of the bench model ISV detector. The half-life of the 1.28-keV level in Ag^{110} was found to be 690 ns with an uncertainty of about 10%.

Isomer cross sections were obtained for a number of the above isomers and were reported in the various theses. Also studied were the interesting cases of In^{114} and In^{116} , which have analogous level schemes with two metastable states each, a higher-lying 8^- isomer (42 ms and 2 s respectively) and a lower-lying 5^+ isomer (50 d and 54 m respectively). Both have a beta-unstable 1^+ ground state. Each nuclide is therefore a good testing-ground for statistical

theories of isomer ratios [Huizenga and Vandenbosch; Sperber] and the similarity of the two isotopes lends added interest. Our results, details of which were reported in Technical Progress Report No. 2 (NYO-3664-9), show that the theory works fairly well in In^{114} but is seriously wrong in In^{116} . Similar cross section ratios for In^{116} had been independently obtained by others [Alexander et al., Phys. Lett. 4, 302 (1963); Ponitz, Nucl. Phys. 66, 297 (1965)] who interpreted the cross section results under the assumption that the theory was correct and assigned the higher isomer in In^{116} a spin of 5 or 6. Either value disagrees with the 8^- assignment from conversion coefficient results. The 8^- value is certainly correct, but the incorrect value has even been adopted in the Table of Isotopes of Lederer et al. The reason for the theoretically anomalous cross section ratio is not known.

Searches for new isomers in the millisecond-to-second half-life range were conducted in the nuclides Kr^{84} , Zr^{91} , Ba^{134} , Ce^{136} , and Nd^{151} , but none were found.

2.2 Multipolarity Determination by the L X-Ray Pattern Method

An isomer in Ta with about 0.3 sec half-life had been discovered in 1949 at Oak Ridge. The only radiations seen were photons of 8 to 11 keV, which were presumably L x rays due to a highly converted transition to the ground state from a level with energy less than the K-shell binding energy. No further characterization of the isomer had been achieved in the intervening years, and a re-investigation was undertaken. Invention of the L x-ray pattern method and the improved energy resolution of modern detectors made a successful result possible. The nature of the method has been covered in Sect. 1.2, and the details of the experiment and analysis have been reported in W. F. Stabenau's thesis (NYO-3664-13) and published in Phys. Rev. Letters 21, 925 (1968). Some citations by others are listed in Appendix B.

The method was also applied by Kime in his studies of $\text{Sm}^{153\text{m}}$, $\text{Gd}^{155\text{m}}$, $\text{Dy}^{157\text{m}}$, and $\text{Ir}^{194\text{m}}$, although in none of these cases was the method the sole determinant of multipolarity as it had been in $\text{Ta}^{182\text{m}}$.

2.3 Atomic Fluorescence Parameters

Values of fluorescence yields and Coster-Kronig transition probabilities are needed in applying the L x-ray pattern method, and experiments were conducted to determine the parameters f_{23} , ω_{L2} , and ω_{L3} in Ho and Er by observation of K and L x rays from internal conversions following beta decay of Dy¹⁶⁵ and Ho¹⁶⁶. Details were reported in Technical Progress Report No. 5 (NYO-3664-18). The results have also been quoted in the extensive review article on fluorescence parameters by Bambynek et al. (see Appendix B).

In collaboration with B. Crasemann and M. H. Chen of the University of Oregon, V. O. Kostroun carried out an extensive set of calculations of atomic radiationless transition probabilities and fluorescence yields. Values were obtained for a large range of Z for both K and L shells; the results were issued as RLO reports and were published in 1971 in Physical Review A₃, 533; 4, 1; and 4, 2161. These tables of parameters are widely useful in atomic physics and have already been cited by a number of authors; they have also been incorporated in the Bambynek et al. review article.

3. OVERALL EVALUATION OF PROGRESS

The foregoing sections are general and specific reviews of the work done under AEC sponsorship. Appendix A is a list of talks, reports, and publications and Appendix B is a partial list of citations by others of our results. Taken together, these summarize the research accomplishments which are to be evaluated in terms of their contribution to progress in the area of nuclear isomerism.

With respect to our results on specific nuclides, none could fairly be called a breakthrough in the sense of overturning a theory or of opening a completely new avenue of research (as, for example, shape isomers have done). Nonetheless, two new isomers, Xe^{134m} and Sm^{153m}, were found, each of which was deliberately sought because of its bearing on systematics through being one of a group of analogous isomers. Further investigation of previously known members of the groups were also carried out, and particularly in the case of

the K-Forbidden $N = 91$ isomers our results very usefully complemented and interacted with contemporaneous work by others. Our exploitation of the low-energy capability of state-of-art detectors yielded results such as the discovery of $\text{Sm}^{153\text{m}}$ and the clarification of the decay schemes of $\text{Gd}^{155\text{m}}$ and other nuclides.

In the area of isomer cross section ratios, all our results except one led to the same conclusion as that reached by others in many experiments; namely, that the theory of Huizenga and Vandenbosch explains the ratios as well as expected for statistical theory. The one exception, in In^{116} , shows for $\sigma(8^-)/\sigma(5^+)$ the most serious disagreement with theory of any case we know of. The anomalous character of this result is emphasized by the fact that in the otherwise very similar nuclide In^{114} , the corresponding ratio (which we were the first to measure) agrees reasonably with theory. The reason for this anomaly in In^{116} is not yet known.

One area in which the program yielded a unique and useful contribution was that of multipolarity determination of low-energy highly-converted transitions. Although such transitions occur in somewhat less than a huge number of cases, when they do occur they can, as in the case of $\text{Ta}^{182\text{m}}$, be completely resistant to attack by previously known techniques. The L x-ray pattern method we originated readily yielded an unequivocal result for $\text{Ta}^{182\text{m}}$. As mentioned previously, its usefulness has recently been demonstrated again in three cases investigated by others. Additional applications of the method can be confidently anticipated.

The values of atomic fluorescence parameters and radiationless transition probabilities are needed in a great range of basic and applied studies. The extensive tables of calculated values produced in collaboration with the University of Oregon will undoubtedly be useful to a great many people. This statement is attested to by the already considerable number of citations of the Physical Review articles in which the tables were published.

Contract-sponsored contributions to progress on shape isomerism were in the form of a new instrument -- the ISV detector -- rather than new physics. A reduction in level of funding came just as initial tests of the detector concept were beginning to yield results. This was in February 1971 and no new

funds were provided after August 1971. As a consequence, testing was slowed and a systematic and reasonably paced development of the detector was forestalled at an awkward in-between stage. That is, the results in hand were enough to indicate that the concept had possibilities worth pursuing, but were not enough to demonstrate quantitatively a performance sufficiently good to merit risking new funds (AEC or NSF) on a program of shape isomer research that would have to rely on the new detector. Despite the funding handicap, development was continued, albeit slowly and irregularly. Results at each stage were encouraging, but only the most recent (1973) prove in quantitative detail that the ISV detector has the originally conceived desirable properties of efficiency, sensitivity, selectivity, and speed in the degree necessary for shape isomer experiments with neutrons.

Because inner shell vacancies occur in conjunction with many different phenomena, the ISV detector is also likely to be useful in a wide variety of atomic and nuclear experiments in addition to ones on shape isomers.

It should also be remarked that an invited article by D. D. Clark on "Shape Isomers and the Double-humped Barrier" appeared in *Physics Today* 24 (12), 23 (Dec. 1971). Although the article was a review and hence not a report of work supported by contract funds, it had a close relationship to the feasibility studies of shape isomer investigations using neutrons. Interestingly, the article, though only semi-technical, has been cited in *Annual Reviews of Nuclear Science*, *Science*, and *Physical Review Letters* as well as in *Physics Today*.

APPENDIX A

LISTS OF TALKS, REPORTS, AND PUBLICATIONS

A.1 Talks

1966

1. "New 270-msec Isomer in Xenon"
W. G. Winn and D. D. Clark, Bull. Am. Phys. Soc. 11, 775 (1966)

1967

2. "Isomer Cross Section Ratios in In^{114} and In^{116} "
M. B. Kime and D. D. Clark, Bull. Am. Phys. Soc. 12, 544 (1967)
3. "Decay of Xe^{125m} and Xe^{127m} "
W. G. Winn and D. D. Clark, Bull. Am. Phys. Soc. 12, 564 (1967)
4. "Decay Scheme of Xe^{125m} "
W. G. Winn and D. D. Clark, Bull. Am. Phys. Soc. 12, 1179 (1967)
5. "Decay Scheme of Xe^{134m} and Comparison with Other $N = 80$ Isomers"
D. D. Clark and W. G. Winn, Bull. Am. Phys. Soc. 12, 1180 (1967)

1968

6. "Decay of 31-ms Gd^{155m} "
D. D. Clark and M. Etzion, Bull. Am. Phys. Soc. 13, 671 (1968)
7. "Utilization of a Pulsed TRIGA Reactor for Nuclear Physics Research"
D. D. Clark, Trans. Am. Nucl. Soc. 11, 287 (1968)
8. "A New Method for Multipolarity Determination and its Application to the 0.3-sec Tantalum Isomer"
D. D. Clark, seminar at Niels Bohr Institute, Copenhagen, September 30, 1968

1969

9. "Использование интенсивностей γ -лучей для определения мультипольностей"
D. D. Clark, paper at 19th Annual Conference on Nuclear Spectroscopy and Atomic Structure, Erevan, USSR, January 31, 1969

10. "Nuclear Structure Studies by L X-Ray Analysis"
M. B. Kime, paper at 1969 Northeastern ANS Student Conference,
MIT, April 25, 1969

1970

11. "Decay of Sm^{153m} "
M. B. Kime and D. D. Clark, Bull. Am. Phys. Soc. 15, 645 (1970)
12. "L-Subshell Fluorescence Yields and Coster-Kronig Transition Probabilities of Ho and Er"
C. P. Holmes and V. O. Kostroun, Bull. Am. Phys. Soc. 15, 561 (1970)
13. "Theoretical K X-Ray Fluorescence Yields"
B. Crasemann, V. O. Kostroun, and M. H. Chen, Bull. Am. Phys. Soc. 15, 1631 (1970)

1971

14. "Theoretical L_2 - and L_3 -Subshell Fluorescence Yields and L_2 - L_3 X Coster-Kronig Transition Probabilities"
V. O. Kostroun, M. H. Chen, and B. Crasemann, Bull. Am. Phys. Soc. 16, 618 (1971)

1972

15. "Half-life of 1.28-keV State of Ag^{110} "
V. O. Kostroun and D. D. Clark, Bull. Am. Phys. Soc. 17, 51 (1972)
16. "Many Body Perturbation Theory Applied to Atomic Radiationless Transitions"
C. P. Holmes and V. O. Kostroun, Bull. Am. Phys. Soc. 17, 68 (1972)
17. "Production of the U^{236} Fissioning Isomer by Thermal Neutrons"
D. D. Clark and V. O. Kostroun, Bull. Am. Phys. Soc. 17, 138 (1972)
18. "Many Body Perturbation Theory Applied to Atomic Radiationless Transitions"
C. P. Holmes and V. O. Kostroun, paper at International Conference on Inner Shell Ionization Phenomena and Future Applications, Atlanta, April 1972.
19. "Low-Energy Level Structure of Ir^{194} "
M. B. Kime and V. O. Kostroun, Bull. Am. Phys. Soc. 17, 606 (1972)
20. "Isomer Experiments with the ISV Detector"
D. D. Clark, seminar at Brookhaven National Laboratory, May 26, 1972

A.2 Reports

- NYO-3664-1 "New 270-msec Isomer in Xenon"
W. G. Winn and D. D. Clark (written version of talk no. 1, Appendix A.1)

NYO-3664-2 [number not used]
 NYO-3664-3 Technical Progress Report No.1 (3/1/66-1/17/67) [CURL-19]
 NYO-3664-4 [number not used]
 NYO-3664-5 " ^{125m}Xe and ^{127m}Xe : Decay Properties and (n, γ) Activation Cross Sections"
 W. G. Winn and D. D. Clark (topical report)
 NYO-3664-6 "Experimental Studies of Ba^{136m} , Xe^{134m} , Xe^{127m} , and Xe^{125m} ,"
 W. G. Winn (Ph.D. thesis) [CURL-24]
 NYO-3664-7 [number not used]
 NYO-3664-8 [number not used]
 NYO-3664-9 Technical Progress Report No. 2 (1/17/67-11/30/67) [CURL-27]
 NYO-3664-10 "A Fast Storage System for Pulse-Height Data and Experiments on 31-msec Gd^{155m} ,"
 M. Etzion (Ph.D. thesis) [CURL-28]
 NYO-3664-11 "Determination of the Multipolarity of the 0.3-sec Ta^{182} Isomeric Transition by its L X-Ray Pattern Alone"
 D. D. Clark and W. F. Stabenau (reprint) [CURL-30]
 NYO-3664-12 Technical Progress Report No. 3 (12/1/67-11/30/68) [CURL-29]
 NYO-3664-13 "Development of the L X-Ray Intensity Pattern Method for Multipolarity Determination and its Application to Ta^{182} ,"
 W. F. Stabenau (Ph.D. thesis) [CURL-31]
 NYO-3664-14 "Utilization of a Pulsed TRIGA Reactor for Nuclear Physics Research"
 D. D. Clark (reprint of published summary of talk no. 7, Appendix A.1)
 NYO-3664-15 [number not used]
 NYO-3664-16 Technical Progress Report No. 4 (12/1/68-12/31/69) [CURL-34]
 NYO-3664-17 "K-Forbidden Isomerism of the $11/2^- [505]$ Nilsson Orbital in the Odd A, N = 91 Isotones"
 M. B. Kime (Ph.D. thesis) [CURL-39]
 NYO-3664-18 Technical Progress Report No. 5 (1/1/70-12/31/70) [CURL-40]

- C00-3160-1 "Initial Studies with the Inner Shell Vacancy Detector: Pm^{145} , Am^{241} , $\text{Ag}^{110\text{m}}$, and $\text{U}^{236\text{mf}}$ "
D. D. Clark and V. O. Kostroun (topical report) [CURL-42]
- C00-3160-2 "Many Body Perturbation Theory Applied to Atomic Radiationless Transitions"
C. P. Holmes and V. O. Kostroun (preprint of talk no. 18, Appendix A.1) [CURL-44]
- C00-3160-3 Technical Progress Report No. 6 (1/1/71-6/30/72) [CURL-45]
- C00-3160-4 Final Report (3/1/66-6/30/72) (this report) [CURL-46]

Note: Three publications (see Appendix A.3) of collaborative work with the University of Oregon were issued as RLO reports rather than double-numbering with an NYO number.

A.3 Publications

1. "Utilization of a Pulsed TRIGA Reactor for Nuclear Physics Research"
D. D. Clark, Trans. Am. Nucl. Soc. 11, 287 (1968) (NYO-3664-14)
2. "Determination of the Multipolarity of the 0.3-sec Ta^{182} Isomeric Transition by its L X-Ray Pattern Alone"
D. D. Clark and W. F. Stabenau, Phys. Rev. Letters 21, 925 (1968) (NYO-3664-11)
3. "Atomic Radiationless Transition Probabilities to the $1s$ State and Theoretical K-Shell Fluorescence Yields"
V. O. Kostroun, M. H. Chen, and B. Crasemann, Phys. Rev. A3, 533 (1971) (RLO-1925-41)
4. "Theoretical L_2 - and L_3 -Subshell Fluorescence Yields and L_2 - L_3 X Coster-Kronig Transition Probabilities"
M. H. Chen, B. Crasemann, and V. O. Kostroun, Phys. Rev. A4, 1 (1971) (RLO-1925-50)
5. "Auger and Coster-Kronig Transition Probabilities to the $2s$ State and Theoretical L_1 Fluorescence Yields"
B. Crasemann, M. H. Chen, and V. O. Kostroun, Phys. Rev. A6, 2161 (1971) (RLO-1925-53)
6. "Shape Isomers and the Double-Humped Barrier"
D. D. Clark, Physics Today 24 (12), 23 (Dec. 71)

7. "Many Body Perturbation Theory Applied to Atomic Radiationless Transitions"
C. P. Holmes and V. O. Kostroun, in R. W. Fink, S. T. Manson, J. M.
Palms, and P. V. Rao (editors), Proceedings of the International
Conference on Inner Shell Ionization Phenomena and Future Applications,
AEC Report CONF-720404, p. 475 (COO-3160-2)

Note: Several additional articles are in preparation.

APPENDIX B

LIST (PARTIAL) OF CITATIONS OF WORK

<u>Item Cited^a</u>	<u>Topic</u>	<u>Citations</u>
A.1.1	Xe ^{134m}	Peker, Izv. Akad. Nauk SSSR, Ser. Fiz. <u>31</u> , 1584 (1967) Brinckmann et al., Nucl. Phys. <u>A96</u> , 318 (1967) Julian et al., Phys. Rev. <u>172</u> , 1208 (1968) + private communication Coryell et al., Nucl. Phys. <u>A179</u> , 689 (1972)
A.1.2	In σ 's	Alexander et al., Nucl. Phys. <u>A112</u> , 474 (1968)
A.1.4	Xe ^{125m} Xe ^{127m}	Kondaiah et al., Nucl. Phys. <u>A120</u> , 329 and 337 (1968)
A.1.5	Xe ^{134m}	Peker, Izv. Akad. Nauk SSSR, Ser. Fiz. <u>34</u> , 1727 (1970)
A.1.6	Gd ^{155m}	Borggreen et al., Nucl. Phys. <u>A143</u> , 255 (1970) + private communication Goncharo et al., Sov. J. Nucl. Phys. <u>14</u> , 1 (1972)
A.1.11	Sm ^{153m}	Bunker et al., Rev. Mod. Phys. <u>43</u> , 348 (1971) + private communication Bennett et al., Nucl. Phys. <u>A171</u> , 113 (1971) + private communication Ward et al., J. Inorg. Nucl. Chem. <u>34</u> , 13 (1972)
A.1.12	F ₂₃ ^w _L	Bambynek et al., Rev. Mod. Phys. <u>44</u> , 716 (1972)
NYO-3654-6	Xe ^{125m} Xe ^{127m} Xe ^{134m}	Carras et al., Compt. rend. <u>B270</u> , 358 (1970) Carras et al., Nucl. Phys. <u>A158</u> , 403 (1970) Nuclear Data Sheets <u>7B</u> , 465 (1972)
A.3.2	L x-ray method, Ta ^{182m}	Wasson et al., Nucl. Phys. <u>A132</u> , 161 (1969) Helmer et al., in Neutron Capture Gamma-Ray Spectroscopy, Studsvik, IAEA (1969), p. 615 Helmer et al., Nucl. Phys. <u>A168</u> , 449 (1971) Andrejtscheff et al., Nucl. Phys. <u>A178</u> , 563 (1972) Schmidt-Ott et al., Z. Physik <u>255</u> , 161 (1972) Schmidt-Ott et al., in Inner Shell Ionization Phenomena and Future Applications, Atlanta, CONF-720404 (1972), p. 1948

^aReferences are to Appendix A

<u>Item Cited</u> [*]	<u>Topic</u>	<u>Citations</u>
A.3.3 } A.3.4 } A.3.5 }	theoret. atomic params.	Bambynek et al., Rev. Mod. Phys. <u>44</u> , 716 (1972) numerous others also
A.3.6	shape isomer review	Nix, Physics Today <u>25</u> (no. 4), 30 (April 1972) Nix, Ann. Rev. Nucl. Science, vol. 22 (1972) Thompson et al., Science <u>178</u> , 1047 (1972) Ross et al., Phys. Rev. Letters <u>30</u> , 55 (1973)
private communication	Xe ^{125m} Xe ^{127m}	Graeffe et al., Nucl. Phys. <u>A107</u> , 67 (1968)
"	Sm ^{153m}	Borggreen et al., Nucl. Phys. <u>A143</u> , 255 (1970)
"	Gd ^{155m}	Meyer et al., Nucl. Phys. <u>A132</u> , 177 (1969) Borggreen et al., Nucl. Phys. <u>A131</u> , 241 (1969) Løvholden et al., Nucl. Phys. <u>A148</u> , 657 (1970) Bunker et al., Rev. Mod. Phys. <u>43</u> , 348 (1971)

APPENDIX C

PERSONNEL

The following personnel worked on the research program and received salary from the contract at various times:

David D. Clark, Principal Investigator
Vaclav O. Kostroun, Co-principal Investigator (earlier, Research Associate)
Willard G. Winn, Graduate Research Assistant
Walter F. Stabenau, Graduate Research Assistant
Milford B. Kime, Graduate Research Assistant
Yigal Ronen, Graduate Research Assistant
Gad Shani, Graduate Research Assistant (one summer)
Kwang Y. Kim, Graduate Research Assistant (one summer)
R. J. R. Knowles, Graduate Research Assistant

The following Ph.D. students worked in the program but did not receive stipends from contract funds:

Moshe Etzion
Charles P. Holmes
Norman E. Siems, Jr.

The following faculty and staff aided the research at no charge to the contract:

Professor Ross McPherson
Professor Raphael M. Littauer
Howard C. Aderhold, Reactor Supervisor
Harry J. Doane, Senior Reactor Operator
Wayne S. Rial, Electronics Engineer
Paul I. Craven, Electronics Technician
John P. Buggle, Electronics Technician