TECHNICAL PROGRESS REPORT

CONTRACT E(11-1)-1760

THE CYCLOTRON AS AN INSTRUMENT FOR CHEMICAL RESEARCH

Washington University

St. Louis, Missouri

SUMMARY OF RESEARCH PROGRESS

SUMMARY OF CYCLOTRON LABORATORY OPERATIONS
DURING TWELVE MONTHS ENDING MAY 31, 1975

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INTRODUCTION

The Nuclear Chemistry Group of the Washington University Department of Chemistry is conducting research actively in the following areas:

- i. studies of fission processes;
- ii. nuclear structure studies, with emphasis on the electromagnetic properties of high-spin states;
- iii. exceedingly short lifetime measurements for processes leading to the formation of bound excited nuclear states;
- iv. studies of nuclear reaction mechanisms, with emphasis on the angular momentum and energy transferred;
- v. nuclear spectroscopy, with emphasis on precision gamma-ray measurement and study of very short-lived isotopes;
- vi. hot atom chemistry, chemical reactions in which the participating atoms have been formed in some preceding nuclear reaction, hence are moving with substantial velocities;
- vii. development of useful radioisotopes for medical diagnosis.

Much of this research is funded by the U. S. Energy Research and Development Administration, through contract E(11-1)-1760, for which this Progress Report is being submitted. Some of it is supported by the USERDA through other contracts, while some parts receive support from other agencies, including the NSF and NIH, and from the Research Corporation. Washington University also contributes through its participation in contract E(11-1)-1760.

The Group comprises five faculty members of the Department of Chemistry (Profs. A. C. Wahl, D. G. Sarantites, Edward S. Macias, Peter P. Gaspar, and Michael J. Welch, who has a joint appointment with the Department of Radiology), plus post-doctoral research associates, degree-seeking graduate students (fluctuating in number between about 12 to 20 due to normal turnover), and the operating staff for the Washington University Cyclotron Laboratory. The Laboratory staff includes a faculty director (Prof. F. B. Shull, Department of Physics), the operations director (John T. Hood), and six full-time or nearly full-time

engineers, technicians, and machinists, plus several persons part-time (secretary, part-time cyclotron operators). Over the past 9 years, the work of the Nuclear Chemistry group has resulted in 16 doctoral degrees earned by graduate students and in the submission of 140 research papers for publication.

The physical facilities of the Nuclear Chemistry Group include two buildings, the Nuclear Chemistry Laboratory and the University Cyclotron Laboratory, next to each other on the main campus of Washington University. The Nuclear Chemistry Laboratory has faculty and student offices, laboratories, counting rooms, and specialized facilities for processing short-lived materials which have been activated by cyclotron bombardment and then delivered by pneumatic rabbit line connecting the two buildings.

The Cyclotron Laboratory houses a 54-inch sector-focused cyclotron in a vault below ground, a large adjacent underground research area into which collimated beams of accelerated particles are delivered through a four-foot concrete wall, a combination control room for the cyclotron and data acquisition and analyzer room for experiments in which electronic particle detectors are used, a well equipped machine shop, an electronics shop, a chemical processing room and a thin target preparation facility, plus staff office space, drafting room, and a variety of auxiliary research and equipment assembly spaces.

The Cyclotron Laboratory staff maintains and operates the accelerator, provides direct assistance to researchers in utilizing it for their investigations, designs and builds most of the specialized operational equipment required for the cyclotron, develops and perfects new modes of using the accelerator and its peripheral facilities, and works on ways to improve the accelerator's performance, characteristics and its usefulness to its research users. In addition to operating and maintaining the cyclotron itself, the engineers and machinists of the staff are frequently involved in designing and constructing research apparatus, as distinguished from operating equipment, for members of the Nuclear Chem-

istry Group and for other research users who do not have access to a machine shop or engineering services of this high quality and experience.

A major improvement project which is being planned is the installation of a Kaman Nuclear neutron generator, Model A-711, which was recently acquired by gift of the Ralston-Purina Company of St. Louis. This generator is capable of producing good yields of 14 MeV neutrons from the $H^3(d,n)He^4$ reaction. It should be a valuable addition to the Cyclotron Laboratory's facilities for the several users who require fast neutrons, especially those concerned with hot atom chemistry. Once installed and in operation, it should increase considerably the frequency with which neutron-initiated experiments can be undertaken.

This Technical Progress Report covers a one-year period, June 1, 1974 to May 31, 1975, in the operations of the Nuclear Chemistry Group. Until this year, support of the Group's work by USERDA was provided through four separate research contracts, covering projects under different faculty members, together with a single Special Research Support Agreement Contract (contract E(11-1)-1760), under which Washington University and the USERDA shared the operating costs for the Cyclotron Laboratory (or at least a substantial fraction of the operating costs). Under the terms of contract E(11-1)-1760, the Cyclotron Laboratory has provided cyclotron time without further charge to personnel working under any of the four ERDA research contracts. In addition, however, the Laboratory sold cyclotron and other laboratory services to other University-connected research groups. This has included a substantial use of machine shop time by the Radiation Sciences Division of the Department of Radiology in the Medical School. It has also included use of the cyclotron by members of the Nuclear Chemistry Group on projects supported by grants or contracts with agencies other than the USERDA, and by Dr. Charles Foster of Indiana University.

After this year, most of the support for the Nuclear Chemistry Group which comes from the USERDA is to be combined in one contract, E(11-1)-1760,

into which three of the four former research contracts are to be merged. The single contract is to cover both research costs and operation of the Cyclotron Laboratory. The process of combining several contracts into one has already been taking place in piecemeal fashion during the current year. As of April 1, 1975, two of the four research contracts were merged into E(11-1)-1760: (1) Radiochemical Studies of Nuclear Fission and Search for Element 118 (eka-radon), AT(11-1)-1162, Prof. Wahl, and (2) Spectroscopy of Nuclear Systems, AT(11-1)-2318, Prof. Macias. Next fall on September 16, 1975, the project on Low-Energy Nuclear Reactions and Spectroscopy, now supported by contract E(11-1)-1530, Prof. Sarantites, will also be added to contract E(11-1)-1760. The fourth research contract, Reaction Studies of Hot Silicon and Germanium Radicals, E(11-1)-1713, Prof. Gaspar, will continue its separate status; the Cyclotron Laboratory will continue as before to provide irradiations to Prof. Gaspar without hourly use charges. As in the past, it is expected that some services of the Cyclotron Laboratory will continue to be purchased by University-connected users, both inside and outside the Nuclear Chemistry Group, for projects which are supported by other agencies than the USERDA.

This rather complex situation concerning support of the Nuclear Chemistry Group and the Cyclotron Laboratory underwent a further complication at about the time when preparation of this annual Technical Progress Report was begun. In a letter dated June 11, 1975, the University was notified by the USERDA that support of the Nuclear Chemistry Group through contract E(11-1)-1760, as outlined in the preceding paragraph, will be continued to April 30, 1976, but will not be renewed after that date.

As a result of these complications, this Report has to summarize a somewhat mixed bag of activities and accomplishments. It includes, besides this Introduction, which was written by Prof. F. B. Shull, Faculty Director of the Cyclotron Laboratory, three lettered sections prepared by different persons, as follows:

- A. Review of Cyclotron Laboratory Operations, for the period June 1, 1974 to May 31, 1975, since the most recent Technical Progress Report was

submitted (COO-1760-7). Prepared by Prof. F. B. Shull.

B. Radiochemical Studies of Nuclear Fission and Search for Element 118 (eka-radon), a review of research progress for the period since December 1, 1974. Prepared by Prof. A. C. Wahl.

C. Spectroscopy of Nuclear Systems, a review of research progress for the period since December 1, 1974. Prepared by Prof. E. S. Macias.

Note that the Report does not include any review of research on Low-Energy Nuclear Reactions and Spectroscopy by Prof. D. G. Sarantites and his co-workers because that project is not scheduled to be joined with contract E(11-1)-1760 until September, 1975, long after this Report is due.

A. REVIEW OF CYCLOTRON LABORATORY OPERATIONS

June 1, 1974 - May 31, 1975

Prepared by Prof. F. B. Shull

In reporting to the USERDA on activities of the Washington University Cyclotron Laboratory for this period, it seems appropriate to begin with a summary of the modus operandi of the Nuclear Chemistry Group and of the Cyclotron Laboratory, with particular emphasis upon the relationship between our level of operational activity and the amount and the variegated nature of our financial support. Three principal points should be made:

1. Usage of the cyclotron and other facilities available in the Cyclotron Laboratory has been characterized for many years by the unusually wide variety of research projects which have been undertaken and the notable diversity of experimental techniques and procedures which those projects have involved. Week in, week out, the Laboratory attempts to serve about 20 to 25 different users (faculty, post-doctoral research associates, graduate students) working on from 10 to 12 different specific projects over any given period of time. Competition for fair share of machine time is strong, and we have developed a workable biweekly operating schedule, under which all regular users receive regularly scheduled periods on the machine every week (biweekly for some). This entails as many as twenty quick-change shifts in the mode of cyclotron operation during each two week period; frequently this requires a switch from one accelerated particle type to another, or at least a change of the particle energy, and usually also a change in the site to which the beam is delivered. Two or three such shifts in one day is not uncommon.
2. Total utilization of the cyclotron by all users adds up to considerably more

than we can provide with simple daytime-only operation for five weekdays (35 hours per week, excluding start-up time each morning). The biweekly schedule provides up to 105 hours of scheduled time, by extending operations to midnight on weekdays and for two full shifts on Saturdays and Sundays. Part-time operators are used to piece out the services of staff operators, who handle the weekday daytimes and do all maintenance. Actual usage tends to run about 50% of total scheduled time, which is pretty good, considering the basically inefficient nature of our many-users, quick-change schedule arrangements. Similarly, our machine shop handles a much larger volume of work than would be required merely to maintain the cyclotron and provide shop services to ERDA-supported research projects. Three full-time machinists are employed, whereas one would probably be sufficient purely for cyclotron maintenance and improvement projects.

3. Since the predecessor contract, AT(11-1)-1760 first went into effect in November, 1967, total operating costs for the Cyclotron Laboratory have consistently exceeded funding by the USERDA. Typically the USERDA contribution has amounted to about 60% of total costs. The balance has been made up partly through Washington University's contribution, partly through contributions from non-ERDA research users in payment for cyclotron time or shop time, and partly through sale of medically-useful isotopes produced with the cyclotron on a small scale.

The Bi-Weekly Operating Schedule

Before reporting on actual cyclotron usage, it is worthwhile to analyze the bi-weekly schedule which governs apportionment of time among our users. This schedule (next page) has undergone revision by negotiation among interested parties at irregular intervals, to bring it into consonance with changing patterns of demand. An attempt is made to give each user a fair allot-

NORMAL BI-WEEKLY SCHEDULE

<u>Day of Week</u>	<u>First Week</u>	<u>Hours</u>	<u>Second Week</u>	<u>Hours</u>
Monday	Maintenance and improvements	4	Maintenance and improvements	4
	Sarantites (C)	11	Macias (C)	11
Tuesday	Welch (C, R)	3	Welch (C, R)	3
	Wahl (C), Gaspar (C) deuteron runs to obtain neutrons	7	Wahl (C), Gaspar (C) deuteron runs to obtain neutrons	7
	Cooling off period	1	Cooling off period	1
	Sarantites (C)	4	Sarantites (C)	4
Wednesday	Sarantites (C)	15	Macias (C)	15
Thursday	Sarantites (C)	15	Macias (C)	15
Friday	Welch (C, R)	3	Welch (C, R)	3
	Wahl (C), Gaspar (C) Deuteron runs to obtain neutrons	7	Wahl (C), Gaspar (C) deuteron runs to obtain neutrons	7
	Cooling off period	1	Cooling off period	1
	Sarantites (C)	4	Macias (C)	4
Saturday	Sarantites (C)	15	Macias (C)	15
Sunday	Sarantites (C)	15	Macias (C)	15

(C) Department of Chemistry
(R) Department of Radiology

ment of the more desirable weekday slots ("prime time") and of the less sought after evening hours and weekends. Prime time is defined as the forty hours per week on weekdays between 8:30 a.m. and 4:30 p.m. which is when our regular full-time operating staff is on duty, so that operations may be expected to proceed most smoothly. Non-prime time entails use of part-time operators; it includes 35 hours of evening shift on weekdays and 30 hours of weekend shifts.

Prime time is almost exclusively assigned to users from the Nuclear Chemistry Group whose research is ERDA-supported. The exceptions are four hours weekly devoted to regular routine maintenance and improvement work by the staff, plus short periods twice weekly for medical isotope production and development involving Dr. Welch, since isotope production work requires experienced supervision. All users who require short, concentrated periods of cyclotron time (usually involving brief and intermittent bombardments interspersed with off periods for chemistry or analysis) are assigned to prime time slots, so that they will receive the benefit of the staff's experience to keep things running smoothly. These include twice-weekly periods devoted to neutron production for experiments by Prof. Wahl on fission studies and by Prof. Gaspar on hot atom chemistry, and the twice-weekly assignments for Prof. Welch for producing isotopes of medical interest.

By contrast, the nuclear spectroscopy and reaction experiments of Profs. Sarantites and Macias tend to require long bombardments with steady beams. Once the beam has been properly established into the target, operation can usually be continued for long periods without close attention, and part-time operators are able to handle operational problems satisfactorily. The bi-weekly schedule includes a large number of 15 and 11 hour assignments to accommodate this kind of run, three on weekdays, two on weekends. In fact, however, it is possible to extend these to uninterrupted periods of more than two days duration by working during the midnight-to-morning unscheduled periods; this is not uncommon.

Summary of Actual Use, June 1, 1974 to May 31, 1975

Tables I, II, III (4 pages), and IV in this section summarize actual use of cyclotron time. Two different time units appear in these tables:

i. Machine hours. Time during which "occupancy" of the machine by one user prevents any utilization of it by any other user, even though the occupant may not actually be receiving beam on target. If beam is not being delivered, the machine remains on standby status, perhaps to permit a period of counting or chemical processing, or to permit apparatus changes.

ii. Beam hours. Time during which beam is delivered to target.

In Table I, a brief month-by-month summary of total cyclotron usage is presented, using both kinds of time units. Total consumption of machine hours for research was 2381.5 hours, which is 43.5% of the machine hours assigned under our bi-weekly schedule. The comparable numbers for the preceding two years were 2135 and 2757 hours. Table II on the same page shows how much time (in beam hours) was provided using each of the several commonly-accelerated ion types. As in prior years, the bulk of our work has been with alpha-particles and He^3 ions. Compared to last year, demand for alphas was greater (857 hours vs. 628 hours) and demand for helions was about the same (532 hours vs. 526 hours). Deuteron requests were down a little (123 hours vs. 165 hours); deuterons are used to generate neutrons. The most notable change occurred for protons (only 20 hours vs. 434 hours last year). Lithium ions were accelerated for the first time here, and work was begun with ^{12}C ions. The drop in proton usage reflects the change of emphasis in Prof. Sarantites research program.

Table III breaks down the consumption of machine hours in more detail. It covers four pages, two pages reporting use of prime time, two for non-prime time. Within each of the two sections, consumption is broken down according to user, with various post-doctoral research associates and graduate students

listed together with the faculty members most closely associated with each. Symbols (C), (R), and (P) designate the home department of the faculty member or principal investigator, Chemistry, Radiology (School of Medicine), and Physics, respectively. Month by month consumption is listed, clearly identifying regular users and occasional users. When all consumption by persons not labelled exclusively with (C) is lumped, it comes to 615 machine hours, or almost 26% of total machine hours used; this means that 74% of our time is spent on research by purely Chemistry researchers (but not including Dr. Welch in this group) and 26% for non-Chemistry users, particularly from the Medical School (including Dr. Welch in this category).

Table I. Monthly Actual Use

6-1-74 to 5-31-75

<u>Month</u>	<u>Machine Hours</u>	<u>Beam Hours</u>	<u>Maintenance Improvement Hours</u>
June 1974	169.5	116.3	16.0
July	134.0	85.7	16.0
August	189.5	127.9	16.0
September	185.5	114.8	16.0
October	228.0	144.0	16.0
November	173.0	117.3	16.0
December	155.0	83.5	16.0
January 1975	197.0	118.7	16.0
February	223.0	139.4	16.0
March	249.0	207.0	16.0
April	186.0	112.7	16.0
May	<u>292.0</u>	<u>210.5</u>	<u>16.0</u>
	2381.5	1577.8	192.0

Table II. Breakdown of Beam Hours by Ion Type

$^1\text{H}^+$	19.8
$^2\text{H}^+$	123.7
$^3\text{He}^+$	2.6
$^3\text{He}^{++}$	532.5
$^4\text{He}^{++}$	857.4
$^6\text{Li}^{++}$	7.7
$^6\text{Li}^{3+}$	1.6
$^{12}\text{C}^{4+}$	<u>32.5</u>
	1577.8

Table III - Part I

6-1-74 to 5-31-75 Machine Hours. Prime Time (8:30 A.M. - 4:30 P.M. Monday - Friday)

	<u>1974</u>	<u>June</u>	<u>July</u>	<u>Aug.</u>	<u>Sept.</u>	<u>Oct.</u>	<u>Nov.</u>	<u>Dec.</u>
Dr. Gaspar (C) R. Hwang, B. Mizes		12.0	12.0	9.0	5.0	14.5	10.0	17.0
Dr. Macias (C) H.C Hseuh, M. Zalutsky E. Jensen, L. Zapata		32.0	37.0	16.0	24.0	48.0	----	11.0
Dr. Sarantities (C) Dr. Barker, Dr. Rutledge* Dr. Urbon, R. Goldworm		28.5	3.0	67.0	52.0	32.0	51.0	36.0
Dr. Ter-Pogossian (R)		2.0	----	----	----	----	----	----
Dr. Phelps (R)		3.5	----	7.5	----	3.5	----	----
Dr. Wahl (C) Dr. Goth, G. Ehrhardt R. Strickert, E. Vine		20.5	23.5	26.5	30.5	23.0	22.0	28.0
Dr. Walker (P) Dr. Zimmerman, S. Sutton		----	5.0	2.0	----	----	2.0	----
Dr. Welch (C) & (R) J. Frost, J. Harwig L. Knight		30.5	30.5	27.5	32.0	40.0	38.5	24.0
Dr. Foster (Ind. Univ.) S. Gronemeyer		----	----	----	----	----	----	----
University of Missouri		----	----	----	----	----	----	----
Cyclotron Tuning		----	----	----	8.0	11.0	----	----
Totals		129.0	111.0	155.5	151.5	172.0	123.5	116.0

*Dr. Rutledge supported 50 - 50 by Dr. Macias and Dr. Sarantities.

Table III - Part II

6-1-74 to 5-31-75 Machine Hours. Prime Time (8:30 A.M. - 4:30 P.M. Monday - Friday)

	1975	Jan.	Feb.	March	April	May	Totals
Dr. Gaspar (C) R. Hwang, B. Mizes		8.0	16.0	7.0	6.0	23.0	139.5
Dr. Macias (C) H.C. Hseuh, M. Zalutsky E. Jensen, L. Zapata		40.0	16.0	----	32.0	12.0	268.0
Dr. Sarantities (C) Dr. Barker, Dr. Rutledge Dr. Urbon, R. Goldworm		32.0	55.0	65.0	16.0	36.0	473.5
Dr. Ter-Pogossian (R)		----	----	----	----	----	2.0
Dr. Phelps (R)		----	----	4.0	2.0	----	20.5
Dr. Wahl (C) Dr. Goth, G. Ehrhardt. R. Strickert, E. Vine		37.0	24.0	16.0	24.0	38.0	313.0
Dr. Walker (P) Dr. Zimmerman, S. Sutton		----	----	2.0	----	----	11.0
Dr. Welch (C) & (R) J. Frost, J. Harwig L. Knight		34.0	37.0	32.0	38.0	17.0	381.0
Dr. Foster (Ind. Univ.) S. Gronemeyer		----	<----	----	----	3.0	3.0
University of Missouri		----	3.0	----	----	----	3.0
Cyclotron Tuning		----	2.0	----	29.0	4.0	54.0
Totals		151.0	153.0	126.0	147.0	133.0	1668.5

Table III - Part III

Machine Hours. Non-Prime Time (Evenings, Nights, Weekends)

	<u>1974</u>	<u>June</u>	<u>July</u>	<u>Aug.</u>	<u>Sept.</u>	<u>Oct.</u>	<u>Nov.</u>	<u>Dec.</u>
Dr. Gaspar (C) R. Hwang, B. Mizes	----	----	----	----	----	----	----	----
Dr. Macias (C) H.C. Hseuh, M. Zalutsky E. Jensen, L. Zapata	20.0	20.0	1.5	16.0	38.0	----	6.0	
Dr. Sarantities (C) Dr. Barker, Dr. Rutledge Dr. Urbon, R. Goldworm	17.5	----	29.0	10.0	2.0	42.5	27.0	
Dr. Phelps (R)	1.5	----	----	----	----	----	----	----
Dr. Wahl (C) Dr. Goth, G. Ehrhardt R. Strickert, E. Vine	----	3.0	3.0	5.0	7.0	4.0	----	
Dr. Welch (C) & (R) J. Frost, J. Harwig L. Knight	1.5	----	0.5	3.0	9.0	3.0	6.0	
Dr. Foster (Ind. Univ.) S. Gronemeyer	----	----	----	----	----	----	----	----
Totals	40.5	23.0	34.0	34.0	56.0	49.5	39.0	
Grand Totals	169.5	134.0	189.5	185.5	228.0	173.0	155.0	

Table III - Part IV

Machine Hours. Non-Prime Time (Evenings, Nights, Weekends)

	<u>1975</u>	<u>Jan.</u>	<u>Feb.</u>	<u>March</u>	<u>April</u>	<u>May</u>	<u>Totals</u>
Dr. Gaspar (C) R. Hwang, B. Mizes	----	----	----	----		1.0	1.0
Dr. Macias (C) H.C. Hseuh, M. Zalutsky E. Jensen, L. Zapata	33.0	5.0	----	13.0	7.0		159.5
Dr. Sarantities (C) Dr. Barker, Dr. Rutledge Dr. Urbon, R. Goldworm	----	41.0	83.0	----	56.0		308.0
Dr. Phelps (R)	----	----	3.0	----	----		4.5
Dr. Wahl (C) Dr. Goth, G. Ehrhardt R. Strickert, E. Vine	----	----	3.0	----	25.0		50.0
Dr. Welch (C) & (R) J. Frost, J. Harwig L. Knight	7.0	16.0	13.0	26.0	11.0		96.0
Dr. Foster (Ind. Univ.) S. Gronemeyer	6.0	8.0	21.0	----	59.0		94.0
Totals	46.0	70.0	123.0	39.0	159.0		713.0
Grand Totals	197.0	223.0	249.0	186.0	292.0		2381.5

Table IV, Particle Energies
6-1-74 to 5-31-75

<u>$^1\text{H}^+$</u>	<u>$^2\text{H}^+$</u>	<u>$^3\text{He}^+$</u>	<u>$^3\text{He}^{++}$</u>	<u>$^4\text{He}^{++}$</u>
4.5 MeV	13.0 MeV	10.0 MeV	9.5 MeV	13.0 MeV
7.0 MeV			18.0 MeV	17.0 MeV
10.0 MeV			25.0 MeV	18.0 MeV
			28.0 MeV	19.0 MeV
			30.0 MeV	19.5 MeV
			32.0 MeV	20.0 MeV
			34.0 MeV	21.0 MeV
				24.0 MeV
				26.0 MeV
				27.0 MeV
				30.0 MeV
<u>$^6\text{Li}^{++}$</u>	<u>$^6\text{Li}^{3+}$</u>	<u>$^{12}\text{C}^{4+}$</u>		
20.0 MeV	45.0 MeV	40.0 MeV		

Non-Operational Activities

Besides operating the cyclotron for users, the staff of the Cyclotron Laboratory spends a lot of time and effort on a variety of non-operational projects. Generally speaking these fall into three categories: (1) fabrication of research apparatus or development of operational techniques for the cyclotron in response to requests by one of the users, (2) fabrication, modification, or repair of operational equipment for the cyclotron, and (3) development of improved general operational procedures which will enhance the reliability or convenience of running the cyclotron. Such projects usually require extensive machine shop work, and the staff engineers do the design, installation, and testing. Sometimes design and planning for projects in the first category is partially done by a user, but more often the engineering is turned over to the Laboratory staff after the user has explained his needs.

In the first category, projects related to research problems, may be listed the following:

- a scattering chamber for Dr. Rutledge (182 man hours)
- a target chamber for Dr. Macias
- a revised rotating beta recoil chamber for Dr. Wahl (262 man-hours)
- improvements of a light ion search apparatus (LISA) for Dr. Wahl and Dr. Goth
- further modifications of a helium jet apparatus for Dr. Macias
- target and catcher assemblies for a recoil distance lifetime measurement system for Dr. Sarantites
- a monitor chamber for Dr. Sarantites (73 man-hours)
- repair and re-installation of a back-angle scattering chamber for Dr. Foster
- magnets and target chamber for measurement of g-factors, for Drs. Sarantites and Macias (229 man-hours)
- modification of a target chamber into a triple-coincidence experimental chamber, for Dr. Barker (94 man-hours)

- development of heavy-ion beams, for Dr. Sarantites

By way of illustration, machine shop time in man-hours has been given for some of these projects. Total time for projects in this category came to over 950 man-hours in 12 months, representing about half a year of work for one machinist. Note that contract E(11-1)-1760 supports one machinist (out of three working in the Laboratory shop).

In the second category, projects involving manufacture, modification, or repair of operational equipment for the cyclotron, may be listed the following, which is an incomplete list, for the sake of illustration:

- 24 adapter units were made and installed in all magnet current regulators, to allow replacement of outmoded operational amplifiers with currently available integrated circuits
- a new gas manifold for the cyclotron ion source was made and installed
- slit assemblies for the beam tubes were modified to improve cooling
- an electron gun assembly was made for the thin-target evaporation chamber, and installed
- a quick-change target assembly was built
- a new type of ion source chimney was designed and built, to permit acceleration of lithium ions

Several of the projects listed in the second category probably could also properly have been listed in the third category, projects concerned with improvement of operational procedures or with obtaining better reliability and convenience of cyclotron operation. Also included in this group are the following projects which are not related to the cyclotron per se but which represent improvements in the Laboratory facilities:

- purchase and installation of a new Bridgeport milling machine in the shop (funds from non-ERDA source)

- acquisition of a used Kaman A-711 neutron generator by gift from the Ralston-Purina Company of St. Louis. When it has been installed it be an important source of fast neutrons, as an alternative to using deuterons to initiate the Be(d,n) reaction

To conclude this summary of non-operational activities of the Laboratory staff and particularly of the machine shop and engineering staff, it seems appropriate to mention a large amount of engineering and shop work done for others, who are not supported by the USERDA through contract E(11-1)-1760. This is why the shop has three machinists rather than only one, which requires correspondingly large financial support from non-ERDA sources. Most of this extra work has been done for the Radiation Sciences Division of the Department of Radiology of the Medical School, Dr. Ter-Pogossian and co-workers. His group is concerned with application of radiation for diagnostic purposes, location of tumors, etc. The biggest single shop project in which the Laboratory has been involved during the past year was the design and construction of a fully-automated positron-emission transverse tomograph for this group. This is a large arrangement of moveable radiation detectors, with which to study the three-dimensional pattern of radiations coming from a patient to whom an appropriate radioisotope-containing solution has been administered. This pattern can be analyzed via computer, using empirical algorithm, to obtain a three-dimensional "picture" of where the radioisotope has lodged within the patient's body. On average, projects like this one account for about one-half of the machine shop's work, and Dr. Ter-Pogossian's research funds provide salaries for two of the three machinists accordingly. Laboratory staff engineers also provide technical design assistance and supervision.

Other Income, Other Expenses

In an earlier section, it was noted that total operating costs for the Laboratory considerably exceeded the amount contributed by the USERDA via contract E(11-1)-1760. The balance is supplied partly by Washington University,

through its contribution to contract E(11-1)-1760, and partly through payments from other users, who are not themselves supported by the USERDA. In this section, we wish to report briefly on income and expenses not covered by the contract.

Through contract E(11-1)-1760, the University and the USERDA provide for a basic minimum level of Laboratory operations, which includes salaries and fringe benefits for a basic staff of three engineers and one machinist, all full-time, plus part-time services from an electronics technician, a secretary, and several hourly-paid cyclotron operators. It also covers a basic allotment for expendable supplies, minimal equipment purchases, minimal services, and minimal electric power, which are adequate to provide daytime operation on weekdays only. It does not cover salaries and fringe benefits for two additional machinists and additional hourly workers, nor additional electric power used for evening and weekend operations.

In the first tabulation below a summary is presented of several different categories of laboratory operational costs, showing for each the budgeted amount provided by the contract, then the amount actually spent or to be spent during the current contract year (11/1/74 to 10/31/75), finally the difference between these two numbers for each category. Numbers have been rounded off, and are given in thousands of dollars (K\$).

<u>Category</u>	<u>Budgeted in E(11-1)-1760</u>	<u>Actually spent</u>	<u>Excess spent over budget</u>
Salaries, wages, and indirect costs based on salaries, plus fringe benefits	132.6 K\$	176.0 K\$	43.4 K\$
Supplies, materials, services	11.5 K\$	15.8 K\$	4.3 K\$
Equipment	6.0 K\$	7.4 K\$	1.4 K\$
Power	5.0 K\$	7.7 K\$	2.7 K\$
	155.1 K\$	206.9 K\$	51.8 K\$

Clearly the greatest excess of actual expenditures over budgeted comes in salaries and salary-related items. This is principally because we have three machinists full-time in the shop, instead of the one provided for by the contract, at an extra cost of about 40.0 K\$ for salaries, indirect costs, and fringe benefits.

In the second tabulation, an outline is given of the hoped-for sources of additional income with which to cover excess costs not covered by the contract:

<u>Sources</u>	<u>Estimated Amount</u>
Prof. M. Ter-Pogossian, Department of Radiology, salaries and salary-related costs for two machinists	40.0 K\$
Irradiation time purchased by non-ERDA users, including Profs. Wahl, Welch, Walker of Washington University and Dr. C. M. Foster of Indiana University	10.5 K\$
Shop charges	1.3 K\$
	51.8 K\$

B. RADIOCHEMICAL STUDIES OF NUCLEAR FISSION
AND SEARCH FOR ELEMENT 118 (EKA-RADON)

Arthur C. Wahl, Principal Investigator
(December 1, 1974 to June 1, 1975)

Introduction

The principal purpose of our investigations, as it has been for many years, is to increase knowledge concerning the distribution of nuclear charge in fission, one of the important quantities that characterize a fission process. This and other experimentally measured quantities such as the mass-yield, kinetic-energy, and excitation-energy (prompt neutron and prompt gamma-ray) distributions help build an empirical understanding of the fission process and serve as useful tests of theoretical models that are developed. These quantities also have practical importance, such as in nuclear-reactor design and operation; for example, the estimates of heating from beta decay of fuel elements soon after shutdown due to a cooling failure are based on current knowledge of beta-decay energies and fission yields (nuclear-charge and mass distributions) of short-lived fission products.

For thermal-neutron-induced fission of ^{235}U , the fission process most thoroughly studied to date, it is known for mass-numbers with high yields ($A = 90$ to 102 and 132 to 144) that the charge dispersion for each mass number is quite narrow, that the light fission products have, on the average, a higher charge density than the heavy products, and that the independent (direct) yields of fission products with even atomic numbers are, on the

average, higher than those with odd atomic numbers [1]. This information has been derived from the results of many radiochemical investigations carried out during the past 30 years and from the results of several physical methods of measurements developed and applied during the past 10 years. The conventional method of describing nuclear-charge distribution involves a Gaussian dispersion curve for each mass number (full-width at half maximum ≈ 1.5 charge units, or $\sigma_Z(A) = 0.56$ for products [1] — less ($\sigma_Z(A') = 0.40$) for fragments before neutron evaporation [2]), the maximum in a curve on the Z axis being called $Z_p(A)$. The combination of a dispersion curve of constant width and a smooth $Z_p(A)$ function gives a fairly satisfactory representation of independent-yield data for mass numbers with high yields [1]. The representation can be improved somewhat by including an even-odd-Z effect of $\sim 25\%$ [1,3-5] and by introducing sharp breaks in the $Z_p(A')$ function near $A_H' = 130$ and near the complementary average fragment-precursor mass number (A_L') for light fission products [5-7].

Results of the physical measurements for other fissioning systems, along with the limited radiochemical data available for these systems, suggest that

1. A.C. Wahl, A.E. Norris, R.A. Rouse, and J.C. Williams, Second Symposium on the Physics and Chemistry of Fission, Paper SM-122/116, IAEA, Vienna, 1969, p. 813.
2. W. Reisdorf, J.P. Unik, H.C. Griffen, and L.E. Glendenin, Nucl. Phys. A177, 337 (1971).
3. S. Amiel and H. Feldstein, Third Symposium on the Physics and Chemistry of Fission, IAEA/SM-174/25, Rochester, U.S.A. (1973).
4. A.R. del Musgrove, J.L. Cook, and G.D. Trimble, Fission Product Nuclear Data, IAEA-169, Vol. II, p. 163, Vienna (1974) — (Proceedings of the Panel at Bologna, Nov., 1973).
5. K. Wolfsberg, Los Alamos Scientific Laboratory Report LA-5553-MS (1974). (unpublished).
6. H.O. Denschlag, Habilitationsschrift, University of Mainz (1971) (unpublished).
7. A.C. Wahl, A.E.C. Progress Report No. C00-1162-49, p. 17 (unpublished).

similar descriptions may apply to thermal-neutron induced fission of ^{233}U and ^{239}Pu , spontaneous fission of ^{252}Cf , and perhaps also to other low-energy fissioning systems.

Little information is available concerning nuclear-charge distribution in mass-number regions of low yield, the sides of the mass-yield peaks and the valley between the peaks. The physical methods of investigation currently available are not well suited for use in these regions because of inadequate mass resolution and/or sensitivity. The radiochemical method, on the other hand, having high sensitivity and perfect charge and excellent mass resolution (usually perfect because isotopes can usually be distinguished by half-lives and radiations) can be used in these regions. However, much effort is required because each measurement of an independent yield presents a new problem requiring development of rapid chemical-separation and perhaps radiation-measuring techniques and the determination of half-lives, genetic relationships, and decay properties of members of the decay chain of interest, if these quantities are not already sufficiently well known.

The large fractional-cumulative yields of tin fission products [8,9] with mass numbers from 127 to 130, for which chain yields increase rapidly, may be due primarily to rapidly increasing independent yields of the tin nuclides ($Z = 50$) or to a distribution of these yields among the tin, indium, and cadmium isobars. The first possibility is a reasonable one because of the stabilizing effect of the 50-proton shell, and it is attractive because

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8. D.E. Troutner, A.C. Wahl, and R.L. Ferguson, Phys. Rev. 134, B1027 (1964).

9. M.M. Fowler and A.C. Wahl, J. inorg. nucl. Chem. 36, 1201 (1974).

it could account for the similarity of mass-yield curves in this region for many fission processes [1,10]. It is supported to some extent by the low total indium independent yields (the sum of isotopic independent yields) deduced from x-ray intensity measurements [2]. Determination of the fractional-cumulative yields of the individual indium fission products would, of course, settle the question, but such measurements are not possible at present because of the very short half-lives involved. New techniques are being developed which may prove useful in the future: these include investigations of recoil from beta decay (discussed later in this report) and investigation of reactions of recoiling fission products with gases to form volatile compounds [11]. However, since these techniques are not presently available, our attention has turned to the complementary technetium isotopes (from fission of uranium isotopes), since their half-lives and those of their molybdenum precursors are sufficiently long for application of conventional rapid radiochemical-separation techniques.

Another phase of our research involves application of the emanation method, which we used successfully for measurement of the fractional-cumulative yields of short-lived krypton and xenon fission products [12,13], to the search for element 118 (eka-radon). Whenever time can be obtained at the Berkeley SuperHILAC, experiments are conducted to try to make and detect atoms of eka-radon using the equipment that was built in the cyclotron shop and that has been described in previous Progress Reports [C00-1162-46,49,50].

10. A.C. Wahl, Physics and Chemistry of Fission, Vol. I, IAEA, Vienna (1965), p. 317.
11. R.G. Strickert, S. Amiel, and A.C. Wahl, Inorg. Nucl. Chem. Letters 10, 129 (1974).
12. A.C. Wahl, J. inorg. nucl. Chem. 6, 263 (1958).
13. A.C. Wahl, R.L. Ferguson, D.R. Methaway, D.E. Troutner, and K. Wolfsberg, Phys. Rev. 126, 1112 (1962).

Compilation and Correlation of Nuclear-Charge Distribution Data

During the past six months work has continued on the two models described in previous Progress Reports [COO-1162-49,50] for estimation of fission-product independent yields. As proposed last December, the sub-routine for comparison of estimated and experimental yields has been incorporated into the computer program EFPY1, which employs the conventional method of calculation using values of $Z_p(A)$, $\sigma_z(A)$, and $Y(A)$ for each A .

Also, the complementary program EFPY2, which uses values of $A_p(Z)$, $\sigma_A(Z)$, $Y(Z)$ as input parameters for each Z , has been modified to make allowance for the change in neutron number $\bar{\nu}_p(A)$ with A . The most probable mass number $A'_p(Z)$ before prompt neutron emission is substituted for $A_p(Z)$, and yields for precursor primary fragments with an average mass number of $A' = A + \bar{\nu}_p(A)$ are derived from Gaussian curves and assigned to each A . The $\bar{\nu}_p(A)$ values are obtained (as in reference [1]) by multiplying the average total number $\bar{\nu}_T(A)$ of neutrons emitted in forming a pair of fission products by the ratio $[\bar{\nu}_p(A)/\bar{\nu}_T(A)]_{\text{Phys.}}$. The $\bar{\nu}_T(A)$ values are derived by Terrell's method [14] from $Y(A)$ values [15], and the ratios are derived from results of physical measurements for thermal-neutron-induced fission of ^{235}U listed in reference [4]. Since for a given Z a different Gaussian curve is used for each A , the calculated independent yields are normalized so that their sum equals $Y(Z)$; however, the normalization corrections are small ($<10\%$).

$Y(Z)$ values were initially taken or extrapolated from the results of x-ray measurements [2], but the values are adjusted in the calculation to give appropriate chain yields, $Y(A)$, which are much better known [15].

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14. J. Terrell, Phys. Rev. 127, 880 (1962).

15. M.E. Meek and B.F. Rider, General Electric Vallecitos Nuclear Center Report No. NEDO-12154-1 (1974) (unpublished).

$A'_p(Z)$ values for $Z_H \geq 50$ have also been derived from results of x-ray measurements [2] by fitting a straight line to the data on a plot of $A'_p(Z) - [A_F/Z_F] \times Z$ vs. Z , the subscript F referring to the fissioning nucleus. For complementary light elements ($Z_L = Z_F - Z_H$), $A'_{p_L} = A_F - A'_{p_H}$, and for elements of intermediate Z , it has been assumed that $A'_p(Z) = [A_F/Z_F] \times Z$. To date, a constant value of $\sigma_A(Z) = 1.42 = 0.56 \times [A_F - \bar{v}]/Z_F$ has been assumed, 0.56 being the average $\sigma_Z(A)$ for thermal-neutron-induced fission of ^{235}U derived from experimental radiochemical data [1].

Calculations have been made by both methods for thermal-neutron-induced fission of ^{235}U (U235T), ^{233}U (U233T), and ^{239}Pu (PU239T), and the results have been compared with experimental data. Copies of sample output for the comparisons are shown in Tables IB and IIB,[#] in which U235T fission products in and near the valley of the mass-yield curve are treated. A summary of the parameters used in the calculations and of the results of the comparisons are given in Table IIIB for all fission products for which data are available.

The symbols for literature references in Tables IB and IIB are the same as those used by Meek and Rider [15], unless an average value has been used or a value has been recalculated. The symbols for type of yields are also those used by Meek and Rider (except for EY), i.e.:

- FI = fractional-independent yield.
- FC = fractional-cumulative yield.
- IN = % independent yield.
- CU = % cumulative yield.
- EY = % elemental yield.

[#]The column headed "AGREE?" and the footnote have been added by typing.

TABLE IB. EPY1 CALCULATION FOR THERMAL-NEUTRON-INDUCED FISSION OF U235

COMPARISON OF INITIAL CALCULATED AND EXPERIMENTAL CHARGE-DISTRIBUTION YIELD DATA											
NUCLIDE	TYPE	LIT. REF.	EXPERIMENTAL VALUE	EXPERIMENTAL RANGE	CALCULATED VALUE	LIMIT SYMBOL	RATIO OF CALC. TO EXP. YIELD (RATIO)			AGREE?	
43 TC 103	FI	69HAS1	< 7.000E-03		4.300E-03	>(	0.614)			---	
43 TC 105	FI	69HAS1	< 3.300E-02		9.997E-02	>(	3.029)			NO	
43 TC 106	FI	69HAS1	< 2.200E-02		1.002E-01	>(	4.556)			NO	
47 AG 112	FI	71ROCI	< 1.000E-04		4.255E-05	>(	0.426)			---	
46 PD 115	1-FC	AVE.	1.100E-01	(1.000E-01 - 1.200E-01)	2.152E-02	(	0.196	(0.215 - 0.179)		NO	
45 RH 117	FC	70WE11	2.500E-01	(1.700E-01 - 3.300E-01)	8.085E-02	(	0.323	(0.476 - 0.245)		NO	
46 PD 117	1-FC	AVE.	2.900E-01	(2.500E-01 - 3.300E-01)	2.212E-01	(	0.763	(0.885 - 0.670)		YES	
47 AG 117	FI	AVE.	2.700E-01	(2.200E-01 - 3.200E-01)	2.098E-01	(	0.777	(0.954 - 0.656)		YES	
48 CD 117	FI	70WE11	3.800E-02	(2.200E-02 - 5.400E-02)	1.137E-02	(	0.299	(0.517 - 0.211)		NO	
46 PD 118	FC	69WE11	2.900E-01	(2.600E-01 - 3.200E-01)	5.410E-01	(	1.866	(2.081 - 1.691)		YES	
47 AG 118	FI	69WE11	5.500E-01	(4.500E-01 - 6.500E-01)	3.984E-01	(	0.724	(0.885 - 0.613)		YES	
48 CD 121	Y-CU	69WE11	< 7.094E-03		6.859E-04	>(	0.097)			---	
50 SN 121	FI	71EP01	< 2.600E-01		6.450E-04	>(	0.002)			---	
50 SN 123	FI	71SR01	1.400E-01	(5.000E-02 - 2.300E-01)	2.174E-02	(	0.155	(0.435 - 0.095)		NO	
51 SB 124	IN	AVE.	> 3.680E-05		8.931E-06	<(	0.243)			NO	
50 SN 125	FI	RECALC.	4.600E-01	(2.400E-01 - 6.800E-01)	2.263E-01	(	0.492	(0.943 - 0.333)		YES	
51 SB 126	IN	AVE.	> 8.300E-04		8.429E-04	<(	1.016)			---	
53 I 126	IN	70TRA1	< 2.000E-06		3.330E-10	>(<	0.001)			---	
51 SB 127	FI	64TR01	5.700E-02	(4.700E-02 - 6.700E-02)	5.231E-02	(	0.918	(1.113 - 0.781)		YES	
51 SB 128	FI	73FOW1	4.900E-02	(2.700E-02 - 7.100E-02)	1.526E-01	(	3.114	(5.652 - 2.149)		NO	
53 I 128	IN	70TRA1	1.400E-05	(1.100E-05 - 1.700E-05)	1.598E-06	(	0.114	(0.145 - 0.094)		NO	
51 SB 129	FI	73FOW1	1.140E-01	(6.800E-02 - 1.600E-01)	3.264E-01	(	2.863	(4.799 - 2.040)		NO	
51 SB 130	FI	73FOW1	3.400E-01	(2.950E-01 - 3.850E-01)	3.023E-01	(	0.889	(1.025 - 0.785)		YES	
53 I 130	IN	70TRA1	2.300E-04	(2.000E-04 - 2.600E-04)	8.862E-05	(	0.385	(0.443 - 0.341)		NO	
49 IN 0	EY	W-R71-1	< 2.800E-01		2.512E-01	>(	0.897)			---	
50 SN 0	EY	W-R71-1	3.340E 00	(2.860E 00 - 3.820E 00)	3.444E 00	(	1.031	(1.204 - 0.902)		YES	

*Agreement within a factor of two is indicated by YES.

TABLE IIB. EPY2 CALCULATION FOR THERMAL-NEUTRON-INDUCED FISSION OF U235

COMPARISON OF CORRECTED CALCULATED AND EXPERIMENTAL CHARGE-DISTRIBUTION YIELD DATA

NUCLIDE	TYPE	LIT. REF.	EXPERIMENTAL VALUE	EXPERIMENTAL (RANGE)	CALCULATED VALUE	LIMIT SYMBOL	RATIO OF CALC. TO EXP. YIELD (RATIO)	EXP. YIELD (RANGE)	AGREE?
43 TC 103	FI	69HAS1	< 7.000E-03		6.487E-07	> (<	0.001)		---
43 TC 105	FI	69HAS1	< 3.300E-02		3.183E-04	> (	0.010)		---
43 TC 106	FI	69HAS1	< 2.200E-02		4.777E-03	> (	0.217)		---
47 AG 112	FI	71ROC1	< 1.000E-04		5.725E-06	> (	0.057)		---
46 PD 115	1-FC	AVE.	1.100E-01	(1.000E-01 - 1.200E-01)	1.277E-02	(	0.116	(0.128 - 0.106)	NO
45 PH 117	FC	70WE11	2.500E-01	(1.700E-01 - 3.300E-01)	7.037E-02	(	0.281	(0.414 - 0.213)	NO
46 PD 117	1-FC	AVE.	2.900E-01	(2.500E-01 - 3.300E-01)	2.455E-01	(	0.847	(0.982 - 0.744)	YES
47 AG 117	FI	AVE.	2.700E-01	(2.200E-01 - 3.200E-01)	2.382E-01	(	0.882	(1.083 - 0.744)	YES
48 CD 117	FI	70WE11	3.800E-02	(2.200E-02 - 5.400E-02)	7.325E-03	(	0.193	(0.333 - 0.136)	NO
46 PD 118	FC	69WE11	2.900E-01	(2.600E-01 - 3.200E-01)	4.472E-01	(	1.542	(1.720 - 1.397)	YES
47 AG 118	FI	69WE11	5.500E-01	(4.500E-01 - 6.500E-01)	5.033E-01	(	0.915	(1.118 - 0.774)	YES
48 CD 121	CU	65WE11	> 5.900E-03		1.236E-02	< (	2.094)		---
50 SN 121	FI	71ERD1	< 2.600E-01		6.010E-05	> (<	0.001)		---
50 SN 123	FI	71ERD1	1.400E-01	(5.000E-02 - 2.300E-01)	1.101E-02	(	0.079	(0.220 - 0.048)	NO
51 SB 124	IN	AVE.	> 3.680E-05		7.259E-06	< (	0.197)		NO
50 SN 125	FI	RECALC.	4.600E-01	(2.400E-01 - 6.800E-01)	3.865E-01	(	0.840	(1.610 - 0.568)	YES
51 SB 126	IN	AVE.	> 8.300E-04		1.330E-03	< (	1.602)		---
53 I 126	IN	70TRA1	< 2.000E-06		6.729E-12	> (<	0.001)		---
51 SB 127	FI	64TRO1	5.700E-02	(4.700E-02 - 6.700E-02)	7.545E-02	(	1.324	(1.605 - 1.126)	YES
51 SB 128	FI	73FOW1	4.900E-02	(2.700E-02 - 7.100E-02)	2.133E-01	(	4.354	(7.902 - 3.005)	NO
53 I 128	IN	70TRA1	1.400E-05	(1.100E-05 - 1.700E-05)	3.516E-08	(	0.003	(0.003 - 0.002)	NO
51 SB 129	FI	73FOW1	1.140E-01	(6.800E-02 - 1.600E-01)	4.620E-01	(	4.053	(6.795 - 2.888)	NO
51 SB 130	FI	73FOW1	3.400E-01	(2.950E-01 - 3.850E-01)	7.194E-01	(	2.116	(2.439 - 1.869)	YES
53 I 130	IN	70TRA1	2.300E-04	(2.000E-04 - 2.600E-04)	6.176E-05	(	0.269	(0.309 - 0.238)	NO
49 IN 0	EY	W-R71-1	< 2.800E-01		5.511E-02	> (	0.197)		---
50 SN 0	EY	W-R71-1	3.340E 00	(2.860E 00 - 3.820E 00)	1.436E 00	(	0.430	(0.502 - 0.376)	YES

* Agreement within a factor of two is indicated by YES.

TABLE III.B. SUMMARY OF THE PARAMETERS USED IN THE CALCULATIONS AND OF THE RESULTS OF THE COMPARISONS WITH EXPERIMENTAL DATA

Fission Process	$\sigma_Z(A)$	$\Delta Z_P^{(a)}$	EFPY1 $EOF^{(b)}$	Comparisons	
				Number	% "Correct" (c)
U235T	0.56	-0.45	1.25	127	81
U233T	0.56	-0.45	1.25	57	86
PU239T	0.56	-0.60	1.00	38	87

Fission Process	σ_A	$\Delta A_P^{(50)}^{(d)}$	EFPY2 $\delta^{(d)}$	Comparisons	
				Number	% "Correct" (c)
U235T	1.42	1.40	-0.065	126	71
U233T	1.42	1.80	-0.136	55	82
PU239T	1.42	1.50	0.000	36	55

$$(a) Z_P(A' > 129.5) = [Z_F/A_F] \times A' + \Delta Z_P$$

$$Z_P(A' < (A_F - 129.5)) = [Z_F/A_F] \times A' - \Delta Z_P$$

$$Z_P(A' < 129.5, A' > (A_F - 129.5)) = [Z_F/A_F] \times A'$$

(b) FI values for even Z nuclides are multiplied by EOF (the even-odd-Z factor) and those for odd Z nuclides are divided by EOF, then values are renormalized for each A so that $\Sigma(FI) = 1.00$.

(c) % of calculated values that are within a factor of two of the experimental values; comparison with experimental limits were counted only if a limit was inconsistent with a calculated value by more than a factor of two.

$$(d) A_P^{(Z \geq 50)} = [A_F/A_F] \times Z + \Delta A_P^{(50)} + [Z - 50] \times \delta$$

$$A_P^{(Z < (Z_F - 50))} = [A_F/Z_F] \times Z - \Delta A_P^{(50)} - [Z_F - Z - 50] \times \delta$$

$$A_P^{(Z < 50, Z > (Z_F - 50))} = [A_F/Z_F] \times Z$$

In order to make the ratios of calculated to experimental yields most meaningful, $1 - FC$ or $Y(Z) - CU$ are listed if FC or $CU/Y(A)$ are >0.5 .

Both calculations are based on deviations from unchanged charge density (UCD) of the fissioning nucleus, the change occurring abruptly when one of the fission products has ~ 50 protons. The method used for the EFPY1 calculations was essentially the one reported at the 1969 Vienna conference [1], except that an abrupt change in Z_p at $A' = 129.5$ has been introduced. The parameters used for the EFPY1 calculations are very similar to those used by Wolfsberg [5] for this calculations of FI and FC values that are incorporated in the ENDF/B-IV file of nuclear data for fission products.

The criterion that calculated and experimental values should agree within a factor of two was chosen arbitrarily as an initial step to allow some comparison; it is very crude, since a factor of two discrepancy is much more serious for large values of FI, for example, than for small ones.

The better agreement with experiment for the EFPY1 calculations is to be expected since the parameters used were derived from the experimental data [1,5]. It remains to be seen if better parameters for EFPY2 can be derived and if the EFPY2 calculations can then represent the data as well or better than EFPY1.

When both $Y(A)$ and $Y(Z)$ are essentially constant, both charge and mass dispersion can, at least in principal, be represented by Gaussian curves. When $Y(A)$ and $Y(Z)$ change rapidly, both dispersions cannot be Gaussian, and it remains to be learned which, if either, dispersion can be approximated satisfactorily by a Gaussian or other simple distribution function.

(Arthur C. Wahl)*

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*Much of the computer programming has been done by Niel J. Falvey and Emily Plachy of the Washington University Computing Center. Also, valuable advise on programming has been given by Richard G. Strickert.

Fractional-Independent Yields of Technetium Isotopes

Comparison of Tables IB and IIB shows that the small fractional-independent yields of ^{105}Tc and ^{106}Tc from thermal-neutron-induced fission of ^{235}U reported by Hastings, Troutner, and Ferguson [16] (reference symbol 69HAS1) are consistent with the estimated yields calculated using EFFY2 but not with those calculated using EFFY1. This finding supports the postulate incorporated in the EFFY2 calculation that an abrupt change in elemental yield occurs between atomic numbers 42 and 43 and between 49 and 50. However, as discussed previously (Progress Reports COO-1162-46,49,50), the chemical procedures used for the measurements [16] separated only TcO_4^- and not lower oxidation states of technetium from molybdenum [17], so the measured fractional-independent yield values may be low. Therefore, new measurements are being made under conditions (acid solutions containing Ce(IV)) which lead to rapid oxidation of lower technetium oxidation states to TcO_4^- before separation of technetium from molybdenum.

As discussed in our last Progress Report (COO-1162-50), the best methods of separation of technetium from molybdenum and of measurement of the fission-product radioactivities that have been developed to date involve adsorption of TcO_4^- on a filter bed of freshly prepared $(\text{C}_6\text{H}_5)_4\text{AsClO}_4$ and measurement of the ^{103}Tc , ^{104}Tc , ^{105}Tc , and ^{97}Zr (^{97}Nb) gamma rays with a Ge(Li) detector. A number of measurements have been made using these methods during the past six months, the times of separation of technetium from molybdenum ranging from 30 to 110 sec after ~ 30 sec irradiations. The data are only partially analyzed at present, but it is clear that more data

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16. J.D. Hastings, D.E. Troutner, and R.L. Ferguson, *Radiochim. Acta* **11**, 51 (1969).

17. E.N. Vine, M.A. Thesis, Washington University, St. Louis, Mo. (1971).

are needed for both longer and shorter separation times. The data for the longer separation times are needed for calibration of the gamma-ray detection efficiencies and yields of the technetium isotopes relative to those of $^{97}\text{Zr}(^{97}\text{Nb})$, the internal fission monitor. The data for shorter separation times are needed to reduce the correction for formation of the technetium isotopes by beta decay of their molybdenum precursors.

The time limitation of our present methods is a mechanical one (opening of a pneumatic rabbit and transferring of solutions), since the chemical separation requires ~ 5 sec. Therefore, a plunger (a sharp ended tube) was built to pierce a diaphragm in a rabbit and to remove the irradiated solution, and the separation apparatus was modified to allow control of the flow of solutions with a preprogrammed timer. Separation times as small as ~ 10 sec (including the ~ 5 sec rabbit transit time) were achieved with this modified apparatus, but TcO_4^- was lost in the process due to adsorption on the stainless-steel plunger. Since TcO_4^- was found to be adsorbed on all metal surfaces tested, a new plunger is being made from glass and teflon.

(Elizabeth N. Vine)

Recoil from Beta Decay

A unique property of independently formed fission products is that they are not formed by beta decay, and use has been made of this property to gain information about nuclear-charge distribution in fission by measurement with mass-separated samples of the number of beta-decay events required to reach a stable or long-lived nuclide [18,19]. Problems with such measurements

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18. K. Sistemich, P. Armbruster, J. Eiden, and E. Roeckl, Nucl. Phys. A139, 289 (1969).
  19. H. Gunther, G. Seigert, R.L. Ferguson, H. Ewald, and E. Konecny, Nucl. Phys. A196, 401 (1972).

include poor mass resolution with the helium-filled mass-separator [18], and, with the Ewald-type separator [19], low intensities and only small fractions of the fission products of interest (i.e., only those with kinetic energies in a given range) are observed. The first type of measurement has given only the general trend in a Z_p function, a trend that is qualitatively consistent with deductions made from radiochemical data [1]. The data derived from the second type of measurement are often inconsistent with radiochemical data.

Relatively little work has been done concerning recoil from beta decay on solid surfaces [references 20-22 and our previous Progress Reports COO-1162-41,45,46,49,50], and most of the measurements reported have been made with relatively long-lived (half-life $\geq \sim 10$ min), low-energy ($Q_\beta \leq \sim 2$ MeV) beta emitters decaying on common metal surfaces (Al, Cu, Ni, Fe, etc.). Generally, only small ($< \sim 1\%$) recoil yields[†] were observed in vacuum at room temperature, and there was some increase (to $\sim 5\%$ in our experiments), at elevated temperatures (200-300° C). Thus, although results were difficult to reproduce, probably due to varying conditions of metal surfaces, very little loss due to beta recoil occurs from most surfaces at room temperature; this is useful information for anyone working with very thin layers of beta-radioactive material in vacuum. Beta-recoil yields apparently do increase with beta-recoil energy, as expected, although no careful, systematic study of this effect has been made and internal-conversion accompanying beta decay

20. F. Strassmann, Z. Elektrochem. Ber. Bunsen, Physik. Chem. 64, 1011 (1960).
21. H. Mundschenk, Radiochim. Acta 15, 193 (1971).
22. G. Herrmann, personal communication of results of D. Jung given in the 1967 and 1968 Annual Reports from Mainz, Germany.

[†] Recoil yield, as used here, is defined as the per cent of product atoms formed by decay on a solid surface that leave the surface and are collected on another surface; 50% is the theoretical maximum recoil yield.

also appears to enhance the recoil-yield.

A few beta-recoil yields larger than those discussed above have been reported: ~9% for ^{101}Tc from decay on Al of ^{101}Mo ($Q_\beta \approx 2.3$ MeV [23]), ~8% for ^{131g}Te from decay of ^{131}Sb ($Q_\beta \approx 3.9$ MeV [23]), and ~15% and ~40% for ^{139}Ba and ^{140}Ba , respectively, from decay on previously ignited Pt of ^{139}Cs ($Q_\beta \approx 4.3$ MeV [23]) and of ^{140}Cs ($Q_\beta \approx 6.6$ MeV [23]), respectively. The first two results are from reference [22], and the last two were discussed in our previous Progress Reports [COO-1162-46,49].

If conditions for very efficient beta-recoil could be achieved (approaching 50%), a high beta-recoil yield for a fission product could be interpreted as a very small fractional-independent yield for the product, and a small beta-recoil yield could be interpreted as a large fractional-independent yield. In principal, if all factors affecting recoil efficiency were understood, values of fractional-independent yields could be calculated.

Even if beta-recoil efficiencies were not high, but were appreciable, short half-lives of precursors of recoiling fission products could be determined by use of a rotating wheel or moving tape. Such half-life values are needed to determine if independent-yield measurements are feasible and to interpret the data obtained if measurements are made. Evidence for the reliability of such half-life measurements has been obtained from three experiments, two reported in a previous Progress Report [COO-1162-49], in which the half-life of ^{140}Cs was correctly determined to be 64 sec.

As discussed in previous Progress Reports [COO-1162-46,49,50] a rotating beta-recoil "wheel" apparatus has been designed, constructed, and tested.

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23. W.D. Myers and W.J. Swiatecki, "Nuclear Masses and Deformations," USAEC Report No. UCRL-11980 (1965) (unpublished).

The original apparatus contained a squirrel-cage-type teflon gasket, which rotated with the wheel. Much difficulty has been experienced in obtaining a vacuum seal with the gasket, first in fitting it to the "wheel" and in "breaking it in," then after ~2 hrs of very rapid rotation during an experiment, it became so worn that a satisfactory vacuum could no longer be maintained.

A modified apparatus containing a tapered teflon "wheel" and brass housing have been made and tested. A short "breaking-in" period is still required, but then the life-time of the tapered wheel for rapid rotation is at least 10 hrs.

Five experiments have been conducted with the tapered "wheel" apparatus to investigate the recoil of ^{132}Te , ^{133}Te , ^{134}Te , and ^{140}Ba from beta decay of their precursors. In all experiments the "wheel" rotated at 2.5 rpm, and a vacuum of ~1 torr was maintained in the beta-recoil chamber. Much of the beta-decay data are still being accumulated or analyzed, but a few preliminary observations can be made.

(1) The beta-recoil yield of ^{140}Ba is only ~10%, much less than the ~40% observed at 0.209 rpm with the original apparatus. The new geometry for beta-recoil is somewhat smaller than the old, possibly only ~80% of the old, but certainly not 25%. Another possibility is that at small rotation rates a large correction (~300%) is made for decay of ^{140}Cs before it reaches the beta-recoil collection chamber; if some of the ^{140}Ba formed by beta decay during this time, when the pressure is 1 atm., reaches the collection plate, the calculated recoil yield of 40% would be high.

(2) The recoil yield of ^{132}Te is also ~10%, about the same as the value for ^{140}Ba under the same conditions. Since both are formed by high-energy

beta decay ($Q_\beta = 6.5$ MeV [23]), the large difference in their electropositive character apparently does not greatly affect recoil efficiency.

(3) Very little ^{133m}Te is observed on the recoil catch plate, an observation that is consistent with the small fraction (0.24) formed by beta decay [24] and with the smaller beta-decay energy ($Q_\beta = 5.0$ MeV) of ^{133}Sb compared to those of ^{132}Sb and ^{134}Sb [23].

(4) The few percent of ^{134}Te found on the catcher plate could indicate that the beta-recoil yield is very high ($\sim 50\%$) from 11-sec ^{134}Sb , from which only ~ 0.04 of the ^{134}Te is formed [24], but which has a large beta-decay energy of ~ 9.4 MeV [23]. Essentially all of the 0.9-sec ^{134}Sb precursor would have decayed before reaching the recoil chamber. Alternatively, some ^{134}Te may be deposited on the catcher plate by a mechanism other than beta recoil in the recoil chamber.

(Gary J. Ehrhardt)

Search for Element 118 (Eka-radon)

In preparation for experiments to attempt to make and detect isotopes of element 118, two pieces of equipment have been designed, built, and tested: the "Eka-Radon Search Apparatus" (ERSA) and the "Light Ion Search Apparatus" (LISA). The design, operation, and tests of ERSA and LISA have been discussed in previous Progress Reports [COO-1162-46,49,50].

During the past six months one 8-hr shift at the SuperHILAC was allotted to our experiment for bombardment of uranyl stearate in LISA with krypton ions. Due to ion-source and other accelerator problems, only a 15-min bombardment (11.5 microCoulombs of charge) was obtained, and the number of tracks observed in the polycarbonate detectors was not above background, as was to

be expected for so little bombardment.

Another 8-hr shift with a krypton beam has been allotted to our experiment, but a definite time has not yet been scheduled.

(George W. Goth and Arthur C. Wahl)

Level of Effort

The principal investigator devoted about one quarter time during the academic year (through May, 1975) and full time during one summer month (June, 1975) to the project. He expects to spend about one quarter time on the project during September and October, 1975.

C. SPECTROSCOPY OF NUCLEAR SYSTEMS

Edward S. Macias

Principal Investigator

Introduction

This work is focused on the study of the nuclear structure of nuclei near closed shells via radioactive decay scheme spectroscopy and in-beam γ -ray spectroscopy. These nearly spherical nuclei are particularly interesting to study because their low-lying levels may be well described by simple nuclear models. In order to have a comprehensive experimental description of these nuclei it is necessary to have lifetimes, spins, and parities of the excited states as well as energies and branching ratios of the γ rays. When possible these quantities are determined by studying γ rays emitted during nuclear reactions as well as γ rays emitted following radioactive decay. In some cases the nucleus of interest can not be studied by simple in-beam reaction spectroscopy because there are no nearby stable nuclei. In these cases the study of short-lived nuclei is one of the best tools for nuclear structure determinations. The first part of this section describes our work in the past year concerning the structure of nuclei near closed shells using decay scheme spectroscopy of short-lived species. The second part of this section describes our recent work on in-beam γ -ray spectroscopy including Doppler-shift lifetime measurements. The final part of this section describes instrument development over the past year.

This report covers work carried out during the past six months under Contract Nos. E(11-1)-2318 and E(11-1)-1760.

DECAY SCHEME STUDIES

Decay of Neutron Deficient Tin Isotopes

^{108}Sn - We have studied the decay of ^{108}Sn to the levels of ^{108}In as part of our study of nuclei near closed nucleon shells. Although the half-life of ^{108}Sn has been known for some time,^{1,2} no high resolution γ -ray decay scheme studies have been reported for the nucleus.³ The ^{108}Sn sources were produced via the $^{106}\text{Cd}(^4\text{He}, 2n)$ reaction by bombarding a 95.5% enriched ^{106}CdO target with 30 MeV alpha particles. The activity was transported to a low background area with the Washington University helium jet recoil transport system. Anti-Compton and direct γ -ray spectra and γ - γ coincidence spectra have been studied using 5, 7, and 12% Ge(Li) detectors. A total of 23 γ rays listed in Table IC have been assigned to the decay of ^{108}Sn on the basis of their half lives. Results of γ - γ coincidence experiments are given in Table IIC.

The half life of ^{108}Sn was determined by measuring the decay of the 104.5-, 169.4-, 236.8-, 273.0-, 397.4- and 670.1-keV γ rays. Non-linear least-squares analysis of eight consecutive 2.5-min spectra yielded a weighted average half-life for ^{108}Sn decay of 10.4 ± 0.4 min.

A preliminary decay scheme of ^{108}Sn based on the gamma-ray energy, intensity and coincidence measurements is shown in Fig. 1C. Some inconsistencies remain between this and the Russian work² due to the total transition probability and multipolarity of several transitions.

In order to obtain more information about the level scheme, transition

1. W. Mead, Ph.D. Thesis, University of California (1956); UCRL-3488 (1956).
2. B.G. Kiselev and V.R. Burmistrov, Sov. J. Nucl. Phys. 11, 137 (1970).
3. F.E. Bertrand, Nucl. Data Sheets B7, 33 (1972).

E_{γ} (keV)	I_{γ} (relative to 397.4)
104.5	23.1 ± 0.6
169.4	27.6 ± 1.0
236.8	9.3 ± 0.5
273.0	65.9 ± 0.5
363.0	1.4 ± 0.3
397.4	100
493.5	1.6 ± 0.3
500.7	3.9 ± 0.3
565.4	3.4 ± 0.3
670.1	27.3 ± 1.0
781.3	1.5 ± 0.4
786.6	1.8 ± 0.5
890.0	6.4 ± 0.6
904.7	1.0 ± 0.3
1138.0	0.6 ± 0.2
1162.5	1.4 ± 0.2
1227.1	0.9 ± 0.4
1375.1	1.8 ± 0.5
1404.1	2.9 ± 0.4
1675.0	0.9 ± 0.4
1686.0	4.5 ± 0.5
1655.4	2.6 ± 0.7
1958.4	1.2 ± 0.3

TABLE IIC. Results of ^{108}Sn γ - γ Coincidence Measurements

γ -Ray Gate (keV)	Coincident γ Rays (keV)
169	104, 397, 786, 890
237	273, 397, 493, 565, 1675
273	237, 396, 890, 1656, 1686
363	178, 273
397	169, 237, 273, 493
501	397, 492
890	170, 273, 1140
1656	103

⁴ Fig. 1C. Decay Scheme of 10.4-min ^{108}Sn .

multipolarities and transition probabilities between the levels of ^{108}In , a conversion electron experiment is planned. In this experiment, ^{108}Sn will be detected with a Ge(Li) gamma ray detector and a Si(Li) surface barrier detector simultaneously. The gamma ray spectrum from Ge(Li) detector and the conversion electron spectrum from the Si(Li) detector will be recorded by different ADC's. The conversion coefficient obtained in this way will allow the determination of level spin and parity assignments and transition probabilities.

^{107}Sn - In recent years the levels of odd-mass indium isotopes especially $^{109-117}\text{In}$ have been under intense study both experimentally and theoretically.⁴ Several different kinds of levels have been identified. The $9/2^+$ ground state and $1/2^-$ first excited state have been classified as holes in the $g_{9/2}$ and $p_{1/2}$ proton orbitals in the $Z = 50$ closed shell. The $3/2^-$ second excited state seen in odd-mass indium isotopes has a combination of $p_{3/2}$ proton hole and $p_{1/2} \times 2^+$ -core configurations.⁵ There has been some confusion about the properties of the states above the $3/2^-$ level. Several theoretical calculations⁶⁻⁸ of odd-mass indium level structure have been carried out based on various models, however none gives a complete explanation of the experimentally determined level properties.

We have studied the level structure of ^{107}In via the decay of ^{107}Sn in order to obtain more information on the level structure of odd-mass

4. E.U. Baranger, in Advances in Nucl. Phys. Vol 4 (1971).
5. W.R. Hasseling, B.R. Kooistra, L.W. Put, R.H. Siemssen and S. van der Werf, Nucl. Phys. A226, 229 (1974).
6. A Bäcklin, B. Flögesberg, and S.G. Malinskog, Nucl. Phys. A96, 539 (1967).
7. J. McDonald, D. Parter and D.T. Stewart, Nucl. Phys. A104, 177 (1967).
8. E.M. Bernstein, G.G. Seaman, and J.M. Palms, Nucl. Phys. A141, 67 (1970).

indium isotopes to enable a systematic comparison of the levels of these nuclei. The ^{107}Sn sources were produced via ^3He bombardments of an enriched ^{106}Cd target and transported from the cyclotron to the detection site in less than 200 msec with a He-jet recoil transport system. The half-life of ^{107}Sn was determined to be 2.90 ± 0.05 min. An isomeric state of ^{107}In at 679 keV has been identified with a half-life of 50.4 ± 0.6 sec. This isomeric state has been assigned a spin and parity of $1/2^-$. A total of 57 gamma rays have been attributed to the decay of ^{107}Sn based on their decay properties. A consistent level scheme is proposed which incorporates 39 of these 57 gamma rays using gamma-gamma coincidence data and gamma-ray energy and intensity measurements.

(H.-S. Hseuh and E. S. Marias)

Decay of Short-Lived Palladium Isotopes: ^{97}Pd and ^{96}Pd

The study of the level structure of $^{97}_{45}\text{Rh}_{51}$ and $^{96}_{45}\text{Rh}_{52}$ populated via the decay of short-lived palladium isotopes was begun during the past year as part of our study of nuclei near closed shells. The identification of 3.3 ± 0.3 -min ^{97}Pd was first reported by Aten and Kapteyn⁹ in 1969. That is the only investigation of ^{97}Pd decay which has been reported;¹⁰ no information about the identification of ^{96}Pd has been reported.¹¹

We have produced ^{97}Pd via the $^{96}\text{Ru}(^3\text{He}, 2n)$ reaction by bombarding 95% enriched ^{96}Ru with 30-MeV ^3He ions. The Washington University helium jet system was used for transporting the activity to a 12% Ge(Li) detector. We have identified several γ rays which we attribute to the decay of 3.3 -min ^{97}Pd . Experiments are in progress to determine low intensity

9. A.H.W. Aten, Jr. and J.C. Kapteyn, *Radiochim. Acta* **12**, 218 (1969).

10. L.R. Medsker, *Nucl. Data Sheets* **10**, 1 (1973).

11. L.R. Medsker, *Nucl. Data Sheets* **8**, 599 (1972).

transitions following the decay of ^{97}Pd and to identify ^{96}Pd .

(E. Jensen, L. Zapata, and E. S. Macias)

Structure of N=81 Nuclei: Levels of ^{141}Nd and ^{139}Ce Populated in Beta Decay

This work has been completed during the past year and submitted to Physical Review. The abstract is given below.

The nuclear level structure of ^{141}Nd and ^{139}Ce has been investigated by studying the decay of 20.9-min ^{141}Pm produced via the $^{141}\text{Pr}(^3\text{He},3n)$ reaction and the decay of 4.5-h ^{139}Pr produced by the $^{140}\text{Pr}(\gamma,n)^{139}\text{Pr}$ reaction. For the ^{141}Pm decay, singles and anti-Compton gamma-ray spectra and gamma-gamma coincidence measurements were used to deduce a decay scheme that includes nine previously unreported levels in ^{141}Nd and incorporates 67 of the 70 gamma rays attributed to the decay of ^{141}Pm . Singles and anti-Compton spectra were taken as a function of time in order to confirm assignment of the ^{139}Pr gamma rays. The level structures of ^{141}Nd and ^{139}Ce are compared to recent measurements in other N = 81 isotones. The results of this work are in good agreement with theoretical predictions based on the hole-vibrational coupling model for levels below 1.3 MeV. There exist more levels between 1.3 and 2.0 MeV than are predicted by this model but these excess levels can be explained qualitatively within a weak coupling framework.

(M. R. Zalutsky, R. A. Meyer, and E. S. Macias)

Decay of $^{89m+g}\text{Nb}$

As part of our investigation of nuclei near closed shells we are continuing our study of the levels of $^{89}_{49}\text{Zr}_{40}$ populated in the decay of 66-min ^{89m}Nb and 122-min ^{89g}Nb . Analysis of anti-Compton γ -ray spectrum indicates many previously unreported γ rays. The results of γ - γ coincidence experiment are presently being analysed in order to construct a coherent level scheme for ^{89}Zr .

(A. LeComte and E. S. Macias)

Decay of ^{149}Pm and ^{149}Eu to Levels of ^{149}Sm

This work has been completed and is being prepared for publication. This work was performed in collaboration with R. A. Meyer of Lawrence Livermore Laboratory

(E. S. Macias and R. A. Meyer)

IN-BEAM GAMMA-RAY SPECTROSCOPY

1. Nuclear structure of ^{93}Mo

The $^{93}_{42}\text{Mo}_{51}$ nucleus with only one neutron outside the closed-shell with $N = 50$, may be considered as simply described by the configurations $(\pi p_{1/2}^2 \pi g_{9/2}^2) (v d_{5/2})$ and $(\pi g_{9/2}^4) (v d_{5/2})$ as was done by Auerbach and Talmi.¹² In these calculations the "spin gap" at the 6.9 hr $21/2^+$ isomer at 2425 keV was properly predicted. However, many levels are not accounted for in these calculations and the inclusion of higher neutron orbitals in the model space are required. Such calculations which include $v d_{5/2}$, $v d_{3/2}$, $v s_{1/2}$ and $v g_{7/2}$ orbitals were carried out by McGroty,¹³ but the

12. N. Auerbach and I. Talmi, Nucl. Phys. 64, 458 (1965).

13. J.B. McGroty, private communication.

$21/2^+$ "spin gap" isomer is not predicted in these calculations indicating that the earlier success¹² could be fortuitous. The more extended calculations¹³ predict the following sequence for the high-spin states $5/2^+$, $17/2^+$, $21/2^+$ and $15/2^+$.

In order to shed some light on the proper description for this nucleus we have undertaken its study by the (p,n) and the (α ,2n γ) reactions.

a. Medium and low spin states in ^{93}Mo via $^{93}\text{Nb}(p,n)$ reaction spectrometry

In this work we measured γ -ray energies, angular distributions and lifetimes by the DSA method in experiments carried out at 3.7 and 4.4 MeV. A $\gamma\gamma$ coincidence experiment was also performed at the latter energy. Lifetimes for 40 levels were obtained and together with $\delta(E2/M1)$ and branching ratio information more definite spin assignments were made and $B(A)$ values for a good number of transitions were obtained.

This study has been completed and has been prepared for publication.

Abstract

The level structure and decay properties of levels in ^{93}Mo have been investigated via $^{93}\text{Nb}(p,n)^{93}\text{Mo}^*(\gamma)$ reaction spectrometry at a proton bombarding energy of 3.7 and 4.4 MeV. A detailed decay scheme for levels in ^{93}Mo up to 3.07 MeV of excitation has been constructed from in-beam γ - γ coincidence measurements along with γ -ray energies and relative intensities derived from anti-Compton singles spectra. Many new levels are proposed including a $15/2^+$ level at 2430.0 keV and a tentative $13/2$ level at 2450.4 keV. By employing photopeak centroid shift analysis of the data, the Doppler-shift-attenuation method (DSAM) was used to extract

lifetime values or limits for 40 levels in ^{93}Mo . Anti-Compton singles γ -ray spectra studied at both proton energies at 9 emission angles between 25° and 90° relative to the beam direction were used in these measurements. Angular distributions were obtained from anti-Compton singles γ -ray spectra observed at 10 emission angles between 0° and 90° relative to the beam direction. Analysis of these angular distributions in terms of the compound statistical theory for nuclear reactions yielded J^π assignments and multipole mixing ratios $\delta(E2/M1)$. $B(A)$ values or limits were obtained for several transitions in ^{93}Mo . The experimental results are compared with predictions of intermediate coupling model and shell model calculations. The transitions rates are found to be in reasonable agreement with the intermediate coupling model. However, this model does not predict the existence of observed low-lying high-spin states with $J \geq 13/2$ as does the shell model.

A partial decay scheme for the levels in ^{93}Mo is shown in Figs. 2C and 3C.

(L. Rutledge, E. Macias and D. Sarantites)

High-spin states in ^{93}Mo via $^{91}\text{Zr}(\alpha, 2n\gamma)$ reaction spectrometry

In order to obtain information about the high-spin states in ^{93}Mo the $^{91}\text{Zr}(\alpha, 2n\gamma)$ reaction was utilized in the energy range 17-30 MeV.

First, absolute excitation functions for 58 γ rays having energies from 130 to 1734 keV were measured. For this purpose, a new scattering chamber was constructed that permitted one to place a Si detector at 25° to the beam in order to monitor the elastically scattered α particles.

Fig. 20. Partial decay scheme for the levels of ^{93}Mo populated in the (p,n γ) reaction at 3.7 and 4.4 MeV.

Fig. 3C. Partial decay scheme for the levels of ^{93}Mo populated in the $(p,n\gamma)$ reaction at 3.7 and 4.4 MeV.

In that arrangement Compton-suppressed spectra could be measured at 55° to the beam. The ^{91}Zr target had a thickness of $3.1 \pm 0.1 \text{ mg/cm}^2$ measured with an α -gauge. The Ge(Li) detector was calibrated for absolute efficiency using absolute standard sources. For each bombardment energy, four 15-min spectra were recorded and the ratio of the monitor counts and the integrated beam charges was checked and found to be constant to $\pm 2.5\%$. Two strong γ rays were used as interval monitors and the cross-sections for the remaining weaker peaks were calculated from spectra taken for about 1 hour each. The dead time in all the runs was measured in each case and it was found to be near 10%. Measurements were taken at 17, 19, 21, 24, 27 and 30 MeV of incident energy. The purpose of these detailed measurements was to establish a more accurate representation of the dependence of the cumulative and eventually the independent (side feeding) cross-section on the level J^π value. Such measurements will also be supported by statistical model calculation and will be of indispensable aid in making definite J^π assignments for high-spin states. Some representative excitation functions are shown in Fig. 4C. The dependence on J is quite apparent. The 1734 keV γ ray, for example must originate from a state with $J \geq 17/2$.

The angular correlation of the γ rays from the $^{91}\text{Zr}(\alpha, 2n)$ reaction were measured with the anti-Compton spectrometer at 25° , 35° , 47° , 65° , 75° and 90° at 30 MeV of bombardment energy. The elastically scattered α -particles were monitored at 45° to the beam in a Si detector.

(L. Rutledge, E. S. Macias, D. G. Sarantites)

In-beam Gamma Ray Spectroscopy of ^{107}In via the $(^3\text{He}, pn)$ Reaction

Recently we have begun in-beam gamma ray studies of the levels of ^{107}In via the $(^3\text{He}, pn)$ reaction to complement the decay scheme studies of ^{107}Sn to

Fig. 4C. Absolute excitation functions for individual γ rays observed in the $^{91}\text{Zr}(\alpha, 2n)^{93}\text{Mo}$ reaction. Forms characteristic of spin are observed.

levels of ^{107}In . These experiments are aimed at gaining more information about the high-spin states.

A 5.07 mg/cm^2 self-supporting enriched (82.1% ^{106}Cd) target has been obtained for this work. Due to the low melting point of metallic cadmium (321°C), a cooling system has been built to cool the target during the bombardment. Excitation functions using an anti-Compton spectrometer have been measured using ^3He bombarding energies from 12-30 MeV. These data are being used to place gamma rays in the appropriate nucleus and to help in the assignment of level spin and parity values. Preliminary analysis indicates that nuclear structure information on adjacent cadmium and tin as well as indium isotopes may also be extracted from these measurements.

(H.-S. Hseuh and E. S. Macias)

Lifetime Measurements by the Recoil Distance Method

As was reported last year the recoil distance apparatus (the plunger) for the measurement of psec lifetimes has been constructed. Preliminary experiments to test the apparatus for energetic beams ($E_\alpha > 20 \text{ MeV}$) have been performed. Difficulties encountered with background radiations from nearby collimators are being reduced by small changes in the diameter of the collimators, backing and catcher foils, etc. Efforts to measure the lifetimes of the 7_1^+ state at 2282.6 keV in ^{56}Co and the 6_1^+ state at 3388.4 keV in ^{56}Fe are in progress.

(E. Jensen, L. R. Rutledge, E. S. Macias and D. G. Sarantites)

G-factors of psec States

We have designed and built the necessary apparatus to measure the g-factors of two "long" lived ($\tau > 2 \text{ psec}$) high-spin states (7_1^+) in ^{56}Co and (6_1^+) in ^{56}Co . These levels together with the already measured 2^+ level

at 846.78 keV with $g = 0.58 \pm 0.16$ will be simultaneously excited by the (α, pn) and $(\alpha, 2p)$ reactions on ^{54}Fe . The magnetic moments for these states will then be measured using the implantation perturbed-angular correlation technique (IMPAC). The apparatus consists of a C-yoke type magnet with a 2.5 cm air gap on which a 3 K Gauss field is achieved to reach saturation. The pole faces are 7.0 cm in diameter. The target chamber is 2.4 cm high and it is connected downstream with a large Faraday cup. The magnet is driven by a 40 v supply and draws ~ 10 Amps. The power supply is driven by a motor and its direction can be reversed. Microswitches sense the end of the travel and turn the motor off. The relays driven by a programming unit switch the polarity and the motor on. The integrated beam current in the Faraday cup is prescaled and used via a scaler timer to stop the measurement and reverse the magnet polarity. Spectra of the γ rays measured with the anti-Compton spectrometer will be routed in many repetitive runs with field up and down to two halves of the pulse height analyzer. The anti-Compton spectrometer can under these conditions be used between 90° and 55° to the beam.

(L. L. Rutledge, D. G. Sarantites and E. S. Macias)

Doppler-Shift Attenuation Lifetime Measurements in ^{196}Hg

Recent calculations by A. Johnson and S. Hjorth which describe the nuclear structure of the strongly back-bending ^{196}Hg nucleus, predict $B(E2)$ for the first 6^+ state has an enhancement of a factor of 3 over that of the first 10^+ state, the 7-nsec isomer. This predicts a lifetime of 0.5-1.0 psec for the 6^+ level. We have made DSAM measurements at 21, 24, and 27 MeV to obtain the lifetimes of the 4^+ , 6^+ , and 8^+ levels in ^{196}Hg using the $^{194}\text{Pt}(\alpha, 2n\gamma)^{196}\text{Hg}$ reaction. Anti-Compton singles spectra were obtained at

5 angles between 25° and 90° to the beam direction. The target consisted of a self-supporting Pt foil approximately 6 mg/cm² thick. The spectra were counted in the presence of standard sources, and the gain was large enough to allow at least 10 channels across each photopeak. This procedure insures precise centroid determinations. The data are being analyzed using a centroid shift technique.

(L. L. Rutledge, E. S. Macias, and D. G. Sarantites)

INSTRUMENTATION AND TECHNIQUE

On-line Conversion Electron Spectrometer

We have purchased a magnetic lens for use as an on-line conversion electron spectrometer. A similar sweeping current lens spectrometer is in operation at the Uppsala (Sweden) EN tandem accelerator.¹⁴ This spectrometer transmits a broad energy range with a large solid angle. The instrument permits easy efficiency calibration and background reductions, and gives data independent of ADC deadtime. The construction and use of this instrument will be carried out in collaboration with Professor Sarantites.

(E. S. Macias and D. G. Sarantites)

On-line Chemistry with a Helium Jet System

The Washington University Helium Jet system, described in previous progress reports (COO-2318-1,7) has been modified to allow the rapid transport and on-line chemical separation of charged particle reaction products. The system is operated without differential pumping with the capillary outlet running directly into a reaction vessel. The helium stream is bubbled

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14. L. Westerberg, L.O. Edvardson, G. Ch. Madueme, and J.E. Thun, Nucl. Inst. and Meth. (in press).

through a liquid and a large fraction of the reaction recoil clusters remain in the liquid. This results in a carrier-free solution of radioactive species which can be analysed with conventional fast radiochemical techniques.

The system has been tested with palladium, rhodium and ruthenium reaction products from the $^{96}\text{Ru}(^3\text{He},x)$ reaction. It is hoped that an on-line chemical separation of palladium from the other radioactive species will aid in the identification and decay of ^{97}Pd and ^{96}Pd .

(E. Jenson, L. Zapata, E. S. Macias)

A New Instrumental Method for Quantitative Analysis of Gold

A new nondestructive method for determining gold content in thin gold sheets, alloys and coins has been developed during the past year. The method takes advantage of the fact that gamma rays with energy slightly less than the energy of the K absorption edge of a given element have a much lower absorption coefficient than gamma rays with energy slightly higher than that K edge energy. The 79.62- and 80.99-keV gamma-ray transitions following ^{133}Ba decay bracket the gold K edge at 80.725 keV and have been used as a "double beam" gamma absorption thickness gauge specific for gold. This method has been tested for thin sheets of pure gold and it was found that an exponential absorption relationship holds for gold thickness up to 150 mg/cm^2 . The absolute accuracy of the method for pure gold and gold alloys is presently under investigation. It is anticipated that this fast, non-destructive analysis method will be useful for numismatic research.

(C. D. Radcliffe, P. P. Gaspar and E. S. Macias)

New Scattering Chambers

Three small scattering chambers have been designed and constructed during the past year. They are (1) A target chamber for absolute cross-section measurement under Compton suppression. This chamber has a monitor detector Si positioned at 25° to the beam direction, (2) A modified miniature chamber for angular distribution measurements, and (3) A miniature chamber for G-factor measurements.

(L. L. Rutledge)

Data Acquisition and Reduction

Several computer programs for the IBM 360 have been written, or are in the process of being developed. The program CONVERT has been completed and is being routinely used. This program reads the output data tape of the SCAN program, corrects the spectra for Compton background coincidences, and writes the corrected spectra onto a second tape. The program HPLØT has also been completed. This program reads both the SCAN and CONVERT output tapes and generates linear histograms plots of the spectra.

The program TRIBODY has been written and is in the process of being de-bugged and refined. This program computes, using the full, classical 3 body kinematics, 5 averaged recoil velocity vectors and their relative weights for a recoiling residual nucleus following a reaction in which two nucleons are evaporated. These vectors are required as input into SHAPES which computes $F(r)$ for Doppler-shift attenuation lifetime measurements.

(L. L. Rutledge)

An improved version of the program GAMANAL written for determining gamma ray peak positions and intensity is presently being modified for use on the Washington University 360/65 computer. An earlier version of this

program currently is in use in our laboratory but is not able to handle multiplet gamma ray lines. The improved program is expected to treat these complex peaks properly.

(H.-C. Hseuh)

Publications during the past six months

M.R. Zalutsky and E.S. Macias, Decay of 5.8-min ^{140m}Pm and 9.2-sec ^{140g}Pm to Levels of ^{140}Nd , Phys. Rev. C (September, 1975).

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M.R. Zalutsky, E.S. Macias and R.A. Meyer, Structure of N=81 Nuclei: Levels of ^{141}Nd and ^{139}Ce Populated in Beta Decay, Phys. Rev. C (submitted May, 1975).

E.S. Macias, W.D. Ruhter, D.C. Camp, and R.G. Lanier, A Program for Calculating Gamma-Gamma Directional Correlation Coefficients and Mixing Ratios, Computer Physics Communications (submitted June, 1975).

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Structure of the N=81 Nuclei: Levels of ^{141}Nd and ^{139}Ce Populated in Beta Decay, Am. Phys. Soc. Meeting, Washington, D.C., April 29, 1975, Bull. Am. Phys. Soc. 20, 623 (1975).

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Papers in Preparation

Lifetime Measurements of Low-Lying Levels in ^{93}Mo Populated via the $^{93}\text{Nb}(p, n\gamma)$ Reaction Using the Doppler-Shift Attenuation Method, L.L. Rutledge, E.S. Macias, and D.G. Sarantites.

Identification and Decay of 2.9-min ^{107}Sn and 50-sec ^{107m}In , H.-C. Hseuh and E.S. Macias.

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Papers by the Principal Investigator not supported under this contract

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