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ANNUAL PROGRESS REPORT
NUCLEAR STRUCTURE STUDIES UTILIZING LAMPF

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MASTER

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AEROJET NUCLEAR COMPANY

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ABSTRACT

A program has been funded to generate new nuclear structure on nuclides off the line of beta stability. These data will be characterized and interpreted to test current theories in nuclear physics and to develop new concepts. To this end, studies are being made of radiations emitted in the decay of neutron-deficient and selected neutron-rich nuclides. Nuclides to be studied are produced primarily by proton-induced "spallation-type" reactions in the Los Alamos Meson Physics Facility (LAMPF). Progress reported includes work in three general categories: studies of the decay of selected radioactive nuclides; theoretical development of nuclear models to aid in the analysis and interpretation of experimental data; and the development of measurement techniques necessary for planned future programmatic efforts.

FOREWORD

This document is a report of technical progress by members of the Nuclear Physics Branch of Aerojet Nuclear Company for FY-1974. The results reported are generally for work still in progress. Consequently, they should be regarded as preliminary in nature and the author should be contacted before including any reference to them in other publications.

CONTENTS

ABSTRACT	ii
FOREWORD	iii
I. INTRODUCTION.	1
II. NUCLEAR LEVEL-SCHEMES STUDIES	3
A. Decay Schemes of ^{128}Ba and ^{128}Cs	3
B. The Decay of ^{131}Ba	9
C. Decay Scheme of ^{134}La	15
D. Energy Levels of ^{151}Gd Excited in the Decay of ^{151}Tb	20
III. NUCLEAR THEORY AND MODELS	21
A. Inclusion of the Effects of Hexadecapole Distortion on Coriolis Mixing and Gamma-Ray Transition Probabilities in Deformed Nuclei	21
IV. DEVELOPMENT OF EXPERIMENTAL TECHNIQUES.	25
A. Beta-Gamma Coincidence System for the Measurement of Endpoint Energies	25
B. Development of a 4π β - γ Counting System	28
C. Gamma-Ray Spectrometer Systems.	30
1. Gamma-gamma coincidence systems	30
2. Traveling gamma-ray spectrometer system	30

FIGURES

1. Gamma-ray spectrum from the decay of ^{128}Ba and ^{128}Cs measured on a Ge(Li) detector.	6
2. Gamma-ray spectrum in coincidence with transition of 526 keV from the decay of ^{128}Cs	7
3. Proposed decay schemes of ^{128}Ba and ^{128}Cs	8
4. Gamma-ray spectrum of ^{131}Ba	12
5. Spectrum of ^{131}Ba gamma radiation in coincidence with the 216-keV gamma ray	13
6. Proposed decay scheme for ^{131}Ba	14
7. Spectrum of gamma radiation associated with the decay chain $^{134}\text{Ce} \rightarrow ^{134}\text{La} \rightarrow ^{134}\text{Ba}$	17

8.	Spectrum of gamma radiation in coincidence with the 604-keV transition in the decay of ^{134}La	18
9.	Spectrum of gamma radiation in coincidence with the 563-keV transition in the decay of ^{134}La	19
10.	Block diagram of the beta-gamma coincidence system for β endpoint determinations	27
11.	Block diagram of 4π β - γ coincidence counting system	29

TABLES

I.	Gamma-Ray Energies and Intensities for the Decay of ^{128}Ba and ^{128}Cs	4
II.	Summary of Coincidences with 526 keV.	5
III.	Energies and Relative Intensities of γ Rays from the Decay of ^{131}Ba	10
IV.	Gamma-Ray Energies Measured for the 2.06-y ^{134}Cs Decay.	16
V.	Relationship between Operators for $E\lambda$ γ -ray Transitions Expressed in the Nuclear (x, y, z) Coordinates and in the Stretched (ξ, η, ζ) Coordinates	24
VI.	Measured β^+ Endpoint Energies to the Ground and Excited States for the Decays of ^{128}Cs and ^{134}La	26

I. INTRODUCTION

This report summarizes the results of work carried out during Fiscal Year 1974 under the program "Nuclear Structure Studies Utilizing LAMPF". The progress reported includes work in three general categories: studies of the decay of selected radioactive nuclides; theoretical development of nuclear models to aid in the analysis and interpretation of experimental data; and the development of measurement techniques necessary for planned future programmatic efforts.

This program, first funded in FY 1974 by the Division of Physical Research of the U.S. Atomic Energy Commission, has two objectives: the generation of new nuclear-structure data on nuclides off the line of beta-stability; and the characterization and interpretation of these data to test current theories in nuclear physics and to develop new concepts. These objectives are being carried out through the study of the radiations emitted in the decay of neutron-deficient and selected neutron-rich nuclides. The primary means for producing these nuclides is at present proton-induced "spallation-type" reactions in the proton-beam irradiation facilities of the Clinton P. Anderson Meson Physics Facility (denoted by the acronym LAMPF) at the Los Alamos Scientific Laboratory. The work of the program is carried out by members of the Nuclear Physics Branch of Aerojet Nuclear Company at the Idaho National Engineering Laboratory.

With the availability of a usable proton beam last fall, provision was made by LAMPF personnel for bombardment of targets for radioactivity-related studies on a limited basis. At first, it was possible to carry out these bombardments only in the main proton beam (in the switchyard area of the accelerator) during times set aside for machine development. Later on, with the development of an irradiation facility in Area B and the capability of delivering a proton beam to it, the bombardments were carried out in this latter facility. Because of the usual problems associated with the bringing "on-line" of a facility of the size and complexity of LAMPF, we have encountered serious difficulties in having our bombardments carried out when scheduled. The impossibility of knowing when a planned irradiation would in fact be carried out has effectively precluded our travelling to LASL to carry out the measurements. Consequently, we have thus far concentrated our efforts on the study of nuclides of moderately long half-life ($\gtrsim 15$ hours), which can be produced and shipped to our laboratory for detailed study.

The nuclides which we have chosen for detailed study lie in the region $50 < Z, N < 82$, where the structure and properties of the collective potential-energy surface are of current interest, and near $N=88$, where the transition between spherical and strongly deformed equilibrium shapes occurs. These studies have generated new nuclear-structure information while at the same time have allowed us to evaluate our experimental techniques in cases where positron emission is an important component of the decay process. Good examples of this approach are provided by the nuclide chains $^{128}\text{Ba}(2.4\text{d}) \rightarrow ^{128}\text{Cs}(3.8\text{m}) \rightarrow ^{128}\text{Xe}(\text{stable})$ and $^{134}\text{Ce}(73\text{h}) \rightarrow ^{134}\text{La}(6.7\text{m}) \rightarrow ^{134}\text{Ba}(\text{stable})$. The half-lives of the parent activities are long enough to permit their study to be made at our

laboratory, yet their daughters have relatively short half-lives and large Q values. Thus, the daughters are in many ways typical of the sort of short-lived activities that we expect to encounter in later work down at LAMPF. As a parallel effort, instrumentation has been assembled for this program to permit acquisition of single-parameter gamma-gamma and positron-gamma coincidence spectra. In addition, theoretical calculations within the framework of specific nuclear models have been made, with the objective of expanding our capabilities in carrying out detailed theoretical analysis and interpretation of nuclear level-scheme information.

During the next fiscal year (FY 1975), additional bombardments will be carried out at LAMPF so that the program of experimental measurements undertaken this year can be completed. The results will then be analyzed and prepared for publication. At the present time it appears that, in addition to new nuclear-structure information, these studies will provide a number of previously unmeasured beta-decay Q values. In addition, the possibility of utilizing a heavy-ion accelerator to produce radioactive nuclides for study will be investigated. If this proves feasible, measurements will be made at this accelerator; the choice of nuclides to be studied will be determined from consideration of the source-production capabilities of the machine and the potential interest of the resultant decay data for current nuclear-structure concepts.

We wish to acknowledge the efforts of several people which have contributed significantly to the work described in this report. In any studies of radioactive decay, the availability of chemically and isotopically pure sources is of great importance. The chemical separations underlying the present work have been carried out by E. H. Turk. The isotope-separated sources have been prepared by R. A. Anderl. A special thanks also goes to M. E. Bunker and J. W. Starner of LASL for their work in preparing target material for bombardment, for carrying out the bombardments and for arranging for the shipment of the radioactive material.

II. NUCLEAR LEVEL-SCHEMES STUDIES

A. Decay Schemes of ^{128}Ba and ^{128}Cs

R. G. Helmer, R. C. Greenwood, R. J. Gehrke, C. W. Reich

The level schemes of the nuclides in the decay chain $^{128}\text{Ba}(2.4\text{ d}) \rightarrow ^{128}\text{Cs}(3.8\text{ m}) \rightarrow ^{128}\text{Xe}$ have been studied. The radioactive material was produced by 800-MeV proton bombardment of 0.003-inch-thick Pr-metal foils. Two such bombardments have thus far been carried out. The samples consisted of four "stacked" foils; and the integrated beam currents were ≈ 5 -10 $\mu\text{amp-hrs}$.

From these samples, the Ba fraction was extracted. In one case, this fraction was isotope separated to provide a pure mass-128 sample. With these samples, measurements have been made of

γ -ray singles spectra,
 γ -ray energy calibration spectra,
 γ - γ coincidence spectra,
 β^+ spectra, and
 β^+ - γ coincidence spectra.

All of the γ -ray spectra were taken on Ge(Li) detectors and the positron spectra were measured with a plastic scintillator. Although more experiments are planned, some preliminary results are available.

A γ -ray spectrum for the decay of ^{128}Ba and ^{128}Cs is shown in Figure 1. All of the γ rays are tentatively assigned to the ^{128}Cs decay, except the 273-keV transition which follows the ^{128}Ba decay. A preliminary list of the corresponding γ -ray energies and intensities is given in Table I. The γ -ray spectrum observed in coincidence with the 526-keV transition is shown in Figure 2. The observed intensities of the γ -rays in coincidence with the 526-keV peak are shown in Table II along with the corresponding singles intensities and the deduced coincidence relationships.

From this experimental information, a preliminary decay scheme has been constructed as shown in Figure 3. This scheme is much more extensive than and differs from that previously proposed.^[1]

[1] T. Kučarova, V. Zvolská, B. Kracík and A. Mastalka, Czech. J. Phys. B18, 24 (1968).

TABLE I
GAMMA-RAY ENERGIES AND INTENSITIES FOR THE DECAY OF ^{128}Ba AND ^{128}Cs

Energy (keV)	Relative Intensity	Energy (keV)	Relative Intensity
215.47(4)	2.6(2)	1764.73(20)	0.18(3)
229.48(6)	4.1(4)	1804.10(18)	0.24(6)
273.44(1)	561.(17)	1810.43 ^c	0.27 ^c
359.12(4)	3.3(3)	1829.81(11)	0.27(3)
375.00(2)	11.5(6)	1837.24(25)	0.14(4)
442.87(1)	$\approx 1000.$	1851.20(40)	0.26(6)
511. ^a	4950.(150)	1868.11(11)	0.29(3)
526.57(1)	91.3(27)	1905.42(20)	0.19(4)
570.08(4)	1.14(15)	1918.84(6)	1.44(7)
590.23(2)	2.6(2)	1978.05(6)	1.78(7)
613.47(2)	13.7(7)	1987.88(6)	1.00(7)
966.60(30)	~ 1	2039.58(6)	1.20(7)
969.46(3)	25.7(15)	2067.80(18)	0.23(7)
986.68(5)	1.27(15)	2078.20(8)	0.48(4)
1030.18(3)	8.3(3)	2141.40(20)	0.28(3)
1081.19(6)	0.73(5)	2148.61(12)	1.90(12)
1140.06(3)	44.5(14)	2155.63(6)	6.14(27)
1157.57(15)	0.40(10)	2190.14(6)	2.21(10)
1162.01(8)	0.38(4)	2255.51(20)	0.09(2)
1203.68(9)	0.34(8)	2275.50(8)	0.61(4)
1239.65(6)	0.50(5)	2361.89(7)	2.38(10)
1283.45(7)	0.45(8)	2394.27(7)	0.93(4)
1303.35(4)	4.60(20)	2416.42(7)	1.33(6)
1340.20(25)	0.24(4)	2430.49(9)	0.26(2)
1372.35(30)	0.08(4)	2466.67(25)	0.11(2)
1392.46(12)	0.61(6)	2482.53(14)	0.17(3)
1434.54(7)	0.50(4)	2510.59(12)	0.17(2)
1461. ^b		2564/26(20)	0.08(2)
1477.69(10)	0.39(4)	2591.33(14)	0.28(3)
1513.01(4)	1.97(11)	2632.89(20)	0.28(2)
1541.25(5)	0.64(6)	2656.60(30)	0.08(3)
1556.80(6)	0.63(4)	2667.32(20)	0.13(3)
1600.18(10)	0.24(3)	2837.70(25)	0.24(2)
1629.11(4)	5.03(18)	2859.20(20)	0.24(2)
1645.07(15)	0.37(8)	2938.00(30)	0.12(3)
1663.65(5)	0.97(4)	3103.90(70)	0.10(4)
1684.16(7)	4.35(18)		
1747.6(10)	0.16(4)		

^aPeak is partly from ^{128}Cs and partly ^{40}K background.

^bOnly a portion of the singles are in coincidence with this transition.

^cUpper limits on intensities were determined from hand calculations, whereas the areas of observed peaks were determined by a computer program.

TABLE II

SUMMARY OF COINCIDENCES WITH 526 keV

Gamma-Ray Energy (keV)	Gamma-Ray Intensity			Coincidence	
	Coincidence		Singles	Yes	No
	(Computer) ^c	(Hand) ^c			
273		<100	8,350		✓
442	1344		13,200	✓ ^b	
459	11				
496			88		
511	1117		69,700	✓ ^b	
526	9		1,180		✓
590			42		
613	165		166	✓	
969		<30	363		✓
986			23	✓	
1030	≅100		≅100		✓
1140		<20	568	✓	
1303	57		60	✓	
1342	10		8	✓	
1461 ^a	13		a	✓	
1513	28		25	✓	
1541	11		8	✓	
1629	57		60	✓	
1663	~10		12	✓	
1684		<3	58		✓
1868		<4	5		
1918		<2	24		✓
1978		<2	22		✓
1987		<2	16		✓
2039		<2	18		✓
2078		<2	8		✓
2148		<2	29		✓
2155		<2	76		✓
2190		<2	30		✓
2275		<2	10		✓
2361		<2	16		✓
2394		<2	16		✓
2416		<2	10		✓

^aPeak is partly from ^{128}Cs and partly ^{40}K background.

^bOnly a portion of the singles are in coincidence with this transition.

^cUpper limits on intensities were determined from hand calculations, whereas the areas of observed peaks were determined by a computer program.

Figure 1. Gamma-ray spectrum from the decay of ^{128}Ba and ^{128}Cs measured on a Ge(Li) detector. The peaks labeled below the spectrum are sum peaks and the background lines.

Figure 2. Gamma-ray spectrum in coincidence with transition of 526 keV from the decay of ^{128}Cs . The boxes indicate the expected positions and peak heights of the indicated transitions if they were in coincidence.

Figure 3. Proposed decay schemes of ^{128}Ba and ^{128}Cs . Energies are in keV.

B. The Decay of ^{131}Ba

R. J. Gehrke, R. G. Helmer, C. W. Reich, R. C. Greenwood

The decay of 11.5-d ^{131}Ba is being studied with Ge(Li) spectrometers. The ^{131}Ba activity was produced by bombarding Pr-metal foils with 800-MeV protons. It was obtained carrier-free by chemically separating the barium activities from the irradiated Pr, followed by isotope separation. Gamma-ray singles spectra for ^{131}Ba were accumulated with a 65-cm³ five-sided coaxial Ge(Li) spectrometer.

A typical gamma-ray spectrum of ^{131}Ba is shown in Figure 4. A list of the gamma-ray energies and relative intensities is given in Table III. Also in Table III is given a comparison of these values with those from three recent investigations^[1-3]. Coincidence measurements were made using 35-cm³ and 50-cm³ Ge(Li) detectors. Spectra were accumulated in coincidence with gamma-ray gates of 123, 133, 216 and 373 keV. As an illustration of these spectra, Figure 5 shows the spectrum in coincidence with the 216-keV gate.

Previously unreported levels in ^{131}Cs have been established at 919.6, 1170 and 1341 keV, as shown in the proposed decay scheme in Figure 6. The present coincidence data confirm the existence of these newly reported levels and verify the placement of previously unreported gamma rays at 369, 546, 563, 703, 1046 and 1126 keV. Other previously unreported gamma rays have been identified at 128, 795, 919, 1170, 1208 and 1341 keV; these gamma rays have been placed in the decay scheme on the basis of energy considerations. Upper limits have been placed on the intensities of gamma rays at 323 and 508 keV, which have been reported by Karlsson^[4].

The only reported measurement of the Q-value of the ^{131}Ba decay is 1165 ± 15 keV^[5]. However, in their 1971 Atomic Mass Evaluation, Wapstra and Gove^[6] pointed out that this value is considerably lower than that computed from the other mass-related information, which implied a Q-value of 1340 keV for this decay. Our observation of the level at 1341 keV supports this upward readjustment of this Q-value, since it requires that this decay energy must be at least 1341 keV.

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- [1] T. Kucarova, B. Kracik and V. Zvolenska, *Sov. J. Nucl. Phys.* 7, 433 (1968).
 - [2] L. Hasselgren, S. Antman, H. S. Sahota and J. E. Thun, *Nucl. Phys.* A153, 625 (1970).
 - [3] R. Singh, C. Rangacharyulu and G. K. Mehta, *Z. Physik* 258, 12 (1973).
 - [4] K. Karlsson, *Arkiv Fysik* 33, 47 (1966).
 - [5] B. L. Robinson, *Bull. Am. Phys. Soc.* 7, 541 (1962).
 - [6] A. H. Wapstra and N. B. Gove, *Nuclear Data Tables* A9, Nos. 4-5 (1971).

TABLE III

ENERGIES AND RELATIVE INTENSITIES OF γ RAYS FROM THE DECAY OF ^{131}Ba

γ -ray Energies (keV)	γ -Ray Relative Intensities				
	Present Experiment	Present Experiment	Ref. [3]	Ref. [2]	Ref. [1]
54.96 ± 0.06		5.0 ± 0.6	1.1	5.6 ± 0.9	4.6 ± 1.0
78.755 ± 0.013		36.9 ± 3.0	48.9	33.1 ± 1.6	45 ± 9
(82)		Not observed		0.87 ± 0.06	
92.301 ± 0.011		34.2 ± 1.8	42.6	35.9 ± 1.6	37 ± 8
123.803 ± 0.012		1440 ± 80	1698	1292	1420 ± 213
128		0.75 ± 0.20			
133.607 ± 0.014		107 ± 6	123	87.7 ± 4.9	101 ± 20
137.372 ± 0.040		1.61 ± 0.15			< 9
157.146 ± 0.023		9.5 ± 0.5	1.9	11.4 ± 0.8	13 ± 4
216.085 ± 0.024		1000	1000	1000 ± 5.2	1000
239.630 ± 0.026		120 ± 3	111	121.7 ± 4.7	121 ± 24
246.916 ± 0.060		30.6 ± 1.3	19	30.0 ± 2.3	35 ± 18
249.444 ± 0.027		141 ± 4	159.7	142 ± 9	146 ± 30
294.537 ± 0.035		8.6 ± 0.6	4.9	7.3 ± 0.4	8.8 ± 2.2
(323)		< 0.4	Not observed	Not observed	< 3
351.154 ± 0.039		5.4 ± 0.7		7.5 ± 1.7	8 ± 4
369		1.5 ± 0.5			
373.250 ± 0.029		718 ± 30	703	603 ± 39	757 ± 76
404.040 ± 0.030		65.9 ± 3.2	72	58.3 ± 4.4	67 ± 7
427.598 ± 0.045		5.0 ± 0.3	1.8	4.5 ± 0.5	6.0 ± 1.8
451.40 ± 0.08		2.19 ± 0.20	4.8	2.1 ± 0.4	< 4
461.170 ± 0.050	}	5.1 ± 0.3	3.7	{ 4.8 ± 0.8 5.0 ± 0.8 }	5.0 ± 1.5
(462)					
480.378 ± 0.040		16.4 ± 0.8	17.5	20.0 ± 1.8	30 ± 12
486.480 ± 0.040		105 ± 6	121	83.5 ± 4.1	98 ± 30
496.280 ± 0.025		2370 ± 70	1817	1944 ± 9	2400 ± 240
(508)		< 0.2			5.5 ± 2.7
546.27 ± 0.18		0.26 ± 0.10			
563.4 ± 0.2		0.29 ± 0.10			1.6 ± 0.5
572.663 ± 0.035		7.9 ± 0.5	11.1	8.3 ± 0.8	7.8 ± 1.9
585.020 ± 0.030		62.3 ± 3.5	55.4	51.3 ± 3.1	69 ± 14
620.053 ± 0.030		79.9 ± 3.8	80.3	57.8 ± 3.1	73 ± 18
674.411 ± 0.040		6.76 ± 0.40	4.7	5.8 ± 0.8	7.0 ± 2.1
696.462 ± 0.040		7.7 ± 0.5	5.5	6.1 ± 0.8	9.3 ± 2.8
703.44 ± 0.10		0.34 ± 0.05			
795.9	}	2.2 ± 0.3			
797.41 ± 0.09					
831.631 ± 0.050		11.7 ± 0.7	27.7	9.9 ± 1.6	15 ± 4
914.086 ± 0.060		2.35 ± 0.15	5.5	1.94 ± 0.36	4 ± 2
919		0.38 ± 0.14			
923.856 ± 0.040		36.8 ± 2.2	35	31.3 ± 4.7	40 ± 10
954.66 ± 0.07		1.71 ± 0.14			
968.87 ± 0.07		1.74 ± 0.14	1.4	1.69 ± 0.28	2.6 ± 0.9

TABLE III (Contd.)

γ -ray Energies (keV) Present Experiment	γ -Ray Relative Intensities			
	Present Experiment	Ref. [3]	Ref. [2]	Ref. [1]
1046.9	67.4 $\pm$ 4.0	71.8	56.6 $\pm$ 4.9	78 $\pm$ 16
1047.562 $\pm$ 0.035				
1126.16 $\pm$ 0.18				
1170	0.15 $\pm$ 0.04			
1208	0.08 $\pm$ 0.03			
1341	0.08 $\pm$ 0.03			
	0.05 $\pm$ 0.02

Figure 4. Gamma-ray spectrum of ^{131}Ba . The peaks identified as background lines are labeled 'BG'.

Figure 5. Spectrum of ^{131}Ba gamma radiation in coincidence with the 216-keV gamma ray. Peaks labeled 'RC' result from random coincidences; those labeled 'BS' result from backscattering between the detectors.

Figure 6. Proposed decay scheme for ^{131}Ba . The energy values are given in keV.

C. Decay Scheme of ^{134}La

R. C. Greenwood, R. G. Helmer, R. J. Gehrke, C. W. Reich

We are studying the decay of 6.7-m ^{134}La produced in the decay chain $^{134}\text{Ce}(73\text{ h}) \rightarrow ^{134}\text{La}(6.7\text{ m}) \rightarrow ^{134}\text{Ba}(\text{stable})$. The long half-life of the parent ^{134}Ce activity allows us to irradiate a spallation target, in this case Pr, at LAMPF and ship it back to our laboratory for subsequent detailed study.

The preliminary data reported herein for ^{134}La decay were obtained from two separate irradiations of Pr-metal foils. Following the first irradiation, the Ce fraction was extracted from the Pr target for study. Unfortunately this sample also contained small contaminants of the Y, Zr, Nb, Sn and Sb fractions, which severely limited the scope of useful data which could be obtained with that source. A pure mass-134 fraction was obtained following the second irradiation by first separating the Ce fraction from the Pr target and then mass separating this Ce fraction.

A γ -ray spectrum of the mass-separated ^{134}Ce is shown in Figure 7. In addition to measuring such singles γ -ray spectra, we have attempted to obtain the best set of energies for the γ rays emitted in the ^{134}La decay. This analysis is incomplete at this time and therefore no data are presented here. In a parallel effort, however, we have also remeasured the energies of the γ -rays emitted in the decay of 2.06-y ^{134}Cs , and which also correspond to transitions in ^{134}Ba . These data are summarized in Table IV.

Further, γ - γ coincidence studies have been made using two large Ge(Li) detectors with active volumes of 50 cm³ and 55 cm³. As an example of these data, Figures 8 and 9 show the γ -ray spectra observed to be in coincidence with the 604- and 563-keV γ -ray transitions, respectively.

These studies of the ^{134}La decay scheme are continuing.

TABLE IV

GAMMA-RAY ENERGIES MEASURED FOR THE 2.06-y ^{134}Cs DECAY

Measured γ -ray Energy (keV)
563.227 $\pm$ 0.015
569.315 $\pm$ 0.015
604.699 $\pm$ 0.015
795.845 $\pm$ 0.022
801.932 $\pm$ 0.022
1038.571 $\pm$ 0.026
1167.938 $\pm$ 0.026
1365.152 $\pm$ 0.032

Figure 7. Spectrum of gamma radiation associated with the decay chain $^{134}\text{Ce} \rightarrow ^{134}\text{La} \rightarrow ^{134}\text{Ba}$.

Figure 8. Spectrum of gamma radiation in coincidence with the 604-keV transition in the decay of ^{134}La .

Figure 9. Spectrum of gamma radiation in coincidence with the 563-keV transition in the decay of ^{134}La .

D. Energy Levels of ^{151}Gd Excited in the Decay of ^{151}Tb

C. W. Reich, R. G. Helmer

The investigation of the level structure of nuclei in the regions of transition between spherical and strongly deformed equilibrium shapes promises to provide valuable information concerning the features of this transition as well as, in many cases, the properties of nuclei at small deformations. The nuclide ^{151}Gd , with 87 neutrons, lies in (or near) such a transition region. Further interest in its level structure has been aroused by recent data from in-beam γ -spectroscopy following α -particle-induced reactions^[1] which strongly suggest the existence in ^{151}Gd of energy-level bands with different equilibrium deformations. Although the two bands involved both originate from high-j orbitals (i.e., the $h_{11/2}$ and $i_{13/2}$ spherical shell-model states), the data suggest that other ^{151}Gd states should also be more characteristic of a deformed rather than of a spherical equilibrium shape. In particular, in this regard, a characterization of the location and properties of the low-spin states in this nucleus should provide interesting new insights.

To attempt to do this, we have undertaken an investigation of the decay of 17.6-h ^{151}Tb ($I = 1/2$) to ^{151}Gd . Several studies of this decay have been carried out previously, the most recent one being that of Gonsior *et al.*^[2] The ^{151}Tb sources were produced by bombardment of 1-mil Ta foils in the 800-MeV proton beam at LAMPF. Typical integrated beam currents were 5-10 $\mu\text{A-h}$. Following irradiation, the Ta foils were dissolved and the rare-earth fraction removed. In some instances, the entire rare-earth fraction was isotope-separated to produce mass-151 samples for study; and in some instances, the Tb fraction was removed from the other rare-earth elements by ion-exchange techniques prior to isotope separation.

The experimental measurements thus far undertaken include γ -ray "singles" spectra and a 2-parameter (2048 x 2048-channel) $\gamma\gamma$ coincidence study^[3] using Ge(Li) spectrometers. Additional measurements of this type are required to complete the experimental phase of our investigation, but already several features have emerged. No evidence has been found for the existence of previously reported^[2] states in ^{151}Gd at 743, 766, 775, 835, 853, 905 and 957 keV. In addition, convincing evidence has been obtained for the existence of previously unreported energy levels at 426, 620 and 1052 keV.

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III. NUCLEAR THEORY AND MODELS

A. Inclusion of the Effects of Hexadecapole Distortion on Coriolis Mixing and Gamma-Ray Transition Probabilities in Deformed Nuclei

C. W. Reich

Two potential wells are currently widely used to treat the independent-particle motion in deformed nuclei. The first of these is the harmonic-oscillator potential, first applied to the study of deformed odd-mass nuclei by Nilsson^[1]. The second is the Woods-Saxon^[2] potential, whose use in low-energy nuclear-structure problems has been discussed by a number of authors^[3-6]. Due in part to its greater formal simplicity, the Nilsson model has, at least until recently, been the more widely employed in detailed calculations aimed at interpreting data on energy-level structure and transition probabilities in deformed nuclei. In its original form, this model considered only a quadrupole deformation of the nuclear potential and treated it through the inclusion in the model Hamiltonian of a term of the form^[1]

$$H_{\delta} = -\delta \cdot \frac{4}{3} \sqrt{\frac{\pi}{5}} \hbar \omega_0 r^2 Y_2^0, \quad (1)$$

where δ is a parameter giving the magnitude of the quadrupole deformation.

Subsequently, the Nilsson model was revised to include the effect of deformations of higher multipole order (see, e.g., References [7-10]). The main thrust of this revised model Hamiltonian has been the calculation of the single-particle level energies, to serve as input for detailed calculation of nuclear potential-energy surfaces.

Some years ago we wrote a computer program to calculate Nilsson-model level energies, γ -ray transition probabilities and Coriolis-coupling matrix elements. This program, expressed in the "old", or δ , representation^[1] of the Nilsson model, has been successfully applied to the analysis of experimental data on a number of strongly deformed nuclei (see, e.g., References [11-14]). We have now begun the revision of this program to include the effect of both a quadrupole and a hexadecapole deformation (the two whose existence in nuclei is the most firmly established experimentally at the present time). The calculation of level energies in this instance is straightforward and the program which carried out these calculations has been written. The calculation of transition probabilities and Coriolis-coupling (i.e., j_+) matrix elements, however, presents problems not encountered in the earlier version. These arise principally because, in its revised form, the Nilsson Hamiltonian and associated wave functions are expressed in the so-called "stretched" coördinates (ξ, η, ζ) instead of the "real" nuclear coördinates (x, y, z) employed in the original formulation. The relations between these two are as follows:

$$\xi = \left[\frac{m\omega_0}{\hbar} \cdot \left(1 + \frac{1}{3} \varepsilon \right) \right]^{\frac{1}{2}} x$$

$$\eta = \left[\frac{m\omega_0}{\hbar} \cdot \left(1 + \frac{1}{3} \varepsilon \right) \right]^{\frac{1}{2}} y$$

$$\zeta = \left[\frac{m\omega_0}{\hbar} \cdot \left(1 - \frac{2}{3} \varepsilon \right) \right]^{\frac{1}{2}} z .$$

(See References [7-10] for a definition of the various quantities and the considerations leading to the use of the "stretched" coördinates.) With the wave functions given in these coördinates, the matrix elements of the electromagnetic transitions and the Coriolis interaction cannot (at least in principle) be calculated directly, since the respective operators are expressed in the (x, y, z) system. It is necessary to transform either the wave functions into the (x, y, z) system or the operators into the (ξ , η , ζ) system in order to enable these matrix elements to be calculated in a logically consistent fashion. We have chosen to adopt the latter course, i.e., to transform the operators into the "stretched" coördinate system.

The transformations have thus far been worked out for the operators for $E\lambda$ -type (with $1 \leq \lambda \leq 4$) γ -ray transitions for all relevant values of ΔK and for the j_+ operator, necessary for Coriolis-coupling calculations. The transformed operators for the $E\lambda$ γ -ray transitions are summarized in Table V.

Work is in progress to obtain transformed operators for $M\lambda$ γ -ray transitions (at least for $\lambda = 1$) and to work out all the matrix elements necessary to calculate Coriolis-mixed $E\lambda$ and $M\lambda$ transition probabilities in a logically consistent manner with the effect of the hexadecapole deformation taken into account.

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TABLE V

RELATIONSHIP BETWEEN OPERATORS FOR $E\lambda$ γ -RAY TRANSITIONS EXPRESSED IN THE NUCLEAR (X,Y,Z) COORDINATES AND IN THE STRETCHED (ξ,η,ζ) COORDINATES. THE QUANTITIES A, B, AND C HAVE THE DEFINITIONS

$$\begin{cases} A = \left(1 + \frac{1}{3} \epsilon\right)^{-\frac{1}{2}} \\ B = \left(1 - \frac{2}{3} \epsilon\right)^{-\frac{1}{2}} \\ C = \left(\frac{\hbar}{m\omega_0}\right)^{\frac{1}{2}} \left(1 - \frac{1}{3}\epsilon^2 - \frac{2}{27}\epsilon^3\right)^{\frac{1}{6}} \end{cases},$$

where ϵ is the quadrupole deformation parameter. (For a definition of the various quantities, see, e.g., References 7-10.)

Multipolarity	ΔK	Operator (x,y,z coordinates)	Operator [stretched (ξ,η,ζ) coordinates]
E1	$\begin{cases} 0 \\ \pm 1 \end{cases}$	$\begin{cases} er Y_1^0 \\ er Y_1^{\pm 1} \end{cases}$	$\begin{cases} CBepY_1^0 \\ CAepY_1^{\pm 1} \end{cases}$
E2	$\begin{cases} 0 \\ \pm 1 \\ \pm 2 \end{cases}$	$\begin{cases} er^2 Y_2^0 \\ er^2 Y_2^{\pm 1} \\ er^2 Y_2^{\pm 2} \end{cases}$	$\begin{cases} C^2 A^2 B^2 e\{\rho^2 Y_2^0 + (2/3)\sqrt{5/16\pi} \epsilon \rho^2\} \\ C^2 A B e \rho^2 Y_2^{\pm 1} \\ C^2 A^2 e \rho^2 Y_2^{\pm 2} \end{cases}$
E3	$\begin{cases} 0 \\ \pm 1 \\ \pm 2 \\ \pm 3 \end{cases}$	$\begin{cases} er^3 Y_3^0 \\ er^3 Y_3^{\pm 1} \\ er^3 Y_3^{\pm 2} \\ er^3 Y_3^{\pm 3} \end{cases}$	$\begin{cases} C^3 A^2 B^3 e\{[1-(4/15)\epsilon] \rho^3 Y_3^0 + \sqrt{21/25} \epsilon \rho^3 Y_1^0\} \\ C^3 A^3 B^2 e\{[1+(2/15)\epsilon] \rho^3 Y_3^{\pm 1} + (2/5)\sqrt{7/2} \epsilon \rho^3 Y_1^{\pm 1}\} \\ C^3 A^2 B e \rho^3 Y_3^{\pm 2} \\ C^3 A^3 e \rho^3 Y_3^{\pm 3} \end{cases}$
E4	$\begin{cases} 0 \\ \pm 1 \\ \pm 2 \\ \pm 3 \\ \pm 4 \end{cases}$	$\begin{cases} er^4 Y_4^0 \\ er^4 Y_4^{\pm 1} \\ er^4 Y_4^{\pm 2} \\ er^4 Y_4^{\pm 3} \\ er^4 Y_4^{\pm 4} \end{cases}$	$\begin{cases} C^4 A^4 B^4 e\{[1-(4/21)\epsilon(1+\epsilon/3)] \rho^4 Y_4^0 + 2/7\sqrt{5}[9\epsilon+(2/3)\epsilon^2] \rho^4 Y_2^0 + (2/3)\epsilon^2 \rho^4 Y_0^0\} \\ C^4 A^3 B^3 e\{[1-(2/21)\epsilon] \rho^4 Y_4^{\pm 1} + (3/7)\sqrt{6} \epsilon \rho^4 Y_2^{\pm 1}\} \\ C^4 A^4 B^2 e\{[1+(4/21)\epsilon] \rho^4 Y_4^{\pm 2} + (3/7)\sqrt{3} \epsilon \rho^4 Y_2^{\pm 2}\} \\ C^4 A^3 B e \rho^4 Y_4^{\pm 3} \\ C^4 A^4 e \rho^4 Y_4^{\pm 4} \end{cases}$

IV. DEVELOPMENT OF EXPERIMENTAL TECHNIQUES

A. Beta-Gamma Coincidence System for the Measurement of Endpoint Energies

R. J. Gehrke, R. G. Helmer, R. C. Greenwood, C. W. Reich

This past year we constructed a beta-gamma coincidence detection system to measure the endpoint energies of β^- or β^+ emitting radionuclides. The slow/fast gating coincidence system was constructed as shown in Figure 10. This system combined good γ -ray energy resolution for the Ge(Li) detector (γ channel) with fast timing (i.e., high count-rate capability) and large dynamic range for the plastic scintillator (β channel). This system will be used to measure the decay energies of both neutron-rich and neutron-deficient isotopes.

With this system, β^+ spectra were obtained for ^{128}Cs , ^{134}La , ^{44}Sc and ^{22}Na . β^+ singles spectra and β^+ spectra in coincidence with the γ ray de-exciting the first excited state of the daughter radionuclide were obtained. The β^+ spectra from the decay of ^{44}Sc ($Q = 3649 \pm 6 \text{ keV}^{[1]}$) and of ^{22}Na ($Q = 2842.3 \pm 0.5 \text{ keV}^{[1]}$) were used for energy calibration. The β^+ endpoint energies were determined by a spectrum comparison technique and the endpoint values are listed in Table VI. These values are also compared in Table VI with the latest literature values.

The data were also analyzed by constructing a Fermi plot, but this method was found to be unsatisfactory for three reasons. First, because of the use of a flat-surfaced plastic scintillator, some of the positrons escaped the scintillator through backscattering and did not lose their entire energy in the detector. This process places extra counts in the lower-energy channels and causes an undesirable change in the shape of the β^+ spectrum. Second, even though the plastic scintillator has a poor efficiency for detecting γ rays, some γ rays are nonetheless detected. This effect is particularly significant for annihilation γ rays because they originate in the plastic scintillator when a positron is annihilated. Hence there is a finite probability that the γ -ray pulses will be summed electronically with the β pulses. This process, which removes counts from the β spectrum and places them in channels corresponding to a higher energy, also causes an undesirable change in the β spectrum shape near and above the endpoint energy. Third, to correctly determine the endpoint energy from a Fermi plot, it is necessary to unfold the detector resolution from the β^+ spectrum. This has not been done in the present experiments.

While this measurement technique thus contains some inherent undesirable features, it does possess some merits because of its simplicity. Even though the estimated uncertainties in the Q values measured in this way are larger than those obtained using more complicated measurement techniques, these uncertainties are still sufficiently small to make the deduced values useful for many applications.

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TABLE VI

MEASURED β^+ ENDPOINT ENERGIES TO THE GROUND AND EXCITED STATES FOR THE DECAYS OF ^{128}Cs AND ^{134}La . THE CORRESPONDING Q VALUES ARE LISTED IN COLUMN 4

<u>Decaying Isotope</u>	<u>Measured Endpoint (keV)</u>		<u>Reported Decay Energy (keV)</u>	<u>Reference</u>
	<u>To Ground State</u>	<u>To 1st Excited State</u>		
^{128}Cs	2994 $\pm$ 120	2566 $\pm$ 120	4023 $\pm$ 85	Present Experiment
			3907 $\pm$ 25	1
	2906 $\pm$ 6	2470 $\pm$ 40	3928 $\pm$ 6	2
^{134}La	2737 $\pm$ 80	2121 $\pm$ 80	3753 $\pm$ 57	Present Experiment
			3720 $\pm$ 25	1

Figure 10. Block diagram of the beta-gamma coincidence system for β endpoint determinations.

B. Development of a 4π β - γ Counting System

R. J. Gehrke, R. A. Coates, M. S. Cole, G. O. English

Accurate measurements of the absolute disintegration rates of radioactive samples, and hence precise γ -ray branching ratios, are needed for many applications including dosimetry for the nuclear industry as well as environmental monitoring. The 4π β - γ coincidence counting technique is one of the most accurate methods of measuring absolute disintegration rates. Our equipment consists of a 4π geometry gas-flow proportional counter to count the beta particles and a 3" x 3" NaI(Tl) scintillation detector to count the γ rays emitted by a source. Figure 11 shows a block diagram of our system. In conjunction with a Ge(Li) spectrometer whose efficiency has been accurately measured, the 4π β - γ coincidence counting system can be used to precisely determine γ -branching ratios of many radionuclides.

Because of our on-going interest in measuring absolute intensities of γ rays (i.e., branching ratios), we have upgraded the electronic equipment of our 4π β - γ coincidence counting system and interfaced it to a PDP-8 computer. The associated PDP-8 computer program controls the scalers of the beta, gamma and coincidence channels, monitors the start and stop times of a run and is programmed to accumulate a sequence of runs. The data from the scalers, along with the time information for each run, are stored on magnetic tape. This program is also capable of performing part or all of the data analysis in the PDP-8.

While source-preparation techniques are being developed, the 4π β - γ counting system has been used to measure the half-lives of short-lived radionuclides (i.e., $T_{1/2} < 3$ d). The above program acquires the data and stores them on magnetic tape. In the IBM 360/75, a nonlinear least-squares fit is made to the data with a function which consists of exponential terms plus a constant background.

Figure 11. Block diagram of 4π β - γ coincidence counting system.

C. Gamma-Ray Spectrometer Systems

1. Gamma-gamma coincidence systems.

R. C. Greenwood, R. J. Gehrke, R. G. Helmer

During the past year, a single-parameter γ - γ coincidence system has been used in several decay-scheme studies. This system uses two large ($\sim 50 \text{ cm}^3$) Ge(Li) detectors in conjunction with timing single-channel analyzers to give a coincidence system which is operated at a resolving time of $\sim 20 \text{ ns}$. A 4096-channel gamma-ray spectrum from one detector is measured in coincidence with those pulses from the other detector which are within a single-channel window.

A two-parameter, computer based coincidence system is under development. This system will allow a 4096 channel x 4096 channel coincidence array to be accumulated. Automatic measurement of the singles spectrum at regular intervals will be provided. This system will have the same coincidence electronics as that used on the present system (above).

2. Traveling gamma-ray spectrometer system.

E. W. Killian, G. O. English, N. C. Dyer, M. S. Cole

In order to make gamma-ray spectrum measurements at LAMPF, a transportable spectrometer system is needed. We have two systems that have been designed for such a purpose. They are generally transported as air freight. One of them has been used successfully at several facilities outside of the INEL. This system consists of a 4069-channel ADC, an 8K, 12-bit-word computer, two cassette-tape units, a full-size tape unit, display scope and printer. This system is programmed to provide some on-line data-analysis capability, including

current status of count-duration clock,

energy of any given channel,

count in any given channel, and

area of a peak.

These routines are valuable for the immediate determination of the isotopes in a sample as well as of the statistical quality of the data; they can operate on a spectrum as it is being accumulated.