Study of Muonic Atoms in the $A = 40 - 70$ and $A = 100 - 130$ Mass Regions
(Nuclear Charge Radii, Isotope and Isotone Shifts)
and in the Sm-Gd and W-Os-Pt Transition Regions
(Electric Monopole and Quadrupole Moments)

MASTER

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ABSTRACT

During the reporting period the muonic X-ray measurements on $^{106,108,110,111,112,113,114,116}\text{Cd}$ and $^{122,124,125,126,128,130}\text{Te}$ have been completed and the data were analyzed in terms of effective Barrett charge radii.

The muonic X-ray spectra of $^{154,155,156,157,158}\text{Gd}$ have been measured with high precision. Special methods were developed to extract "isotopically" clean spectra from the measurements with the "separated" Gd target which contained large amounts of isotopic impurities. The even-A Gd spectra have been analyzed in terms of nuclear monopole and quadrupole parameters and isomer shifts.

Additional studies of the nuclear polarization corrections in muonic ^{208}Pb have been made.

The isomer shift of the excited 2^+ state of ^{204}Pb has been measured: $\Delta E_{\text{iso}} = 1.98 \pm 0.16 \text{ keV}$.

The transfer of muons stopped in liquid hydrogen to Au nuclei contained in thin foils ($30 \mu\text{g}/\text{cm}^2$) that are suspended in the liquid hydrogen has been observed. About 20 times more muonic Au atoms were produced in this LH_2 -Au arrangement as compared to a solid Au target of the same mass.

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1. Introduction

All measurements discussed in this progress report have been performed at the stopped-muon-channel (SMC) of LAMPF at Los Alamos Scientific Laboratory. The Purdue group consists of R. M. Steffen (principal investigator), Dr. Y. Tanaka (postdoctoral research associate), and Dan Laubacher (graduate student). The research work was done in collaboration with the SMC group at Los Alamos (Drs. E. B. Shera, M. V. Hoehn, and D. H. Wohlfahrt).

2. Systematics of Nuclear Charge Distributions in the $1f_{7/2}$ Shell
Nuclei Deduced from Muonic X-Ray Measurements.

With H. D. Wohlfahrt, E. B. Shera and M. V. Hoehn (Los Alamos)

As mentioned in last year's progress report, the muonic X-ray measurements on the isotopes of K, Ca, Sc, Ti, V, Cr, Mn and Fe have been completed some time ago and the data have been analyzed in terms of effective Barrett radii and effective isotope and isotone shifts. In fact, a complete paper discussing these experiments and their analysis has been ready for publication. However, we recently discovered a small discrepancy between our energy measurements of the K^{39} muonic K X-rays and those of the Fribourg group. Even though the discrepancy is small (70 eV), it leads to an error in the nuclear charge radius of about 3 mfm. In view of the high precision we claim for our measurements, it was, therefore, imperative to investigate the source of this discrepancy in detail. Dr. E. B. Shera, in cooperation with the Fribourg group, repeated their experiment at SIN (Switzerland) with the Fribourg set-up and confirmed the existence of a slightly smaller discrepancy (~ 60 eV), which is still serious enough to warrant further investigation.

It was discovered that radiation from the logic-pulse cables (small coaxial cables) affected the linear signals in the cables carrying the muonic X-ray signals somewhat differently than the calibration signal cables. The effect is extremely small (1 in 10^6); nevertheless, it could account for the discrepancy. Proper precautions have been taken to prevent this "radiation" effect and a test experiment is in progress at LAMPF. It should be mentioned that the muonic X-ray measurements

for larger Z-nuclei are not affected by this calibration shift because the calibrations are done also with muonic X-rays from a ^{208}Pb target.

As soon as the test experiments are completed, the necessary corrections will be applied to the $1f_{7/2}$ data and the paper will be published.

3. Systematics of Nuclear Charge Distributions in the

A = 100 to 130 Region.

With H. D. Wohlfahrt, E. B. Shera and M. V. Hoehn

The muonic X-ray measurements on $^{106,108,110,111,112,113,114,116}\text{Cd}$ and $^{122,124,125,126,128,130}\text{Te}$ have been analyzed in terms of effective Barrett radii. Since the Cd-Te muonic X-ray measurements were done with the same energy calibration procedure as the $1f_{7/2}$ measurements, some test experiments will be performed to check the claimed accuracy before the results are published. The small calibration error caused by the "radiation" effect discussed in the preceding section should be much smaller, if at all present, in the Cd-Te measurements. It is expected that these problems will be solved within a few weeks and that the Cd-Te paper is ready for publication in early 1980.

Some separated Pd and Ru isotopes ($^{106,108,110}\text{Pd}$, $^{100,101}\text{Ru}$) have been obtained from Oak Ridge and the muonic X-ray measurements on these targets are in progress at this time (LAMPF run, December 4-10, 1979).

4. Monopole and Quadrupole Charge Distributions in
Transition Nuclei I = Os, Pt, W.

With M. V. Hoehn, Y. Yamazaki*, E. B. Shera and D. Wohlfahrt.

The data of the muonic X-rays of $^{186,188,190,192}\text{Os}$ and $^{194,196,198}\text{Pt}$ have been analyzed and a preliminary draft of the paper has been written. Our measurements of the transition E2 matrix elements of the Os nuclei agree well with the Coulomb excitation measurements. Similarly, our muonic static-quadrupole measurements agree well with Mössbauer effect measurements and with perturbed-angular-correlation measurements. However, in the latter type measurements only ratios of quadrupole moments can be measured reliably. The muonic measurement of the quadrupole moment Q_{22} of the 2^+ state of ^{186}Os does not agree with Coulomb excitation measurements. It should be emphasized, however, that in muonic X-ray measurements a "generalized" quadrupole matrix element is measured, from which the point quadrupole moment Q_{22}^{point} that is observed in Coulomb excitation, must be extracted. This extraction procedure requires knowledge of the quadrupole charge distribution of the 2^+ state. Extensive computer calculations are presently performed to assess the uncertainties involved in this extraction process. The results of these calculations suggest that most "reasonable" nuclear models give very similar results for Q_{22}^{point} which, for ^{186}Os , still deviate from the reported Coulomb excitation value. A careful scrutiny of the limits of the theory of the reorientation effect in Coulomb excitation from which Q_{22}^{point} is deduced, did not reveal any obvious difficulty which could explain the discrepancy between the muonic and Coulomb excitation value of Q_{22}^{point} in ^{186}Os .

The analysis of the W data in terms of nuclear quadrupole and monopole parameters is nearing completion.

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5. Monopole and Quadrupole Charge Distributions in

Transition Nuclei II: Gd

With D. Laubacher, Y. Tanaka, Y. Yamazaki, E. B. Shera, M. V. Hoehn
and D. Wohlfahrt.

The muonic spectra of isotopically enriched $^{154,155,156,157,158,160}\text{Gd}$ targets were measured with excellent precision. Most of the targets contained considerable amounts of isotopic impurities as seen from Table 1. The standard method of correcting for such isotopic impurities is based on a "smoothing" process where the impurity lines are represented by a Gaussian or similar line shape which can easily be parametrized by a few parameters. The impurity lines are then subtracted from the original spectrum. This method works very satisfactorily for spherical nuclei and for targets that contain only even-even transition nuclei. However, if odd-A target nuclei are present, the unresolved complex lines of odd-A muonic spectra make such a parametrization impossible, and hence a point-by-point analysis of the spectra using the actual experimental line shape must be undertaken. This can be done by using the spectra of a complete set of isotopes of interest and impurity isotopes in a matrix algorithm. The relevant matrix equation can be written symbolically

$$[\%] \cdot \begin{bmatrix} ^{154}\text{Gd "pure"} \\ ^{155}\text{Gd "pure"} \\ ^{156}\text{Gd "pure"} \\ \vdots \\ \vdots \end{bmatrix} = [\text{Spec.1, Spec.2, . . .}]$$

where [%] is the "percentage" matrix of Table 1, and Spec.1 is the experimentally determined spectrum of the ^{154}Gd target, etc. Thus,

solving the above matrix equation for the "pure spectrum" eigenvector:

$$\begin{bmatrix} {}^{154}\text{Gd "pure"} \\ \vdots \\ \vdots \end{bmatrix} \text{ gives the desired pure spectra of the various isotopes:}$$

$$\begin{bmatrix} {}^{154}\text{Gd "pure"} \\ \vdots \\ \vdots \end{bmatrix} = [\%]^{-1} [\text{Spec.1, Spec.2, ...}]$$

The inverse of the [%] matrix is shown in Table 2.

Whereas the "standard" methods of analysis resulted in spectrum fits with $\chi_n^2 > 2$, the "matrix" method yielded excellent fits as shown in the following figures. In particular, the ${}^{154}\text{Gd}$ spectrum, which was practically impossible to fit with the "standard" methods because of the large amounts of isotopic impurities (see Table 1), could be cleanly extracted (see Fig. 1) from the raw data.

The "clean" muonic X-ray spectra of the even-A Gd isotopes were least-square fitted using a Lorentzian convoluted Gaussian with a small exponential tail for the peak shapes. The energies and relative intensities of the muonic X-ray peaks for the even-A muonic atoms of Gd are shown in Tables 3 to 6.

Table 1. Enriched Gd - Targets

Gd - Isotopes

Targets		154	155	156	157	158	160
	154	66.53	17.50	7.32	3.24	3.45	1.88
	155	0.38	84.39	12.35	1.36	1.08	0.45
	156	0.38	7.11	82.1	6.61	2.91	0.83
	157	0.09	1.54	4.31	88.63	4.61	0.82
	158	<0.05	0.60	0.76	1.77	95.81	1.06
	160	0.02	0.18	0.33	0.44	0.94	98.10

The "matrix" table shows the amount of the various isotopes in % that are present in the various targets.

Table 2. Inversion of % Matrix

Muonic X-ray Spectra

	Spec 1	Spec 2	Spec 3	Spec 4	Spec 5	Spec 6
Pure						
I	154	1.505407	-0.303788	-0.085741	-0.042932	-0.045860
S	155	-0.005822	1.201484	-0.179887	-0.004637	-0.007610
O	156	-0.006350	-0.101173	1.238863	-0.089930	-0.031845
T	157	-0.001080	-0.015307	-0.056606	1.133873	-0.052545
O	158	-0.000676	-0.006262	-0.007571	-0.020132	1.045134
P	160	-0.000264	-0.001674	-0.003493	-0.004573	-0.009648
E						1.019553
S						

Spec 1 = ¹⁵⁴Gd Target Spectrum
 Spec 2 = ¹⁵⁵Gd Target Spectrum
 Spec 3 = ¹⁵⁶Gd Target Spectrum
 Spec 4 = ¹⁵⁷Gd Target Spectrum
 Spec 5 = ¹⁵⁸Gd Target Spectrum
 Spec 6 = ¹⁶⁰Gd Target Spectrum

154Gd KFE

Fig. 1. Muonic X-ray Spectrum (K-lines, full-energy peaks) of ^{154}Gd obtained with "matrix" method.

156GD KFE

Fig. 2. Muonic X-ray Spectrum (K-lines, full-energy peaks) of ^{156}Gd obtained with "matrix" method.

Fig. 3. Muonic X-ray Spectrum (L-lines, full-energy peaks) of ^{156}Gd obtained with "matrix" method.

158GD KFE

Fig. 4. Muonic X-ray Spectrum (K-lines, full-energy peaks) of ^{158}Gd obtained with "matrix" method.

Fig. 5. Muonic X-ray Spectrum (L-lines, full-energy peaks) of ^{158}Gd obtained with "matrix" method.

Table 3. ^{154}Gd - MUONIC X-RAYS

Transition		Energy(keV)		Intensity	
Initial	Final	Experi- ment	Stat. Error	Experi- ment	Stat. Error
<u>K X-Rays</u>					
$ 0^+ \otimes 2p_{3/2}; F = \frac{3}{2} \rangle$	$ 0^+ \otimes 1s_{1/2}; F = \frac{1}{2} \rangle$	4680.892	0.074	0.26	0.04
$ 2^+ \otimes 2p_{3/2}; F = \frac{3}{2} \rangle$	$ 2^+ \otimes 1s_{1/2}; F = \frac{3}{2} \rangle$	4645.068	0.230	0.06	0.01
$ 2^+ \otimes 2p_{3/2}; F = \frac{1}{2} \rangle$	$ 2^+ \otimes 1s_{1/2}; F = \frac{3}{2} \rangle$	4607.659	0.487	0.03	0.01
$ 0^+ \otimes 2p_{3/2}; F = \frac{3}{2} \rangle$	$ 2^+ \otimes 1s_{1/2}; F = \frac{5}{2} \rangle$	4592.929	0.042	0.69	0.09
$ 0^+ \otimes 2p_{3/2}; F = \frac{3}{2} \rangle$	$ 2^+ \otimes 1s_{1/2}; F = \frac{3}{2} \rangle$				
$ 2^+ \otimes 2p_{1/2}; F = \frac{3}{2} \rangle$	$ 0^+ \otimes 1s_{1/2}; F = \frac{1}{2} \rangle$	4556.327	0.059	0.41	0.06
$ 0^+ \otimes 2p_{1/2}; F = \frac{1}{2} \rangle$	$ 0^+ \otimes 1s_{1/2}; F = \frac{1}{2} \rangle$	4522.203	0.035	1.00	0.02
$ 2^+ \otimes 2p_{1/2}; F = \frac{3}{2} \rangle$	$ 2^+ \otimes 1s_{1/2}; F = \frac{3}{2} \rangle$	4468.420	0.053	0.53	0.07
<u>L X-Rays</u>					
$ 0^+ \otimes 3d_{3/2}; F = \frac{3}{2} \rangle$	$ 0^+ \otimes 2p_{1/2}; F = \frac{1}{2} \rangle$	1678.340	0.070	0.90	0.05
$ 0^+ \otimes 3d_{5/2}; F = \frac{5}{2} \rangle$	$ 2^+ \otimes 2p_{1/2}; F = \frac{3}{2} \rangle$	1623.830	0.050	1.00	0.05
$ 0^+ \otimes 3d_{3/2}; F = \frac{3}{2} \rangle$	$ 2^+ \otimes 2p_{1/2}; F = \frac{3}{2} \rangle$	1607.770	0.190	0.12	0.01
$ 0^+ \otimes 3d_{5/2}; F = \frac{5}{2} \rangle$	$ 0^+ \otimes 2p_{3/2}; F = \frac{3}{2} \rangle$	1536.110	0.070	0.63	0.03
$ 0^+ \otimes 3d_{3/2}; F = \frac{3}{2} \rangle$	$ 0^+ \otimes 2p_{3/2}; F = \frac{3}{2} \rangle$	1519.720	0.290	0.04	0.01
$ 0^+ \otimes 3d_{3/2}; F = \frac{3}{2} \rangle$	$ 2^+ \otimes 2p_{3/2}; F = \frac{1}{2} \rangle$	1468.730	0.310	0.06	0.01

Table 4. ¹⁵⁶Gd - MUONIC X-RAYS

Transition		ENERGY					INTENSITY			
Initial	Final	Experiment	Stat. Error	Total Error	Calculation	DeV	Exp.	Error	Calc.	DeV
<u>K-X-Rays</u>										
$ 0^+ \otimes 2p_{3/2}; F = \frac{1}{2} \rangle$	$ 0^+ \otimes 1s_{1/2}; F = \frac{1}{2} \rangle$	4652.532	0.077	0.164	4652.470	-0.062	0.60	0.04	0.600	0.00
$ 2^+ \otimes 2p_{3/2}; F = \frac{3}{2} \rangle$	$ 2^+ \otimes 1s_{1/2}; F = \frac{3}{2} \rangle$	4637.236	0.251	0.240	4637.454	0.223	0.12	0.02	0.090	-0.03
$ 2^+ \otimes 2p_{3/2}; F = \frac{1}{2} \rangle$	$ 2^+ \otimes 1s_{1/2}; F = \frac{3}{2} \rangle$	4598.925	0.582	0.600	4598.319	-0.606	0.05	0.02	0.06	0.01
$ 0^+ \otimes 2p_{3/2}; F = \frac{3}{2} \rangle$	$ 2^+ \otimes 1s_{1/2}; F = \frac{5}{2} \rangle$	4563.771	0.139	0.199	4563.646	-0.125	0.11	0.02	0.11	0.00
$ 0^+ \otimes 2p_{3/2}; F = \frac{3}{2} \rangle$	$ 2^+ \otimes 1s_{1/2}; F = \frac{3}{2} \rangle$	4563.226	0.139	0.199	4563.101	-0.125	0.36	0.04	0.37	0.01
$ 2^+ \otimes 2p_{1/2}; F = \frac{3}{2} \rangle$	$ 0^+ \otimes 1s_{1/2}; F = \frac{1}{2} \rangle$	4557.214	0.159	0.213	4557.253	0.039	0.43	0.04	0.47	0.04
$ 2^+ \otimes 2p_{1/2}; F = \frac{1}{2} \rangle$	$ 0^+ \otimes 1s_{1/2}; F = \frac{1}{2} \rangle$	4504.084	0.060	0.153	4504.116	0.032	1.00	0.06	1.00	0.00
$ 2^+ \otimes 2p_{1/2}; F = \frac{3}{2} \rangle$	$ 2^+ \otimes 1s_{1/2}; F = \frac{3}{2} \rangle$	4467.813	0.086	0.165	4467.884	0.071	0.61	0.04	0.63	0.03
$ 0^+ \otimes 2p_{1/2}; F = \frac{1}{2} \rangle$	$ 2^+ \otimes 1s_{1/2}; F = \frac{3}{2} \rangle$	4415.093	0.348	0.375	4415.292	0.199	0.11	0.02	0.10	-0.01

Table 4. ^{156}Gd - MUONIC X-RAYS (continued)

Transition		ENERGY					INTENSITY			
Initial	Final	Experiment	Stat. Error	Total Error	Calculation	DeV	Exp.	Error	Calc.	DeV
<u>L-X-Rays</u>										
$ 0^+ \otimes 3d_{3/2}; F = \frac{3}{2} \rangle$	$ 0^+ \otimes 2p_{1/2}; F = \frac{1}{2} \rangle$	1682.662	0.024	0.075	1682.667	0.005	1.00	0.04	1.00	0.00
$ 0^+ \otimes 3d_{5/2}; F = \frac{5}{2} \rangle$	$ 2^+ \otimes 2p_{1/2}; F = \frac{3}{2} \rangle$	1645.624	0.028	0.075	1645.631	0.007	0.80	0.04	0.90	0.10
$ 0^+ \otimes 3d_{3/2}; F = \frac{3}{2} \rangle$	$ 2^+ \otimes 2p_{1/2}; F = \frac{3}{2} \rangle$	1629.414	0.158	0.173	1629.531	0.117	0.08	0.02	0.10	0.02
$ 0^+ \otimes 3d_{5/2}; F = \frac{5}{2} \rangle$	$ 0^+ \otimes 2p_{3/2}; F = \frac{3}{2} \rangle$	1550.419	0.025	0.072	1550.413	-0.006	0.98	0.04	0.90	-0.08
$ 0^+ \otimes 3d_{3/2}; F = \frac{3}{2} \rangle$	$ 0^+ \otimes 2p_{3/2}; F = \frac{3}{2} \rangle$	1534.486	0.137	0.153	1534.313	-0.173	0.11	0.02	0.08	-0.03
$ 0^+ \otimes 3d_{3/2}; F = \frac{3}{2} \rangle$	$ 2^+ \otimes 2p_{3/2}; F = \frac{1}{2} \rangle$	1499.841	0.218	0.228	1499.640	-0.201	0.07	0.02	0.06	-0.01
$ 0^+ \otimes 3d_{5/2}; F = \frac{5}{2} \rangle$	$ 2^+ \otimes 2p_{3/2}; F = \frac{3}{2} \rangle$	1476.700	0.136	0.152	1476.600	-0.100	0.11	0.02	0.08	-0.03

$$\chi^2 = 9.16$$

$$\chi^2 = 20.5$$

$$\chi_n^2 = \frac{\chi^2}{16-5} = 0.83$$

$$\chi_n^2 = \frac{20.5}{16}$$

$$= 1.28$$

Table 5. ¹⁵⁸Gd - MUONIC X-RAYS

Transition		Energy (keV)			Intensity	
Initial	Final	Experiment	Stat. Error	Total Error	Exp.	Stat. Error
<u>K X-Rays</u>						
$ 0^+ \otimes 2p_{3/2}; F = \frac{3}{2} \rangle$	$ 0^+ \otimes 1s_{1/2}; F = \frac{1}{2} \rangle$	4639.844	0.064	0.158	0.67	0.02
$ 2^+ \otimes 2p_{3/2}; F = \frac{3}{2} \rangle$	$ 2^+ \otimes 1s_{1/2}; F = \frac{3}{2} \rangle$	4629.211	0.192	0.239	0.16	0.01
$ 2^+ \otimes 2p_{3/2}; F = \frac{1}{2} \rangle$	$ 2^+ \otimes 1s_{1/2}; F = \frac{3}{2} \rangle$	4590.265	0.300	0.333	0.08	0.01
$ 0^+ \otimes 2p_{3/2}; F = \frac{3}{2} \rangle$	$ 2^+ \otimes 1s_{1/2}; F = \frac{5}{2} \rangle$	4560.645	0.076	0.161	0.15	0.01
$ 0^+ \otimes 2p_{3/2}; F = \frac{3}{2} \rangle$	$ 2^+ \otimes 1s_{1/2}; F = \frac{3}{2} \rangle$	4560.104	0.076	0.161	0.37	0.01
$ 2^+ \otimes 2p_{1/2}; F = \frac{3}{2} \rangle$	$ 0^+ \otimes 1s_{1/2}; F = \frac{1}{2} \rangle$	4539.395	0.102	0.174	0.34	0.01
$ 0^+ \otimes 2p_{1/2}; F = \frac{1}{2} \rangle$	$ 0^+ \otimes 1s_{1/2}; F = \frac{1}{2} \rangle$	4492.539	0.050	0.150	1.00	0.03
$ 2^+ \otimes 2p_{1/2}; F = \frac{3}{2} \rangle$	$ 2^+ \otimes 1s_{1/2}; F = \frac{3}{2} \rangle$	4459.836	0.072	0.157	0.61	0.02
$ 0^+ \otimes 2p_{1/2}; F = \frac{1}{2} \rangle$	$ 2^+ \otimes 1s_{1/2}; F = \frac{3}{2} \rangle$	4413.005	0.311	0.340	0.11	0.01
<u>L X-Rays</u>						
$ 0^+ \otimes 3d_{3/2}; F = \frac{3}{2} \rangle$	$ 0^+ \otimes 2p_{1/2}; F = \frac{1}{2} \rangle$	1684.139	0.026	0.075	0.94	0.02
$ 0^+ \otimes 3d_{5/2}; F = \frac{5}{2} \rangle$	$ 2^+ \otimes 2p_{1/2}; F = \frac{3}{2} \rangle$	1653.179	0.029	0.076	0.73	0.01
$ 0^+ \otimes 3d_{3/2}; F = \frac{3}{2} \rangle$	$ 2^+ \otimes 2p_{1/2}; F = \frac{3}{2} \rangle$	1636.875	0.105	0.126	0.09	0.01
$ 0^+ \otimes 3d_{5/2}; F = \frac{5}{2} \rangle$	$ 0^+ \otimes 2p_{3/2}; F = \frac{3}{2} \rangle$	1552.750	0.026	0.073	1.00	0.02
$ 0^+ \otimes 3d_{3/2}; F = \frac{3}{2} \rangle$	$ 0^+ \otimes 2p_{3/2}; F = \frac{3}{2} \rangle$	1536.496	0.107	1.127	0.10	0.01
$ 0^+ \otimes 3d_{3/2}; F = \frac{3}{2} \rangle$	$ 2^+ \otimes 2p_{3/2}; F = \frac{1}{2} \rangle$	1507.517	0.118	0.136	0.09	0.01
$ 0^+ \otimes 3d_{5/2}; F = \frac{5}{2} \rangle$	$ 2^+ \otimes 2p_{3/2}; F = \frac{3}{2} \rangle$	1483.918	0.097	0.118	0.11	0.01

Table 6. ^{160}Gd - MUONIC X-RAYS

Transition		Energy(keV)		Intensity	
Initial	Final	Experi- ment	Stat. Error	Experi- ment	Stat. Error
<u>K X-Rays</u>					
$ 0^+ \otimes 2p_{3/2}; F = \frac{3}{2} \rangle$	$ 0^+ \otimes 1s_{1/2}; F = \frac{1}{2} \rangle$	4630.255	0.097	0.68	0.01
$ 2^+ \otimes 2p_{3/2}; F = \frac{3}{2} \rangle$	$ 2^+ \otimes 1s_{1/2}; F = \frac{3}{2} \rangle$	4621.913	0.403	0.13	0.02
$ 2^+ \otimes 2p_{3/2}; F = \frac{1}{2} \rangle$	$ 2^+ \otimes 1s_{1/2}; F = \frac{3}{2} \rangle$	4581.402	0.182	0.10	0.01
$ 0^+ \otimes 2p_{3/2}; F = \frac{3}{2} \rangle$	$ 2^+ \otimes 1s_{1/2}; F = \frac{5}{2} \rangle$	4554.961	0.053	0.52	0.01
$ 0^+ \otimes 2p_{3/2}; F = \frac{3}{2} \rangle$	$ 2^+ \otimes 1s_{1/2}; F = \frac{3}{2} \rangle$				
$ 2^+ \otimes 2p_{1/2}; F = \frac{3}{2} \rangle$	$ 0^+ \otimes 1s_{1/2}; F = \frac{1}{2} \rangle$	4525.758	0.075	0.32	0.01
$ 0^+ \otimes 2p_{1/2}; F = \frac{1}{2} \rangle$	$ 0^+ \otimes 1s_{1/2}; F = \frac{1}{2} \rangle$	4481.986	0.038	1.00	0.01
$ 2^+ \otimes 2p_{1/2}; F = \frac{3}{2} \rangle$	$ 2^+ \otimes 1s_{1/2}; F = \frac{3}{2} \rangle$	4450.464	0.048	0.63	0.01
$ 0^+ \otimes 2p_{1/2}; F = \frac{1}{2} \rangle$	$ 2^+ \otimes 1s_{1/2}; F = \frac{3}{2} \rangle$	4407.146	0.234	0.13	0.01
<u>L X-Rays</u>					
$ 0^+ \otimes 3d_{3/2}; F = \frac{3}{2} \rangle$	$ 0^+ \otimes 2p_{1/2}; F = \frac{1}{2} \rangle$	1685.198	0.014	0.98	0.01
$ 0^+ \otimes 3d_{5/2}; F = \frac{5}{2} \rangle$	$ 2^+ \otimes 2p_{1/2}; F = \frac{3}{2} \rangle$	1657.496	0.017	0.07	0.01
$ 0^+ \otimes 3d_{3/2}; F = \frac{3}{2} \rangle$	$ 2^+ \otimes 2p_{1/2}; F = \frac{3}{2} \rangle$	1641.464	0.075	0.10	0.01
$ 0^+ \otimes 3d_{5/2}; F = \frac{5}{2} \rangle$	$ 0^+ \otimes 2p_{3/2}; F = \frac{3}{2} \rangle$	1553.109	0.014	1.00	0.01
$ 0^+ \otimes 3d_{3/2}; F = \frac{3}{2} \rangle$	$ 0^+ \otimes 2p_{3/2}; F = \frac{3}{2} \rangle$	1536.909	0.083	0.09	0.01
$ 0^+ \otimes 3d_{3/2}; F = \frac{3}{2} \rangle$	$ 2^+ \otimes 2p_{3/2}; F = \frac{1}{2} \rangle$	1511.097	0.081	0.10	0.01
$ 0^+ \otimes 3d_{5/2}; F = \frac{5}{2} \rangle$	$ 2^+ \otimes 2p_{3/2}; F = \frac{3}{2} \rangle$	1486.585	0.073	0.11	0.01

Using the muonic X-ray energies as shown in Tables 3 - 6, the Gd data were analyzed in terms of the nuclear monopole and quadrupole charge parameters by a least-square-fit. The methods employed in this analysis have been discussed in previous Progress Reports and in Ref.1. The results are shown in Table 7. As an example, the computed data are shown in Table 4 together with the experimental results. The errors quoted for the experimentally extracted "point" quadrupole parameters do not include possible model-dependent contributions to the extraction process. Such effects are presently under investigation. Also, the isomer shifts have not been corrected yet for the small magnetic splitting effects in the 2^+ state.

Table 8 shows a comparison of our quadrupole data with the predictions of the rotation-vibration coupling model of Faessler and Greiner and of the rigid triaxial rotor model of Davydov and Filippov. The general trends in the $^{154}\text{Gd} - ^{160}\text{Gd}$ chain are reasonably well predicted by these models. However, the models cannot account for the detailed quantitative trends. This is especially true for the R(22;02) ratio.

1. Yamazaki, Shera, Hoehn and Steffen, Phys. Rev. C18, 1474 (1978).

Table 7. Nuclear Monopole and Quadrupole Charge Parameters

Extracted from the Muonic X-Ray Spectra

Parameter	Gd - Nuclei			
	154	156	158	160
c(fm.)	5.955 ± 0.007	5.980 ± 0.002	6.014 ± 0.012	6.038 ± 0.001
a(fm.)	0.531 ± 0.004	0.522 ± 0.001	0.514 ± 0.007	0.506 ± 0.003
β_2	0.268 (fixed)	0.280 (fixed)	0.329 (fixed)	0.337 (fixed)
β_4	0.130 (fixed)	0.064 (fixed)	0.016 (fixed)	0.016 (fixed)
$B(F2; 0^+ \rightarrow 2^+) e^2 b^2$	3.952 ± 0.007	4.686 ± 0.005	5.287 ± 0.027	5.357 ± 0.012
$Q(2^+) \text{ eb}$	-1.875 ± 0.012	-1.962 ± 0.005	-2.037 ± 0.015	-2.130 ± 0.008
Isomer Shift(keV)	0.899 ± 0.113	0.186 ± 0.077	-0.729 ± 0.352	-1.06 ± 0.58
R(22;02)	1.041 ± 0.006	1.000 ± 0.002	0.978 ± 0.006	1.016 ± 0.004

Table 8: Experimental and Calculated B(E2) and Quadrupole moments for the first 2^+ States in Gd Isotopes.

Nucleus	Model	β γ	Q (e.barn)	B(E2; $0^+ \rightarrow 2^+$) (e^2 barn 2)	R(22;02) ¹⁾
<u>^{154}Gd</u>	Exp.		-1.875(12)	3.957(07)	1.041(06)
	Cal.1 ²⁾	0.281	-1.812	3.952	1.006
	Cal.2 ³⁾	0.294	-1.768	3.907	0.987
		14°			
<u>^{156}Gd</u>	Exp.		-1.962(05)	4.686(05)	1.000(02)
	Cal.1	0.306	-1.961	4.695	0.999
	Cal.2	0.314	-1.955	4.705	0.995
		11°			
<u>^{158}Gd</u>	Exp.		-2.037(15)	5.287(27)	0.978(06)
	Cal.1	0.323	-2.087	5.335	0.997
	Cal.2	0.329	-2.084	5.325	0.997
		10°			
<u>^{160}Gd</u>	Exp.		-2.130(08)	-5.357(12)	1.016(04)
	Cal.1	0.325	-2.108	5.481	0.994
	Cal.2	0.333	-2.123	5.534	0.996
		11°			

1) $R(22;02) = \langle 2^+ || r^2 Y_2 || 2^+ \rangle / \sqrt{\langle 2^+ || r^2 Y_2 || 0^+ \rangle}$

2) The rotation-vibration coupling model of Faessler and Greiner. The β - and γ -vibrations are taken into account.

3) The triaxial rotor model of Davydov and Filippov.

6. Muonic Spectra of Odd-A Isotopes

With D. Laubacher, Y. Yamazaki, Y. Tanaka, E. B. Shera,
M. V. Hoehn and H. D. Wohlfahrt.

As discussed in Progress Report No. 3, the complex, partially unresolved, muonic spectra of odd-A isotopes can be analyzed in terms of the nuclear parameters of the low-lying nuclear states, if the total muonic spectra of an isotope are directly analyzed in terms of nuclear parameters. Such an analysis requires that a very well measured and clean muonic spectrum of the odd-A muonic atom is available.

We measured the muonic spectra of ^{155}Gd and ^{157}Gd with a high precision. However, a fair amount of the even-A Gd isotopes in the target material requires first an exact knowledge of the even-A Gd impurity spectra before a proper subtraction procedure can be applied. As discussed in the preceding section, even the extraction of clean even-A Gd spectra from an actual measurement is not a trivial matter. The even-A Gd muonic spectra are now well known (see Figures in the preceding section) and their contribution to the odd-A Gd spectra can now be properly subtracted. As soon as the clean odd-A Gd spectra have been constructed they will be analyzed in the manner discussed in Section 6 of Progress Report No. 3.

7. Nuclear Polarization Corrections in Muonic ^{208}Pb

With Y. Tanaka

The coupling of a bound muon with various nuclear excited states gives rise to a line shift as well as a line broadening in the muonic X-ray spectrum. The former is called the nuclear polarization effect and its theoretical estimation involves a considerable uncertainty. This uncertainty is much greater than the experimental accuracy. However, until recently, it was not a subject of serious attention. The uncertainty could always be compromised with the uncertainty of the nuclear charge density distribution.

Quite recently, however, the charge density distribution of ^{208}Pb was accurately determined by electron scattering experiments and this information enabled us to determine the nuclear polarization correction from experiment (see reprint in Appendix). Surprisingly, no theoretical calculation so far reported is found to agree with experiment. Since the calculated nuclear polarization correction has always been the basis in extracting all the nuclear information available in the muonic X-ray analysis, this discrepancy between theory and experiment is sufficiently serious to deserve serious attention.

The nuclear polarization correction was calculated using the latest experimental results for the relevant nuclear states as well as the most probable transition charge densities for those states. Results are given in black triangles in Fig. 1. The shaded area in each figure is the nuclear polarization determined from experiment. Some improvement may be noticed when the present calculation is compared with our previous one (denoted by the open and black circles and the square). This

improvement is mainly due to three low lying 1^- states now taken into account. However, the discrepancy between theory and experiment is still obvious.

Meanwhile, we also found that there seems to be a similar discrepancy in the muonic d states. Since these d states are usually well calculated in other nuclei, we are now examining the experimental binding energies of these states.

Fig. 1: Calculated Nuclear Polarizations in ~~the~~ Muonic ^{208}Pb .

8. Isomer Shift of the First Excited 2^+ State in Muonic ^{204}Pb

With M. V. Hoehn, E. B. Shera, H. D. Wohlfahrt and Y. Yamazaki

An experiment was performed to search for evidence of the $2^+ \rightarrow 0^+$ nuclear gamma-ray transition in the muonic spectrum of ^{204}Pb . The 2^+ state of ^{204}Pb was expected to be populated via a muonic-nuclear resonance involving the $4f_{7/2}$ muonic state coupled to the nuclear ground state and the $3p_{3/2}$ muonic state coupled to the nuclear 2^+ state. An additional population mechanism was expected through a $3^- \rightarrow 2^+$ gamma-ray transition following resonance excitation of the 3^- state at 2.6 MeV. The 3^- is in approximate resonance with the muonic $3d$ - $2p$ transitions. The two effects should give an excitation probability of the 2^+ state of about 5 percent (relative to the intensity of the muonic $3d_{5/2} - 2p_{3/2}$ transition).

The nuclear gamma ray, corresponding to the nuclear $2^+ \rightarrow 0^+$ transition in ^{204}Pb was indeed found and its energy was determined

$$E_{\gamma}^{\mu} = 897.17 \pm 0.13 \text{ keV}$$

The relative intensity of the nuclear gamma transition was determined to be 0.051 ± 0.010 relative to the intensity of the muonic $3d_{5/2} - 2p_{3/2}$ transition.

A comparison with the "normal" gamma-ray energy

$$E_{\gamma}^0 = 899.15 \pm 0.10 \text{ keV}$$

of ^{204}Pb $2^+ \rightarrow 0^+$ transition, yields an isomer shift of the nuclear E2 transition of

$$\Delta E_{\text{iso}} = 1.98 \pm 0.16 \text{ keV}$$

The magnetic splitting correction ($\delta E_{\text{mag}} < 0.07 \text{ keV}$) and the nuclear polarization is not included in this result.

The ^{204}Pb measurements were reported at the Vancouver Meeting (August 1979). A copy of the paper, to be published in the Proceedings of the International Conference of High-Energy and Nuclear Physics, Vancouver, 1979, is included in the Appendix.

9. Transfer of Muons in Liquid Hydrogen

Considerable progress was made in our study of the transfer probability of muons that are stopped in liquid hydrogen to solid targets which are suspended in the liquid hydrogen. The experiment was run in the Stopped-Muon-Channel West in July 1979. The liquid hydrogen cell used in this experiment has been described in Progress Report 3. However, instead of using a LAMPF refrigerator for the cooling of the LH_2 , a surplus LH_2 dewar was modified to use with our cell. This modification resulted in a considerable simplification in the running of the experiment and greatly reduced the set-up time inside the SMC. Since there was great demand for the SMC at LAMPF during the summer months, efficient use of the allotted time in the SMC was essential. The modified arrangement worked very satisfactorily. The LH_2 remained in the supply dewar that was connected to the LH_2 cell for more than 12 hours and hence transfer of LH_2 from the main LH_2 supply tank was only infrequently required. A schematic diagram of the LH_2 supply to the target is shown in Fig. 1.

With the gold target distributed on 80 mylar foils, each being plated with a $30 \mu\text{g}/\text{cm}^2$ Au layer on one side of the foil and the foils immersed in liquid hydrogen, we observed an enhancement factor of

$$E \simeq 20 \pm 5$$

which is close to the estimated value, that is quoted in Progress Report 2.

(November 1977)

Unfortunately the LAMPF run was not long enough to get satisfactory statistics on all muonic X-ray lines of gold. It would be of considerable interest to measure the relative intensities of the K-, L-, M-, and N-lines precisely and to compare these intensity ratios with those obtained from an ordinary Au - metal target. Also, it would be of interest to record a time-spectrum of the Au-muonic X-rays emitted from the Au-foil in the liquid hydrogen bath to gain information about the diffusion process of the $p-\mu$ system in the liquid hydrogen. Such experiments are planned.

In the course of our measurements an unexpected effect was discovered which may be of considerable interest. In addition to muonic X-rays from Au, a rather strong 350 keV gamma line was observed. This gamma line can be interpreted as the $2^+ \rightarrow 0^+$ gamma line from ^{196}Pt which can be produced from a (μ, n) muon capture in ^{197}Au . With an ordinary Au target the intensity of this ^{196}Pt line relative to the muonic $5g_{9/2} \rightarrow 4f_{7/2}$ transition is 0.52 ± 0.3 , whereas in the LH_2 muon transfer experiment the intensity ratio was 3.7 ± 0.7 . This effect will be further investigated.

Fig. 1

10. List of Publications

November 15, 1978 - November 30, 1979

1. Model-Independent Analysis of the Muonic X-Rays of ^{194}Pt .
M. V. Hoehn, E. B. Shera, H. D. Wohlfahrt, Y. Yamazaki, and
R. M. Steffen. Bull. Am. Phys. Soc. 24, 53 (1979).
2. Discrepancy between Theory and Experiment in Nuclear Polarization Corrections of Muonic ^{208}Pb . Y. Yamazaki, H. D. Wohlfahrt, E. B. Shera, M. V. Hoehn, and R. M. Steffen.
Phys. Rev. Letter 42, 1470 (1979).
3. The Spin-Expansion Hamiltonian and Quadrupole Moments of the Even Os Nuclei. Y. Yamazaki, E. B. Shera, M. V. Hoehn, H. D. Wohlfahrt, and R. M. Steffen. Journal of Physical Society (Japan).
4. Isomer Shift of the First Excited 2^+ State in Muonic ^{204}Pb .
M. V. Hoehn, E. B. Shera, H. D. Wohlfahrt, R. M. Steffen, and Y. Yamazaki. Proceedings of the International Conference on High Energy and Nuclear Physics, Vancouver, B.C. To Be Published.

11. Personnel and Percentage of Effort

Principal Investigator

R. M. Steffen, Professor of Physics

Percentage of Effort: 25% Academic Year;

100% - 3 Summer Months.

Research Associates

Dr. Y. Yamazaki

Percentage of Effort: 100%; termination of appointment

March 30, 1979.

Dr. Y. Tanaka

Percentage of Effort: 100%, starting date, June 15, 1979.

Graduate Student

Dan Laubacher

Percentage of Effort: 100%, whole year.

12. Appendix

Reprints and Preprints of Papers published in 1979.