MASTER

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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)

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Abstract

During the reporting period the work on the "Nuclear Charge distributions in $1f_{7/2}$-Shell Nuclei from Muonic X-Ray Measurements" has been completed and the paper has been printed (Phys. Rev. C 23 (1980)).

The muonic x-ray spectra of the stable Ru and Pd isotopes have been measured and the data have been analyzed in terms of the effective Barrett radii and in terms of isotope shifts. The effects of the neutron subshell closure on the $\Delta N = 2$ isotope shifts at $N = 56$ is much smaller in the Ru ($Z = 44$) isotopes as compared to the recently observed effect in the Mo ($Z = 42$) isotope shifts. This is the first time a pronounced difference in $\Delta N = 2$ isotope shifts has been observed for different values of Z.

The muonic x-ray measurements on 24 stable isotopes of Cd, Sn, Te, and Ba have been completed and the analysis of the 74 spectra (including calibration spectra) is progressing.

The work on the quadrupole parameters of the even-A Os nuclei has been completed.

The analysis of the muonic x-ray spectra of the even-A Gd isotopes is near completion. Monopole and quadrupole charge parameters of the 0_g^+ and 2_g^+ states (and in the case of ^{160}Gd, of the 3^- state) have been determined.

The model dependence of extracting point-quadrupole matrix elements from muonic x-ray measurements has been carefully investigated. It was found that neither the β-vibration nor the γ-vibration modes incluence the value of the extracted point moments by more than 2 percent.

Further attention was paid to the whole problem of nuclear polarization corrections.

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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 H. D. Wohlfahrt).

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

H. D. Wohlfahrt, E. B. Shera, M. V. Hoehn, Y. Yamazaki* and R. M. Steffen.

Abstract of paper (in print) Phys. Rev. C. Vol. 23.

Precise 2p - 1s muonic x-ray transition energies and energy shifts were measured for the $1f_{7/2}$-shell nuclei $^{39,41}K$, $^{40,42,43,44,46,48}Ca$, ^{45}Sc, $^{46,47,48,49,50}Ti$, ^{51}V, $^{50,52,53,54}Cr$, ^{55}Mn, and ^{56}Fe. The data were analyzed in terms of the Barrett moments $\langle r^k e^{-\alpha r}\rangle$ of the nuclear charge distribution, from which equivalent nuclear radii R_k and isotopic and isotonic differences ΔR_k were computed. For those nuclei for which electron-scattering data were available, model-independent rms radii and radius differences were deduced from a combined analysis of the present data and elastic electron-scattering data. The $\Delta N = 2$ isotope shifts between even-A nuclei decrease nearly linearly with increasing N and become negative in the second half ($24 \leq N \leq 28$) of the $1f_{7/2}$ shell; a strong shell-closure effect is evident at N = 28. The isotope shifts are independent of Z, suggesting that the added neutrons interact with the entire proton core rather than with the valence protons. The $\Delta Z = 2$ isotone shifts between even-A nuclei decrease smoothly and uniformly with increasing Z for $20 \leq Z \leq 28$ and are essentially independent of N. Like the isotope shifts, the isotone shifts display a sudden increase at Z = 28. Both the $\Delta N = 1$ isotope shifts and the $\Delta Z = 1$ isotone shifts show pronounced

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odd-even staggering. A strong correlation is found between nuclear deformation, as revealed by experimental B(E2) values, and the measured isotope and isotone shifts. The measured isotope and isotone shifts, including those for odd-A nuclei, are satisfactorily described by a simple empirical formula. The experimental results were compared with Hartree-Fock calculations; some recent calculations that include ground-state correlations display improved agreement with experiment through the inclusion of these deformation-related effects.

3. Systematics of Nuclear Charge Radii in the A = 100 to 130 Region.

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

The muonic x-ray spectra of ^{98,99,100,101,102,104}Ru and ^{102,104,105,106,108,110}Pd, have been measured in the stopped-muon-channel of LAMPF. The analysis of the data is not yet completely finished, but some important trends of the isotope shifts are already in evidence.

As discussed in previous progress reports our systematic investigation of nuclear charge radii R_k in the A = 19 to A = 60 region clearly indicates the following trends. The $R_k = r_o A^{1/3}$ behavior, expected on the basis of the liquid drop model, is strongly modified by nuclear shell structure. The $\Delta N = 2$ isotope shifts are largest at the beginning of a neutron shell and become small (or even negative) just before the shell closure. As a new shell begins a sudden increase of the nuclear charge radius is observed; this phenomenon has been observed at N = 20, 28, 50, 82 and 126. The remarkable feature observed in these muonic x-ray experiments is that the measured $\Delta N = 2$ isotope shift values are essentially independent of Z.

Preliminary results of the Mainz-Fribourg-LASL collaboration at SIN indicated a sudden increase of the isotope shifts in Mo at N = 56 indicating the existence of a subshell closure at the end of the $2d_{5/2}$ shell. In these studies only one single isotope, i.e., ^{100}Mo, lies above the postulated N = 56 shell closure.

Our measurements on the Ru isotopes involved the isotopes with N = 54, 55, 56, 57, 58 and 60, those on Pd included N = 56, 58, 59, 60, 62 and 64. No sudden increase of the $\Delta N = 2$ isotope shift was observed at N = 56. In fact the isotope shift for the $^{98-100}_{44}$Ru pair seems to be somewhat larger than the isotope shift of the $^{100-102}_{44}$Ru pair. Similarly,

the observed isotope shifts in the Pd-isotopes fall on the smooth monotonously decreasing curve (for increasing N) that is characteristic for nuclei with $50 < N < 82$.

The extraction of very accurate values for the Barrett-charge radii R_k is still somewhat hampered by the uncertainties in the calculation of the nuclear polarization corrections. In particular the determination of even-odd staggering effects in the isotope shifts requires a re-examination of the nuclear polarization-correction differences for even-A and odd-A muonic atoms. The corrections for the latter are systematically smaller than those for even A muonic atoms. There may be valid physical reasons (blocking effects? different transition-charge distribution?) for this difference. Nevertheless the differences are larger than one may expect. A careful study of this effect is planned (see Renewal proposal).

The x-ray measurements on the muonic atoms of $^{106,108,110,111,112,113,114,116}Cd$, $^{118,120,122}Sn$, $^{120,122,123,124,125,126,128,130}Te$ and $^{134,135,136,137,138}Ba$ have been completed sometime ago and the analysis of the data in terms of equivalent Barrett radii of the nuclear charge distributions is still in progress. Together with the calibration spectra the evaluation involves the analysis of 74 muonic x-ray and gamma ray spectra, a formidable task indeed.

In contrast to the muonic x-ray measurements in the A = 60 region it is possible in the A > 100 region to determine not only the charge radii of the nuclei but also the skin-thickness of the nuclear charge distribution. This is possible because the charge moments $\langle n'j'||r^k e^{-\alpha r}||nj\rangle$ of the $2p \rightarrow 2s_{1/2}$ muonic transitions ($k \approx 2.2$) are quite different from those of the $3d_{5/2} \rightarrow 2p_{3/2}$ transitions ($k \approx 3.0$) and of the $3d_{3/2} \rightarrow 2p_{3/2}$ transitions

($k \approx 4.1$). Hence, both the charge radius and the skin thickness can be treated as "independent" unknown parameters in the solution of the Dirac equation for the muonic states. On the basis of a preliminary analysis the nuclear charge radii can be determined with an accuracy of $\pm 10^{-18}$ m and the skin thickness can be obtained with about a 1 percent accuracy.

In addition, the $2p \rightarrow 2s_{1/2}$ transition energies could, in general, be observed with an error of only about $\pm$ 30 eV. These data are of particular importance for a check of the nuclear polarization corrections.

It is planned to complete the analysis of the muonic spectra of the 24 nuclei Cd-Sn-Te-Ba chain in the coming project period.

4. Monopole and Quadrupole Charge Parameters in Transition Nuclei I: The Os-Pt Region.

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

The muonic x-ray data of the even-A Os and Pt isotopes have been analyzed for some time and a preliminary draft of the Os paper was included in last year's Progress Report. All the muonic quadrupole data agree very well with the Coulomb excitation data, except the quadrupole moment of the first excited 2^+ state of ^{192}Os which deviates by 30 percent. Because the structure of the ^{192}Os nucleus indicates a strong presence of the γ-vibrational mode, it was decided to investigate the influence of the γ-vibrations on the extraction of quadrupole parameters from muonic x-ray measurements. (For details see Section 7 of this Progress Report.) It was found that the influence of the γ-vibrations affects the extracted point value of the nuclear quadrupole moment by at most 2 percent. Thus the discrepancy between the muonic x-ray measurements and the Coulomb excitation results in ^{192}Os remains unexplained. The Os-paper is being revised and the results of the γ-vibration calculations are being included.

5. Monopole and Quadrupole Charge Parameters in Transition Nuclei II: The Even-A Gd Series.

D. Laubacher

The analysis of the muonic x-ray data for the gadolinium nuclei A = 154, 156, 158, and 160 is almost completed and a paper describing the results is in progress.

The many difficulties involved in the analysis of the even-A gadolinium data have been overcome, and provide some generally useful methods for future muonic x-ray research.

The general impurity problems involved with separated isotopes causing difficulties with our high precision measurements seem to have been solved by the use of the % matrix diagonalization method. (See last year's Progress Report No. 4.) This method was tested for the slightly impure (15%) case of ^{156}Gd. The experimental spectrum shows no obvious impurity effects (see Figure 1). Yet, when the energy centroids from this spectrum are used in our analysis, difficulties occur. The χ^2 of the theoretical energies fit was more than two times larger than those for any other gadolinium nuclei. The spectrum extracted using the % diagonalization method, while not visibly different, provided precise energy centroids whose fit χ^2 was on the order of those for the other nuclei. Also, the fitted charge parameters: quadrupole moment of the 2_g^+ state, $B(E2;0_g^+ \rightarrow 2_g^+)$ and isomer shift seem to be more in line with the systematics of the other nuclei.

The % diagonalization method, when applied to the very impure (35%) ^{154}Gd spectrum yields similarly satisfactory results (see Figure 2). As is seen, the 4646.026 keV line appears with good lineshape from a part

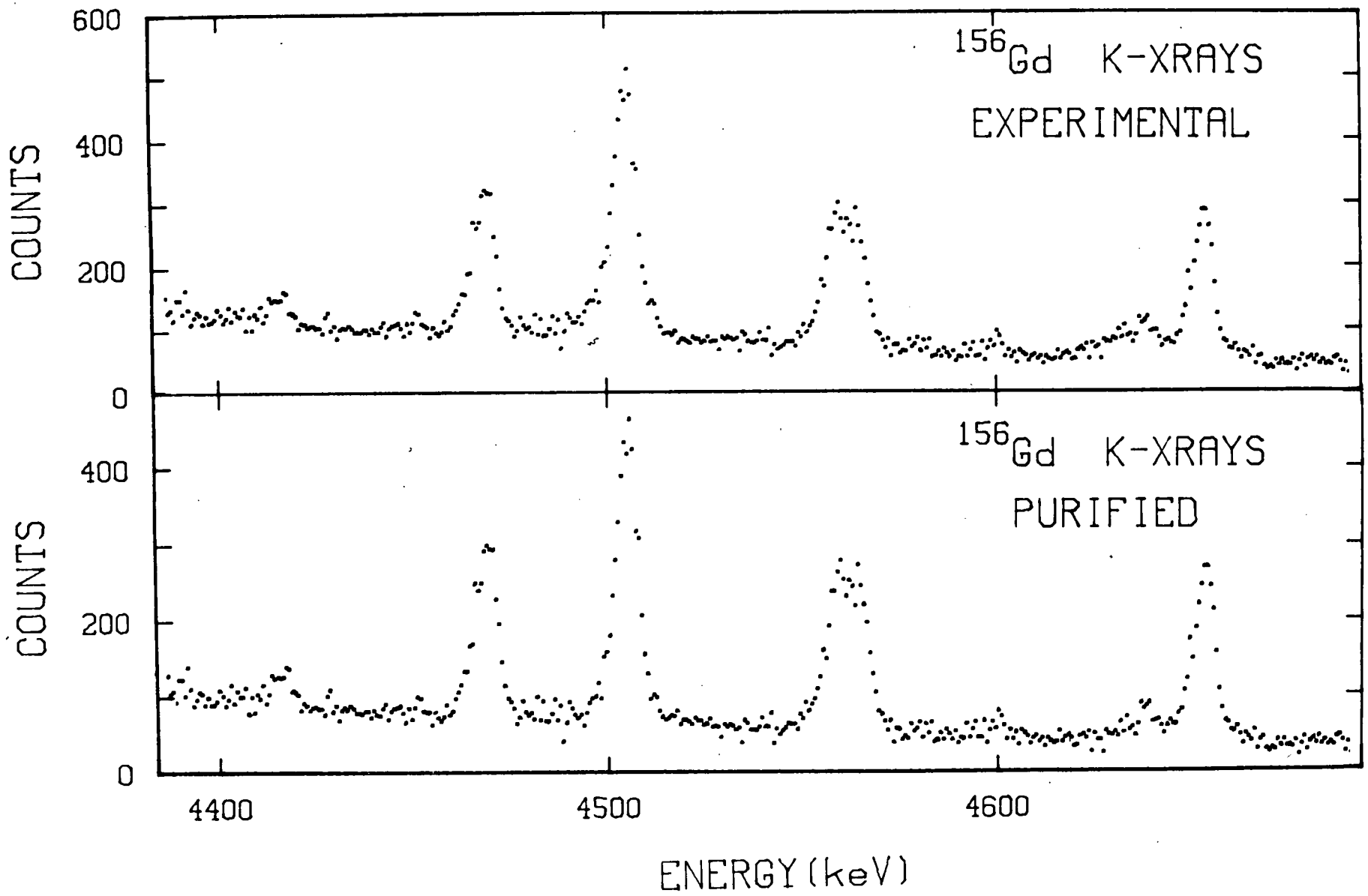

Figure 1: Measured Muonic X-Ray Spectrum of "^{156}Gd" Target (upper part) and the Extracted Spectrum (lower part)

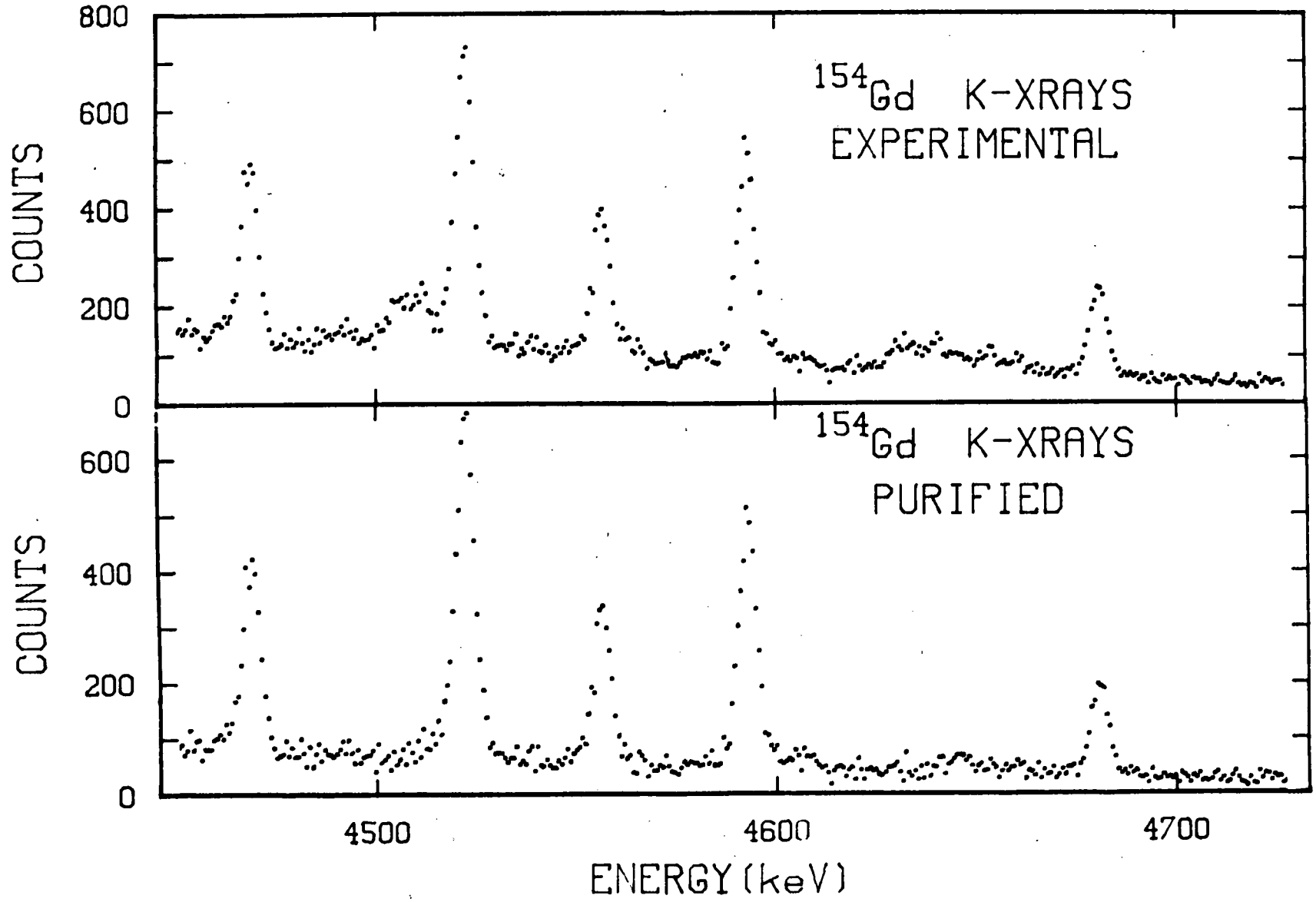

Figure 2: Measured Muonic X-Ray Spectrum of "^{154}Gd" Target (upper part) and the Extracted Spectrum (lower part)

of the spectrum where the impurity contamination is worse. After careful analysis of this isotope, the fit χ^2 is comparable to those of the other nuclei and the systematics are again satisfactory.

As with some other nuclei (e.g., ^{208}Pb) a near degeneracy between a particular $3^- \otimes 2p_{3/2}$ state and the $0_g^+ \otimes 3d_{5/2}$ state appears in the case of ^{160}Gd. While the resultant mixing does not dramatically change the resultant experimental spectrum, it does have the effect of raising the $0_g^+ \otimes 3d_{5/2}$ state by approximately 75 eV. This value was arrived at by an advance in the analysis code allowing the nuclear polarization effect or simply an addition to the energy of a particular muonic state in our model space to be fit in a least-squares method. The effect on the states involved can now be directly treated. Combining this new knowledge with previously measured nuclear parameters, the quadrupole moment of this 3^- state can be calculated; a preliminary value of $Q_{3^-} = -0.5 \pm 0.2$ b has been obtained.

Table 1 presents a summary of the monopole and quadrupole parameters of the even-A Gd isotopes that have been determined so far.

Table 1: Monopole and Quadrupole Charge Distribution Parameters From Muonic Atoms.

	Mass Number			
	154	156	158	160
c(fm)	5.967(17)	5.983(16)	5.978(16)	5.989(18)
a(fm)	0.520(11)	0.518(11)	0.526(11)	0.532(11)
β_2	0.268(fixed)	0.312(fixed)	0.329(fixed)	0.337(fixed)
β_4	0.130(fixed)	0.055(fixed)	0.049(fixed)	0.016(fixed)
Isomer Shift(keV)	0.971(80)	0.213(125)	0.160(81)	-0.142(55)
$B(E2;0_g^+\rightarrow 2_g^+)(e^2b^2)$	4.128(5)	4.764(5)	5.049(5)	5.304(5)
$Q(2_g^+)$(eb)	-1.911(8)	-1.972(5)	-2.025(4)	-2.092(4)
$\Delta E_{M1}(2_g^+\times 1s_{1/2})$(keV)	0.708(400)	0.713(262)	0.477(152)	0.618(91)

6. Muonic Spectra of Odd-A Nuclei.

With D. Laubacher and Y. Tanaka.

Using the methods described in Progress Report No. 4 (1979) clean x-ray spectra of muonic ^{155}Gd and ^{157}Gd were extracted from the measured Gd spectra. These spectra contained a considerable amount (several percent; up to 17.5 percent) of muonic x-rays from the even-A Gd isotopes. Since the even-A Gd spectra have been precisely determined, an accurate extraction of the odd-A Gd spectra was possible. Using the lineshape information obtained from the even-A Gd analysis, preliminary calculations yield good general agreement for the muonic M lines. (See Figures 3 and 4.) The resolved splitting is mainly due to the quadrupole moment of the ground state ($I^{\pi} = 3/2^{-}$). Satisfactory calculations for the ground state quadrupole moments will be forthcoming once understandings of M1 effects on hyperfine splitting and relative intensities of the many unresolved lines is made (16 lines with $I > 1.5\%$).

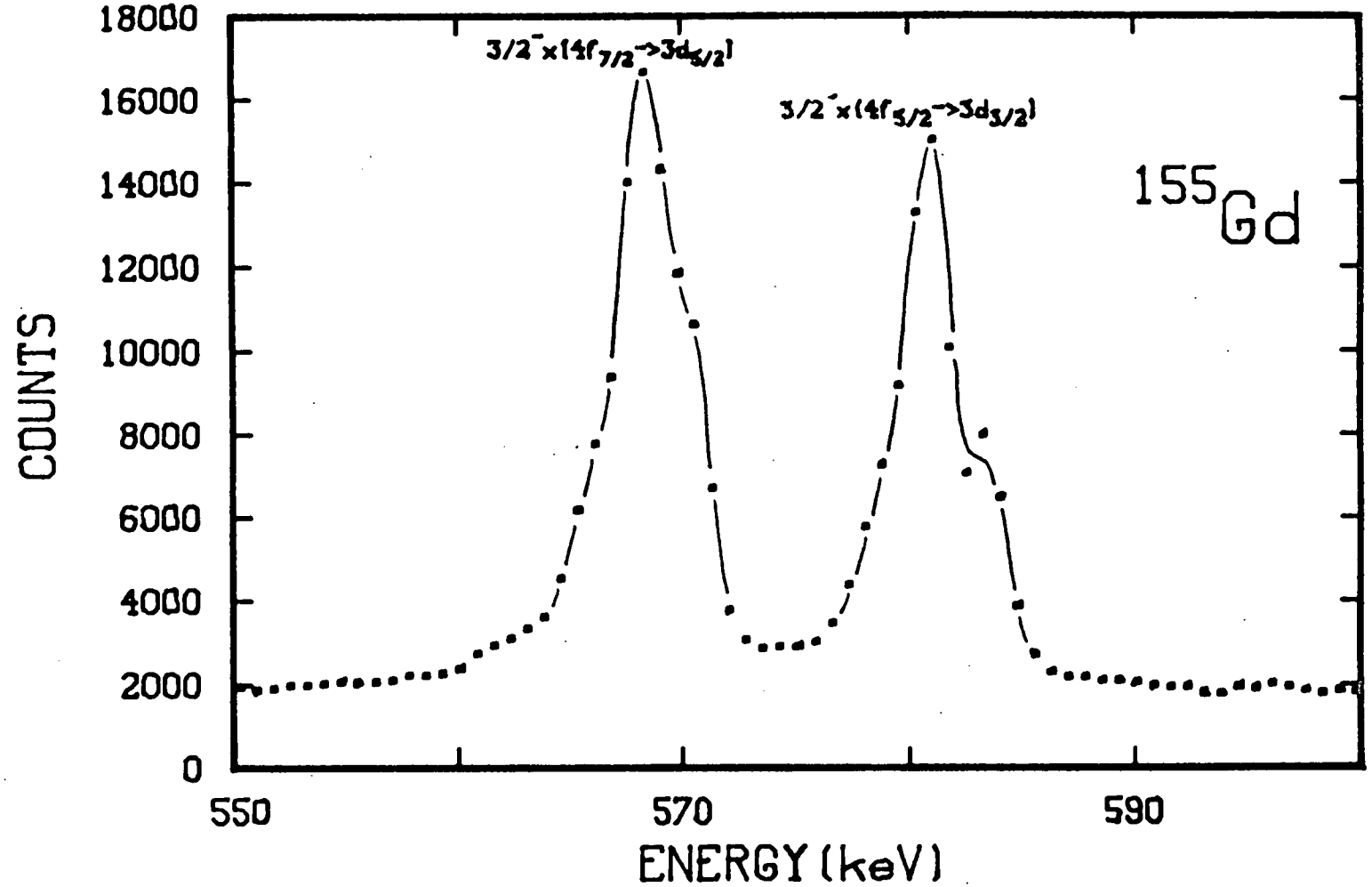

Figure 3: Observed Muonic M - Lines of ^{155}Gd.

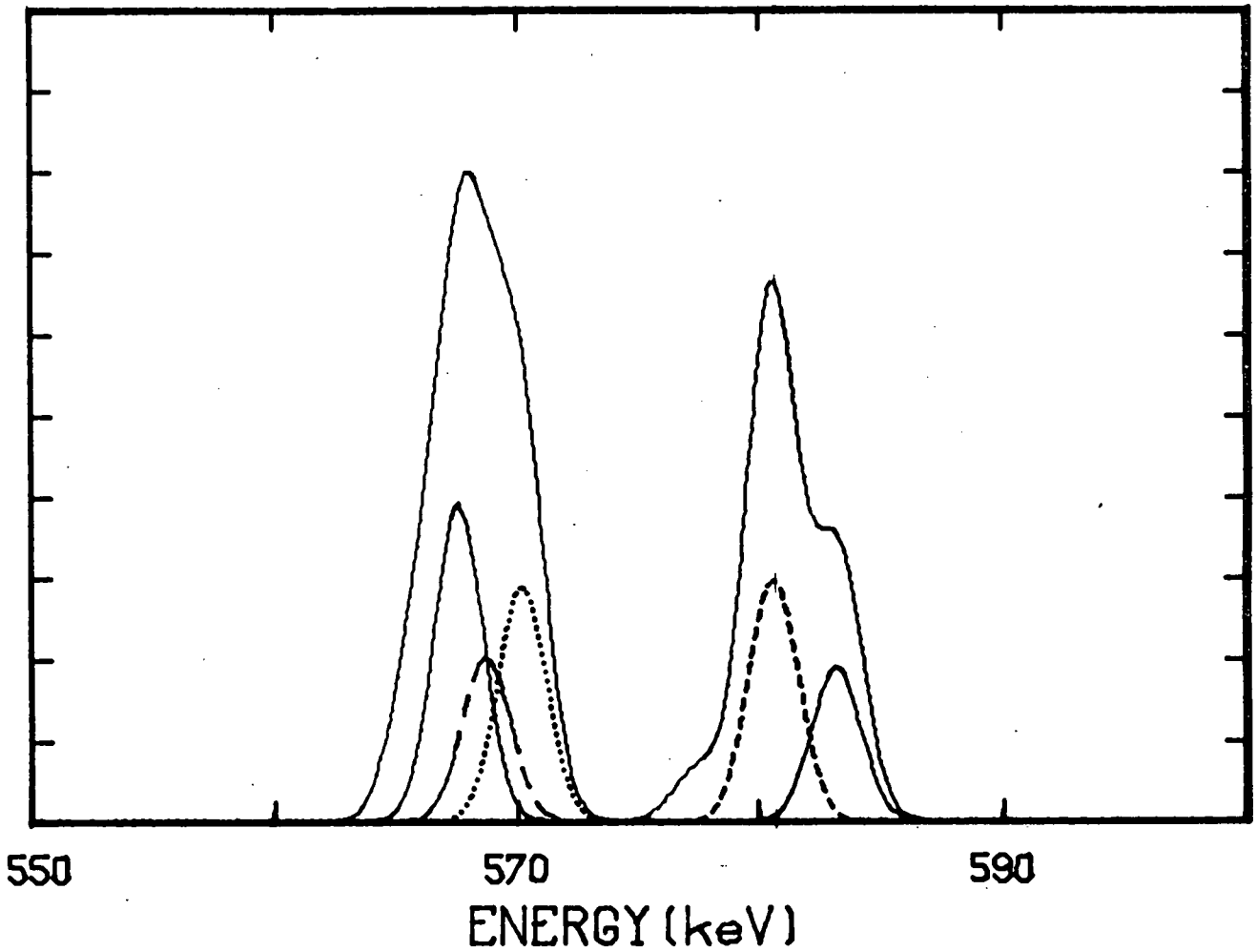

Figure 4: Theoretical M - Line Spectrum of ^{155}Gd. $Q_{3/2-} = -1.2b$. All Hyperfine Components With Intensities Greater Than 1.5% Have Been Taken Into Account.

7. The Model Dependence of Nuclear Quadrupole Matrix Elements Extracted From Muonic X-Ray Measurements.

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

Abstract of paper to be submitted to The Physical Review.

The model dependence is investigated for the nuclear quadrupole matrix elements extracted from muonic x-ray analysis. It is shown that the extracted quadrupole matrix elements are hardly affected by the deformation parameters β_2, β_4 and γ of the nuclear charge distribution.

A preliminary version of the complete paper is included in the appendix.

A discussion of the calculations in this paper were the major part of an invited paper presented by R. M. Steffen at the Vth International Conference on Hyperfine Interactions, held in Berlin (West), July 20-25, 1980. A copy of this paper is included in the appendix.

8. Nuclear Polarization Corrections in Muonic X-Ray Studies.

The nuclear-polarization energy correction for the muonic s-, p- and d-states are large enough to play a significant role in the extraction of nuclear charge parameters from muonic x-ray data. Ever since we discovered a discrepancy of the theoretical and experimental values of the energies of the muonic states of ^{208}Pb (see last year's Progress Report No. 4), we are concerned about the nuclear polarization correction, which is the only higher-order correction that is not well understood.

It is imperative for the determination of accurate nuclear data from muonic x-ray measurements that the nuclear polarization theory and its underlying assumptions be further examined and studied. (See also Renewal Proposal.)

A. Nuclear Polarization Energy Corrections for Muonic Levels of ^{208}Pb.

Y. Tanaka

In spite of the fact that the levels of ^{208}Pb have been quite extensively studied in recent years and these experimental results should provide accurate enough nuclear polarization energies for muonic levels of this nucleus, the observed x-rays from the muonic ^{208}Pb are not satisfactorily explained by the calculation. The difficulties involved in the calculation are summarized as (1) both 3d muonic levels are bound deeper by $\sim$ 150 eV than indicated by experiment and (2) the Δ2p splitting is larger by $\sim$ 200 eV than indicated by experiment. The above deviations are serious, since they are three times larger than the experimental errors.

In order to investigate the reason for these difficulties, we first examined the nuclear polarization correction energies. Despite the use of all the latest experimental informations on the nuclear states of ^{208}Pb and using widely varying transition charge densities, the calculation essentially remains unimproved.[1)]

A possible reason might be found in the fact that, in the nuclear polarization energy calculation, all the intermediate muonic states are taken into account by the reference spectrum method. However, no intermediate nuclear states are considered. Another point, though it is not probable, is to look very carefully into the vacuum polarization and the anomalous moment terms.

During the course of this study, we found that the surface diffuseness mode of vibration does equally well as the breathing mode of vibration in explaining the α-particle inelastic scattering involving the

giant monopole resonance.[2] Although the surface diffuseness mode of vibration does not explain the discrepancies mentioned above, further experiments should prove whether this mode is adequate for the monopole vibration.

References

1) Y. Tanaka et al., Proc. Intern. Conf. on Nuclear Structures, Berkeley, Abstract p. 165 (1980).

2) Y. Tanaka, submitted to Phys. Rev. Communications.

B. The Isoscalar Monopole Nuclear Polarization Energy for the Muonic ^{208}Pb*

Y. Tanaka

Abstract

Various modes of monopole vibrations were studied by analyzing inelastic hadron reactions on the monopole resonance. Among the vibrations of a breathing mode, a surface diffuseness mode and the wine bottle mode, the (α,α') experiment exhibits that the surface diffuseness mode seems to be important for the monopole vibration. The mode gives rise to a polarization energy shift of 626 eV for the muonic 1s level of ^{208}Pb, which is 30% smaller than a value calculated by the breathing mode of vibration.

*Paper to be submitted to the Physical Review. A copy of this paper is included in the Appendix.

C. Anomalous Energy Shifts in Muonic Levels of ^{208}Pb*

Y. Tanaka,† E. B. Shera, M. V. Hoehn and H. D. Wohlfahrt, Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87545 and D. Laubacher and R. M. Steffen, Department of Physics, Purdue University, W. Lafayette, Indiana 47907

In light of recent work,[1)] we have reexamined the nuclear polarization (NP) correction for muonic ^{208}Pb. All known states up to 8 MeV, including the near-resonant 6-8 MeV 1^-, 2^+ and 3^- states that have recently been observed in (α,α'), (p,p'), (e,e') and (γ,γ') experiments, were included in the NP calculation, as were the giant resonances. Despite the use of various giant resonance parameters and widely differing transition charge densities, the calculations still display the following anomalies: 1) both 3d muonic levels are bound deeper by 150 eV than indicated by experiment,[2)] 2) the 2p levels are bound approximately 400 eV deeper than indicated by experiment, 3) the $\Delta 2p$ splitting is larger by 200 eV than indicated by experiment. From a theoretical viewpoint, explanations of these discrepancies might be found in the reference spectrum method used in the NP calculation, in the Lamb shift correction, or in the vacuum polarization correction. However, calculations of the latter two corrections are in essential agreement with experiment in other levels of ^{208}Pb and in other nuclei.[3)] The transverse interaction (defined in the Coulomb gauge), which was mentioned in Ref. 1 as a possible explanation of the $\Delta 2p$ discrepancy, has been investigated and found to have negligible influence.

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*Abstract of paper presented at the Int. Conf. on Nuclear Structure, Berkeley, Aug. 25 - 30, 1980.

†Supported in part by Purdue University.

From an experimental viewpoint, it appears desirable to remeasure the values of the 4f-3d and 3d-2p transition energies. The table below shows the results of a typical calculation in which the Fermi charge distribution parameters have been adjusted to best fit the experimental energies.[2,3] The anomalies mentioned above are evident.

Transition	Experiment (MeV)	Calculation (MeV)	Transition	Experiment (MeV)	Calculation (MeV)
$2p_{3/2}-1s_{1/2}$	5.962770(420)	5.962804	$4f_{5/2}-3d_{3/2}$	0.971850(60)	0.972000
$2p_{1/2}-1s_{1/2}$	5.777910(400)	5.777750	$4f_{7/2}-3d_{5/2}$	0.937980(60)	0.938112
$3d_{3/2}-2p_{1/2}$	2.642110 (60)	2.642195	$5g_{7/2}-4f_{5/2}$	0.437748(12)	0.437754
$3d_{5/2}-2p_{3/2}$	2.500330 (60)	2.500227	$5g_{9/2}-4f_{7/2}$	0.431360(11)	0.431340

References

1) Y. Yamazaki et al., Phys. Rev. Lett. 42 (1979) 1470; G. A. Rinker et al., Nucl. Phys. A 306 (1978) 360.

2) D. Kessler et al., Phys. Rev. C 11 (1975) 1719.

3) L. Tauscher et al., Z. Physik A 285 (1978) 139.

9. Development of Computer Programs for the Analysis of Muonic X-Ray Data.

A. Computer Programs for the Muonic X-Ray Analysis.

Y. Tanaka

Until June 1979, there were five different programs used in the analysis of muonic transition energies. Since each of the programs had quite similar functions we decided to reorganize the programs in order to minimize the computational errors. Two programs were newly written and the original four programs were replaced by the new ones. Besides, the following new functions were added.

(1) Nuclear parameters can be least squares fitted by the observed muonic transition energies involving noncircular orbitals as well as circular orbitals.

(2) In the hyperfine splitting calculation of muonic levels, a triaxially deformed charge distribution may be assumed in constructing the monopole charge density and the transition charge density.

The programs being used have the following functions.

(1) NEWMUON

The program calculates the QED corrections for muonic levels.[1] It also provides the Spline space for the interpolation of the charge parameters c and a and the radial integrals for the calculation of hyperfine splitting energies and E1 cascade transitions.

(2) NEWXRAY

The program calculates the energy spectrum of muon-nuclear coupled system and relative intensities of E1 cascade transitions between the levels. It also contains the least squares fitting routine to

optimize the nuclear parameters, i.e., charge parameters, isomer shift energies and magnetic and quadrupole matrix elements between low lying nuclear states.

(3) RURP[1)]

The program calculates the nuclear polarization energy of muonic levels with the effect of intermediate muonic states outside the model space included. It also calculates the energy spectrum of muon-nuclear coupled system and relative intensities of E1 cascade transitions between the levels. The program does not contain the least squares fitting routine to optimize the nuclear parameters.

Reference

1) G. A. Rinker, Comp. Phys. Comm. 16, 221 (1979).

B. Computer Program Advance - DISSPLA Graphics

D. Laubacher

Several useful computer graphics programs have been written and adapted for use on several graphics devices including hard copy ZETA plotters, electrostatic printers and Tektronics display terminals.

1. GENPLOT - A program designed to produce publication-quality figures with a minimum of user effort.
2. SPPLOT - Produces publication-quality labelled spectra with a minimum of user effort.
3. GAPLOT - Produces a calculated muonic spectra by assuming a gaussian lineshape for each transition and folding them together.

10. Muon Transfer in Liquid Hydrogen.

With D. Laubacher

We had only two 20-shift runs (December 1979, February 1980) and one 12-shift run (July 1980) on the LAMPF accelerator during the reporting period. Because of accelerator trouble the last run actually provided only 6 useful shifts.

In view of these limitations and in view of the fact that a LAMPF construction project (started Aug. 25, 1980) is disrupting the link (50 cables!) between our data-accumulation electronics and the stopped-muon-channel no measurements on muon-transfer problems could be scheduled.

11. List of Publications

1. 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, Proc. Int. Conf. on High-Energy and Nuclear Physics, Vancouver, B C. B1 - 1 (1980).

2. Charge Distribution Parameters of the Stable Ru and Pd Nuclei Deduced from Muonic X-Ray Measurements, M. V. Hoehn, E. B. Shera, H. D. Wohlfahrt, D. B. Laubacher, R. M. Steffen and Y. Tanaka, BAPS 25 (1980) (abstract).

3. Nuclear Charge Distributions in $1f_{7/2}$-Shell Nuclei from Muonic X-Ray Measurements, H. D. Wohlfahrt, E. B. Shera, M. V. Hoehn, Y. Yamazaki, and R. M. Steffen, Phys. Rev. C 23 (in print).

4. Nuclear Parameters from Muonic and Pionic X-Rays, R. M. Steffen, Proc. of Vth Int. Conf. on Hyperfine Interactions, Berlin (West), in print.

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12. Personnel and Percentage of Effort

Principal Investigator

R. M. Steffen, Professor of Physics

Percentage of Effort: 25% Dec. 1, 1979 - May 15, 1980

100% May 16, 1980 - October 15, 1980.

(On sabbatical leave from Purdue University, stationed at Los Alamos)

Research Associates

Dr. Y. Tanaka

Percentage of Effort: 100%, whole year

Graduate Student

Dan Laubacher

Percentage of Effort: 100%, whole year

Removed

13. Appendix

Reprints and preprints of papers published in 1980.