The 5g→4f Pionic Transition in Th^{232} and U^{238} (*)

NGL-47-004-006

D. A. Jenkins and R. J. Powers

Virginia Polytechnic Institute, Blacksburg, Virginia

and

A. R. Kunselman

University of Wyoming, Laramie, Wyoming

ABSTRACT

Early measurements of pionic x-ray energies and widths in Th^{232} and U^{238} have suggested the possibility of an anomalous effect for the interaction between high Z nuclei and a pion in the 4f-atomic state. We have remeasured the 5g→4f x-ray energies and widths in these isotopes and we compare them to a calculation which considers the distortion of the nucleus. A small disagreement between theory and experiment persists, but it is probably due to uncertainties in the calculation of the strong interaction effects.

1. Introduction

In comparing available pionic x-ray data with present theory, one finds two areas of disagreement. The experimental widths for the 2p→1s transition in nuclei with Z (atomic number) greater than 8 are less than the predicted values[1], and the experimental energy shifts and widths for the 5g→4f transition for $Z \geq 90$ are greater than the predicted values[2]. The present situation for the 2p→1s transitions is ambiguous because of disagreement among the different measurements; the measurements are difficult because the x-rays have a low yield and nuclear gammas from pion capture fall near the x-rays in the energy spectrum. An early measurement of the nuclear shift and width for the 5g→4f x-ray in high Z nuclei gave results which were three times larger than values predicted in a perturbation calculation[2]. Krell and Ericson calculated the nuclear shift and width by integrating the Klein-Gordon equation and obtained results which are larger than the perturbation calculation but still significantly less than experiment[3]. However, these results were somewhat ambiguous because the nuclear size was not well known. A typical example is the measured energy shift in U^{238} of 5.96 ± 1.1 keV which can be compared to Krell and Ericson's result of 3.48 keV.

Recent results of McKee[4] from muonic atoms provide parameters which describe the distorted shape of the nuclear densities of Th^{232} and U^{238}. With this nuclear density, we can construct an optical model potential which is free of the ambiguities in nuclear size present in earlier calculations. In this paper we present more accurate measurements of the shift and width for the 5g→4f transition in Th^{232} and U^{238}, and we compare the results with a theoretical calculation which includes the distortion of the nuclear shape.

2. Experimental Method

X-rays were detected by a 40 cc lithium-drifted germanium detector, and the x-ray spectrum was analyzed with an 8192 channel analog-to-digital converter which allowed us to observe all pionic x-rays with energy above 100 keV. The gain was stabilized on peaks which were present in the x-ray spectrum. The experimental arrangement for a similar measurement has been given in a recent paper[5].

We used the element in metallic form for target materials; each weighed about 200 grams and was at least 99% isotopically pure. The linearity of the pulse height spectrum was checked with many gammas of known energy, and the gammas in the region of interest are given in Table I. With these sources, we were able to make non-linearity corrections of 0.7 keV to an accuracy of ± 0.15 keV.

Our data for the 5g→4f peak in Th^{232} had about 7500 counts with a peak height of 290 counts on top of a background of 200 counts. The U^{238} peak had 7800 counts with a peak height of 266 counts on top of a background of 310 counts. A calculation of muonic x-ray energies for thorium and uranium does not reveal any lines near in energy to the 5g→4f pion transition, therefore, we did not consider the problem of interference from muonic x-rays in our pion data.

The dynamic quadrupole effect observed when muons form atoms with Th^{232} and U^{238} is not expected to make a significant contribution to our transitions since the pion is in a 4f atomic state.

3. X-ray Energy and Width

The peaks in the pulse height spectrum were analyzed for their position and width by fitting the peaks with a Voightian profile. The method of analysis has been described[8]. The data is shown in Fig. 1 with a best fit Voightian profile which determined the centroid and width of the peaks. Compared to the spectra given in Ref. 6 for lower Z isotopes, the peak to valley ratio for the pion transitions is good and the background is relatively smooth. The small peak at 718 keV appeared in all of our spectra and is resolved from the pionic x-ray peaks. However, we did add a small Gaussian to fit this peak while analyzing the uranium data.

The centroid positions were found to be (in channels)

Th^{232} 2407.9 ± 0.25, and
U^{238} 2522.1 ± 0.45,

where the errors reflect uncertainties in statistics and background. The energy scale was determined from the 511 keV annihilation gamma and the 1273 keV gamma from Na^{22} decay which appear in the spectrum, and the slope of the calibration line was found to be 0.285 keV/channel. The resulting energies are

Th^{232} 698.15 ± 0.22 keV, and
U^{238} 730.88 ± 0.25 keV.

The errors are tabulated in Table II. These results are in good agreement with the earlier measurements[2] of 698.0 ± 0.6 for Th^{232} and 731.4 ± 1.1 for U^{238}. The energies of other pionic x-rays from these targets agreed with the values computed for a point nucleus.

Using a value of 3.8 ± 0.3 keV for the instrumental resolution, we found for the widths

Th^{232} 3.53 ± 0.46 keV, and
U^{238} 4.05 ± 0.86 keV.

The errors are due to uncertainties in background, statistics and instrumental resolution. These widths are significantly lower than earlier results[2] of 6.0 ± 0.9 keV for Th^{232} and 6.1 ± 1.0 keV for U^{238}. Reexamining the earlier data, we find that the errors were not evaluated correctly and should have been ± 3.0 keV for Th^{232} and ± 2.0 keV for U^{238}. The width of Pu^{239} should have been quoted with an error of ± 3.0 KeV. With these corrections, there is good agreement between the two sets of measurements.

4. Optical Model Analysis

To calculate the expected x-ray energies and widths for the 5g→4f transition in Th^{232} and U^{238}, we use an optical model potential with strong interaction parameters determined from other pionic x-ray data[9] and with the charge distribution derived by McKee[4] from muonic x-rays in Th^{232} and U^{238}. McKee found that the distorted charge distribution of these nuclei can be represented by the density

$$\rho(r,\theta) = \rho_o/[1 + e^{n(\frac{r}{R} - 1)}]$$

with

$$R = a/[1 - \frac{b^2 - a^2}{b^2} \cos^2\theta]^{1/2}$$

where θ is the polar angle and ρ_o is a normalization constant. The parameters a, b, and n are given in Table III. Since the ground states of Th^{232} and U^{238} have zero spin, there is no coupling between the nuclear and pion coordinates.

We derived the shape of the mass density from McKee's charge density by adjusting the skin thickness parameter n such that the mean-square mass density be equal to the difference of the mean-square charge density and the mean-square proton charge density (.60 F^2). The resulting distribution is given by the parameters a, b and n' of Table III. We assumed that the mass densities of the protons and neutrons have the same shape, and the shape was averaged over the polar angle θ

$$\rho(r) = \int_o^{+1} \rho(r,\theta)\, d\,(\cos\theta)$$

to find a density ρ(r) to use in the optical potential given in I. The results of the calculation are given in Table IV.

Tabel IV lists the Klein-Gordon energy computed for a point nucleus with reduced mass, and the vacuum polarization computed to 2nd order (in e) by perturbation theory for a finite nucleus using wave functions distorted by the nuclear interaction. The vacuum polarization was computed in the same way by McKee and he obtained good agreement between his calculated and measured 4f energies for muons. The nuclear shift listed in the table is the difference between the Klein-Gordon point value and the solution of the Klein-Gordon equation with the optical potential described in I. It includes effects from both the strong interaction and the finite distribution of charge.

A measured nuclear shift is derived by subtracting the point Klein-Gordon value and the vacuum polarization correction from the measured value. This measured nuclear shift then contains effects due to both the strong interaction and the finite Coulomb size of the nucleus, but the finite Coulomb size effect is small and reduces the total nuclear shift by about 100 ev.

Calculations of the nuclear shift and width are less than the measured values by about 25% for both nuclei. Increasing the rms radius of the neutron distribution would only reduce the calculated values. However, we believe that the difference between theory and experiment is probably not significant when uncertainties in the optical potential are considered.

CONCLUSION

We have measured the $5g \rightarrow 4f$ pionic x-ray energy and width in Th^{232} and U^{238}. The results are found to be greater than, but still in fair agreement with, a prediction made from an optical model analysis. The large disagreement of a factor of three between theory and experiment reported in an earlier measurement has been largely resolved by (1) more reliable optical-model potential parameters, (2) an improved measurement of the x-ray width, and (3) a better knowledge of the charge distribution. We attribute the remaining difference between theory and experiment to uncertainties introduced by the optical model.

ACKNOWLEDGEMENTS

We thank members of the William and Mary physics group for help in the data collection, Mr. Duane Reaugh for help in the data analysis, Dr. David Anderson for assistance in the theoretical calculations, and the staff of the NASA Space Radiation Effects Laboratory for their assistance during the experiment.

FOOTNOTES

*Work supported by the National Aeronautics and Space Administration.

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Table I. Calibration Sources. The energies are taken from Ref. 6 except for Ag^{110m} from Ref. 7.

Source	Energy (keV)
Ir^{192}	612.435 ± 0.017
Ag^{110m}	620.22 ± 0.03
Ag^{110m}	686.80 ± 0.03
Ag^{110m}	706.68 ± 0.04
I^{131}	722.91 ± 0.05
Ag^{110m}	744.19 ± 0.04

Table II. Errors in energy analysis (in keV).

	Th^{232}	U^{238}
Statistics and background	0.07	0.13
Gain	0.15	0.15
Non-linearity	0.15	0.15
Total	0.22	0.25

Table III. Parameters for the charge distribution.[a]

	Th^{232}	U^{238}
a	6.506 ± 0.28 F	6.501 ± 0.024 F
b	8.189 ± 0.038 F	8.396 ± 0.033 F
n	14.9 ± 0.7	14.9 ± 0.6
n'	16.0	16.0

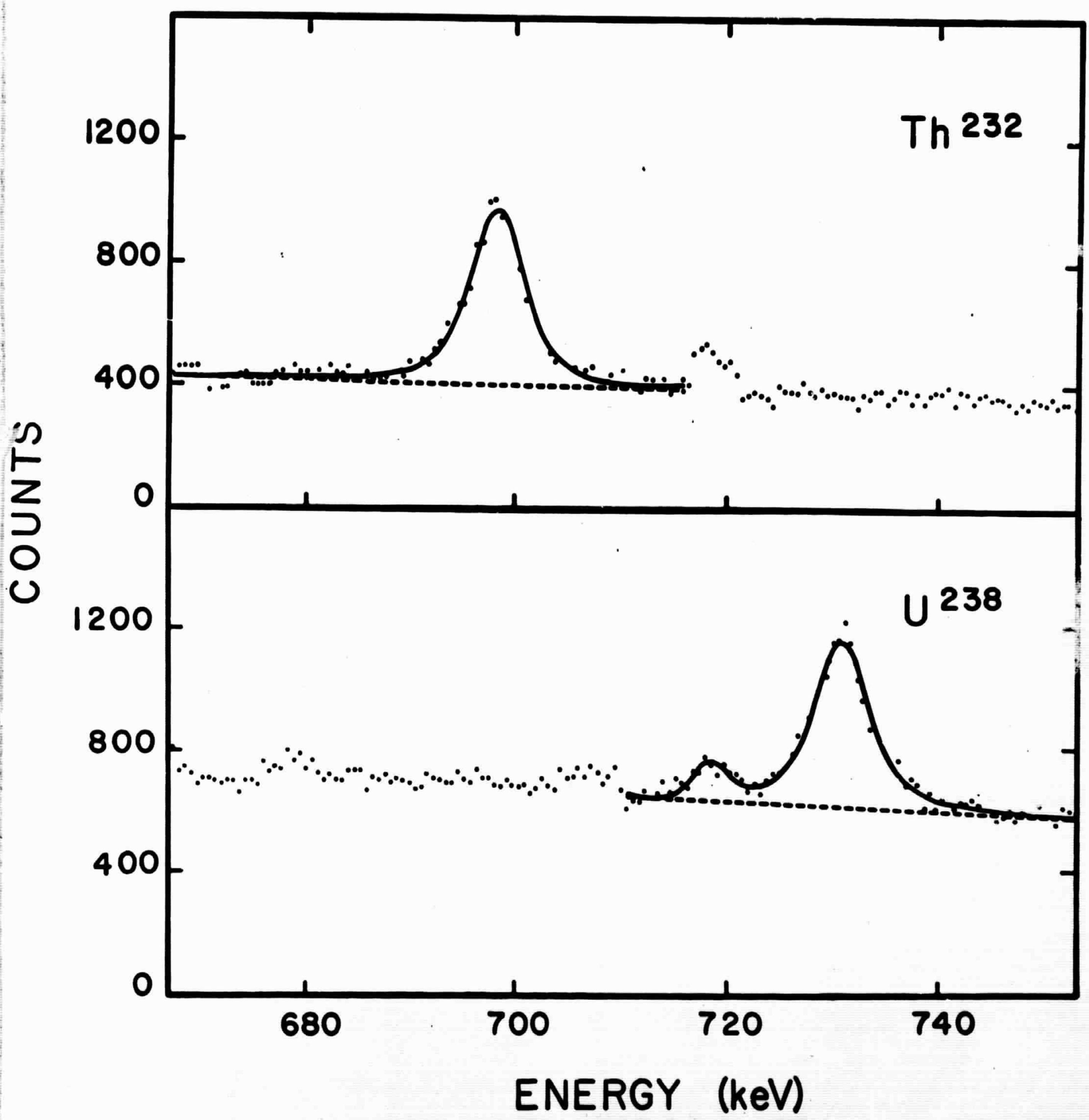
[a] From Ref. 4.

Table IV. Comparison of prediction with experimental results (in keV).

	Th^{232}	U^{238}
<u>Energies</u>		
Klein-Gordon	689.54	721.15
Vacuum polarization	4.27	4.54
Nuclear shift	3.40	4.09
Total Calculated	697.21	729.78
Measured total	698.15 ± 0.22	730.88 ± 0.25
Measured nuclear shift	4.34 ± 0.22	5.19 ± 0.25
<u>Widths</u>		
Calculated	2.82	3.45
Measured	3.53 ± 0.46	4.05 ± 0.86

FIGURE LEGENDS

Fig. 1. Pulse height spectra of the 5g→4f pionic x ray. The solid line is a least-squares-fit to the data, and the dashed line is the assumed shape of the background. The gain on the horizontal scale is 0.57 keV/channel.


Th 232
U 238
COUNTS
1200
800
400
0
1200
800
400
0
680
700
720
740
ENERGY (keV)