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Muonic isomer shifts of the 803- and 2648-keV states in ^{206}Pb

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The decay of the 2648- and the 803-keV excited states in muonic ^{206}Pb has been observed and the isomer shifts of these states have been measured. The isomer shift of the nuclear 2^+ state at 803 keV is -1.45 ± 0.31 keV; the isomer shift of the nuclear 3^- state at 2648 keV is $+6.81\pm0.46$ keV. The measured shifts in ^{206}Pb are similar to those measured in ^{208}Pb and support the suggestion that the corresponding states in those nuclei have similar origin.

[NUCLEAR STRUCTURE ^{206}Pb; measured isomer shifts of 803-keV 2^+ and 2648-keV 3^- nuclear states.]

I. INTRODUCTION

The muonic isomer shift is related to the difference of the monopole charge distribution between an excited nuclear state and the ground state. The isomer shift of an excited state can be measured if the nucleus is excited to that level during the cascade that follows the thermalization and capture of a negative muon into an atomic orbit. Such muonic excitation of the low-lying excited states of deformed nuclei is common and a large number of isomer shifts of rotational states have been measured.[1] In spherical nuclei, for which the lowest excited states occur at much higher energies, muonic excitation is rarer but nevertheless occasionally occurs because of accidental resonances between muonic and nuclear transition energies. The 2.6-MeV 3^- state of ^{208}Pb is such a case,[2] as is the 899-keV 2^+ state in ^{204}Pb.[3]

In an early study of muonic ^{206}Pb, Hargrove and co-workers[4] observed a prompt γ-ray line with an energy of 802.0 keV, which they interpreted as arising from the 2^+ state of that nucleus. The observation suggests that resonance excitation occurs in muonic ^{206}Pb. This conclusion is supported by calculations recently published by Rinker and Speth,[5] which indicate that the 2.6-MeV 3^- state of ^{206}Pb, like that of ^{208}Pb, may be excited via a $3d$-$2p$ muonic-nuclear resonance. Since the 3^- state decays to the 803-keV 2^+ state, the isomer shifts of both states should be measurable given sufficient resonance excitation of the 3^- state.

II. EXPERIMENT

Accordingly, an experiment was initiated at the LAMPF stopped-muon channel to search for the isomer-shifted $3^-\rightarrow2^+$ and $2^+\rightarrow0^+$ nuclear γ-ray transitions in muonic ^{206}Pb. An isotopically enriched (99.98%) 9 g sample of ^{206}Pb, which was in the form $Pb(NO_3)_2$, was used in the experiment. The Ge(Li) spectrometer system and the data acquisition techniques used in the experiment were similar to those described previously.[6] Energy calibration was derived from the ^{206}Pb muonic x-ray lines and from a separate spectrum of ^{54}Mn and ^{113}Sn radioactive decay lines that was stored simultaneously with the muonic data.

The 800-keV region of the muonic x-ray spectrum for ^{206}Pb is shown in Fig. 1. In addition to the $7\rightarrow4$ muonic transitions,[7] an additional transition at approximately 802 keV is seen in the spectrum, which we interpret as the isomer shifted $2^+\rightarrow0^+$ γ-ray transition. To precisely determine the energy of this γ-ray transition, the muonic spectrum was fitted with a function composed of a linear background and a Gaussian distribution convoluted with exponential tails. Exponential tail parameters were determined from the $4f\rightarrow3d$ muonic lines and from the 834-keV ^{54}Mn line; energy calibration was established from those lines and from the ^{113}Sn line at 391 keV. The relative energies and intensities of the $7\rightarrow4$ transitions were held constant in the fit. An estimate of the detector system nonlinearity was determined from ^{113}Sn,

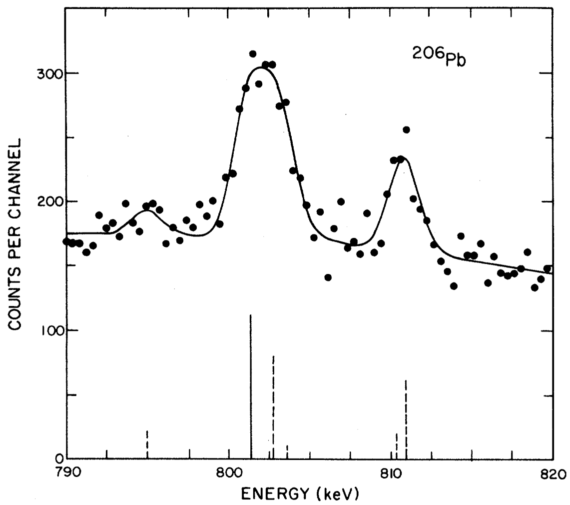

FIG. 1. Spectrum of the electromagnetic radiation emitted by muonic ^{206}Pb in the 800-keV energy range. The individual fitted transitions are indicated by lines below the spectrum; muonic $7g_{9/2} \rightarrow 4f_{7/2}$, $7h_{11/2} \rightarrow 4f_{7/2}$, $7f_{7/2} \rightarrow 4d_{5/2}$, and $7g_{7/2} \rightarrow 4f_{5/2}$ transitions, which have energies of approximately 803.2, 804.0, 810.9, and 811.4 keV, respectively, are indicated by dashed lines. The solid line indicates an additional transition at 802 keV which we interpret as the isomer shifted $2^+ \rightarrow 0^+$ transition. The transition at 795 keV occurs in the delayed spectrum and is presumably a transition associated with ^{205}Tl.

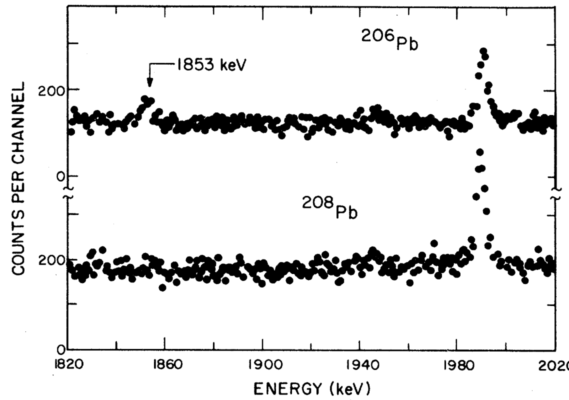

FIG. 2. Spectrum of the electromagnetic radiation emitted in muonic ^{206}Pb (top) and in muonic ^{208}Pb (bottom) in the 1900-keV region. The transitions at about 1990 keV are single escape peaks from a muonic $3d \rightarrow 2p$ transition. The 1853-keV transition in the ^{206}Pb spectrum is notably absent from the ^{208}Pb spectrum.

^{54}Mn, and ^{124}Sb calibration sources in a separate run. The measured energy of the $2^+ \rightarrow 0^+$ transition in the muonic spectrum is 801.65 ± 0.31 keV. The quoted error is the quadratic sum of the statistical uncertainties of the data, the uncertainty of the energy calibration, and the uncertainty associated with the detector system nonlinearity.

The 1.8-MeV region of the muonic x-ray spectra of ^{206}Pb and, for comparison, that of ^{208}Pb, are shown in Fig. 2. The major line appearing in both spectra at about 1990 keV is the single escape peak of the muonic $3d_{5/2} \rightarrow 2p_{3/2}$ transition. An additional line at about 1853 keV is seen in the muonic spectrum of ^{206}Pb, which we interpret as the $3^- \rightarrow 2^+$ γ-ray transition. This portion of the spectrum was fitted in a manner similar to that described above. The energy calibration was determined from the energies of the muonic $3d \rightarrow 2p$ and $4f \rightarrow 3d$ transitions in ^{206}Pb.[8] An estimate of the detector system nonlinearity was made in a separate run with ^{124}Sb and ^{56}Co γ-ray sources. The energy of the isomer shifted $3^- \rightarrow 2^+$ transition was found to be 1852.76 ± 0.39 keV.

The measured excitation probability of the 3^- state, based on the observed $3^- \rightarrow 2^+$ transition, is 0.026 ± 0.008 relative to the $3d_{5/2} \rightarrow 2p_{3/2}$ muonic transition. The branching ratio for the decay of the 3^- state to the 2^+ state is 0.94.[9] Hence, the total excitation probability of the 3^- state is 0.028 ± 0.008. We have repeated the $3d$-$2p$ muonic resonance calculation of Rinker and Speth,[5] using the most recent value of the $B(E3)$ (Ref. 10) and assuming a quadrupole moment of the 3^- state that is the same as that for ^{208}Pb.[10] Our calculation predicts an intensity of 0.032 (relative to the muonic $3d_{5/2} \rightarrow 2p_{3/2}$ transition), in good agreement with that observed.

The experimental excitation probability of the 2^+ state was determined, after appropriate corrections for target self-absorption and detector efficiency, to be 0.034 ± 0.006. This value is in substantial disagreement with that observed by Hargrove and co-workers,[4] who report an intensity of 0.085. A calculation of the excitation of the 2^+ state indicates that the state is excited principally from the decay of the 3^- state and yields an excitation probability of 0.030, in agreement with the present experiment. The calculation indicates only a negligible contribution (0.0006) from direct resonance excitation of the 2^+ state.

III. EXTRACTION OF ISOMER SHIFT

As indicated above, the isomer shift is the difference in the energies of the γ-ray transitions as observed in muonic and in normal atoms. The energy of the $2^+ \rightarrow 0^+$ γ ray in normal ^{206}Pb is 803.10 ± 0.05 keV.[11] The energy difference is therefore -1.45 ± 0.31 keV. This experimental energy difference must, in principle, be corrected for the (unresolved) magnetic hyperfine splitting that occurs due to the interaction of the 2^+ state with the $1s_{1/2}$ muon. However, the very small value of the magnetic dipole moment of the 2^+ state [($\mu_{2^+} = -0.02 \pm 0.14$ nm) (Ref. 12)] results in an entirely negligible correction in this case.[13] Correction for possible differences in nuclear polarization between the excited and ground states is discussed below.

The energy of the $3^- \rightarrow 2^+$ γ-ray transition in normal ^{206}Pb is 1844.49 ± 0.10 keV.[11] Taking into account the isomer shifted energy of the 2^+ state, the 3^- state energy difference is therefore 6.82 ± 0.45 keV. Again, the "raw" shift should be corrected for the magnetic hyperfine splitting of the 3^- nuclear state. The magnetic hyperfine corrections depends on several parameters: (1) the half-life of the $M1$ interdoublet transition (which we compute to be 9 ± 2 ps by assuming that internal conversion occurs in the M and higher shells and that the g factor for the 3^- state is the same as that for ^{208}Pb), (2) the lifetime of the 3^- state [(taken to be 0.125 ± 0.030 ps) (Ref. 14)], and (3) the population ratio of the magnetic substates [calculated[15] to be $P(\frac{7}{2})/P(\frac{5}{2}) = 1.60$]. With those parameters, we estimate the shift of the centroid due to the magnetic correction to be -13 ± 20 eV. The measured isomer shift is, therefore, 6.81 ± 0.46 keV.

Before a muonic isomer shift can be interpreted as a direct indication of differences in charge radii between ground and excited nuclear states, the question of nuclear polarization should be considered. The nuclear polarization effect shifts the binding energy of the muonic $1s_{1/2}$ state in heavy nuclei by several keV, and a possible difference in the $1s_{1/2}$ nuclear polarization depending upon whether the nucleus is in the ground state, $|1s_{1/2}, 0^+\rangle$, or in an excited state, $|1s_{1/2}, I\rangle$, would appear as a contribution to the measured isomer shift. Using the program RURP,[15] we have estimated the nuclear polarization of the $|1s_{1/2}, 3^-\rangle$, $|1s_{1/2}, 2^+\rangle$, and the $|1s_{1/2}, 0^+\rangle$ states. From the nuclear structure information available for ^{206}Pb, we conclude that the difference in nuclear polarization between the ground and either excited state probably does not exceed 300 eV, a value that is comparable to the experimental uncertainty in the isomer shift. We have included no correction for this effect in the isomer shifts presented here.

In Table I the isomer shifts in ^{206}Pb measured in the present work are compared with those determined by Budick *et al.*[13] from measurements on a ^{207}Pb target. In muonic ^{207}Pb, nuclear states in ^{206}Pb are occasionally excited due to radiationless transitions that result in prompt neutron emission. The agreement between the results of the two techniques is seen to be quite good.

IV. CHARGE RADIUS DIFFERENCES AND DISCUSSION

The isomer shifts measured in the present work are interpreted in terms of the Barrett charge radius parameters[16] of the ground and excited nuclear states. The values, which were calculated from the energy-radius derivatives C_z listed in Ref. 1, are given in Table I. For ease of comparison with other experiments, the differences in Barrett radii have been converted to mean-square radius differences by assuming $\Delta\langle r^2\rangle^{1/2} = 0.782\ \Delta\langle R_k\rangle$ as described in Ref. 17.

The radius difference measured for the 2^+ state is comparable to differences reported for some excited nuclear states in transitional nuclei (e.g., Os and Gd, see Ref. 1) as well as in lead and other spherical nuclei. The 3^- state isomer shift is large; shifts of this magnitude have only been observed in highly excited states of nuclei near Pb and in ^{153}Eu.

The muonic isomer shifts in ^{206}Pb are compared with those of ^{204}Pb and in ^{208}Pb in Table II. The

TABLE I. Isomer shifts of ^{206}Pb measured in the present work compared with those measured in Ref. 12. Uncertainties are indicated in parentheses. The Barrett (ΔR_k) and $\Delta\langle r^2\rangle$ radius differences are discussed in the text. The $\Delta\langle r^2\rangle$ values were derived with a Fermi distribution assuming a constant skin thickness and are somewhat model dependent (see Ref. 17).

Nuclear state	Isomer shift (keV) Present experiment	Isomer shift (keV) Ref. 13	ΔR_k (10^{-3} fm) Present experiment	$\Delta\langle r^2\rangle$ (10^{-3} fm^2) Present experiment
2^+	$-1.45(31)$	$-1.55(7)$	$-2.03(43)$	$-17.4(3.7)$
3^-	$+6.81(46)$	$+6.0(1.2)$	$+9.55(64)$	$+82.0(5.5)$

TABLE II. Certain properties of the excited states of the stable even-A Pb isotopes. Values of the ^{206}Pb isomer shifts are taken from the present work; the values of the other parameters are taken from the indicated references.

Isotope	State	Energy (keV)	Isomer shift (keV)	$B(E3;0^+\rightarrow 3^-)$ (e^2b^3)
^{204}Pb	2^+	899.15[a]	$-1.98(16)$[b]	
^{206}Pb	2^+	803.10[c]	$-1.45(31)$	
^{206}Pb	3^-	2647.59[d]	$+6.81(46)$	0.60(4)[e]
^{208}Pb	3^-	2614.49[a]	$+6.25(28)$[f]	0.665(35)[e]

[a]Reference 9.
[b]Reference 3.
[c]Reference 11.
[d]Deduced from Ref. 11.
[e]Reference 18.
[f]Reference 2.

isomer shifts of the 3^- states in ^{206}Pb and in ^{208}Pb have remarkably similar values. The similarity of the properties of the 3^- states [e.g., excitation energies, $B(E3)$ values, isomer shifts] support the suggestion[18] that the states have a common origin. Comparison of the measured 3^- state isomer shift of ^{208}Pb with a calculation[2] for that isotope indicates that the 3^- state is not a simple volume-conserving octupole vibrational state. However, a calculation by Ring and Speth[19] based on a renormalized random phase approximation and Migdal's theory of finite Fermi systems is able to reproduce the measured shift in ^{208}Pb reasonably well. As indicated in Table II, the isomer shifts of the lowest 2^+ state of ^{204}Pb and ^{206}Pb are also quite similar in magnitude and are both negative. The interpretation of the 2^+ state isomer shift in ^{206}Pb in terms of a particle-hole model of this state is discussed in Ref. 13. A recent shell-model calculation[20] yields a 2^+-state isomer shift of the correct sign but nearly an order of magnitude smaller than that observed.

Isomer shift values are now available for excited states of three even-A Pb isotopes (Table II); these data provide a challenge to nuclear theory and an opportunity for an improved understanding of nuclei near the $Z=82$ shell closure.

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