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NUCLEAR REACTION ^{206}Pb(^{40}Ar, ^{40}Ar'γ), E = 170 MeV, Recoil-distance Doppler-shift method, measured τ ^{206}Pb (2^+,803 keV), deduced B(E2)

LIFETIME MEASUREMENT OF THE FIRST EXCITED STATE IN ^{206}Pb[†]

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Abstract

The first excited state of ^{206}Pb (2^+,803 keV) was produced by Coulomb excitation using 170 MeV ^{40}Ar projectiles, and the mean life of this state was determined by the recoil-distance Doppler-shift method to be: $\tau = (13.2 \pm 0.8)$ ps.

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1. Introduction

The doubly even nucleus ^{206}Pb is a convenient target to use in projectile reorientation studies and in particular for projectiles with high-lying first excited states. In these cases, for bombardment at the same fraction of the barrier energy, the largest yields, as well as the largest reorientation effects^{1}) in the projectile, are obtained with the highest Z targets. However, in such studies as that of ref. 2, where the yield of the first 2^+ state in the projectile is determined relative to that of the first excited state in the target (so as to minimize errors in the instrumental corrections), it is necessary to know rather accurately the B(E2) of the target excitation. That is, the B(E2) and quadrupole moment of the projectile are sensitive to the target values. Since a search of the literature produced a range of measured B(E2) values for the 803 keV, 2^+ level in ^{206}Pb (ref. 3, 4, 5, 6), it was essential to try to redetermine this value more accurately. The several-picosecond lifetime of the state and the possibility of Coulomb exciting it by high energy ^{40}Ar projectiles led us to try to apply the recoil-distance Doppler-shift method^{7,8}).

2. Experimental Method

The experiment has been performed at the Berkeley HILAC using a 170 MeV argon beam of ∿ 2 nA intensity. The thin target of enriched ^{206}Pb(1.48 mg/cm^2) was evaporated onto a nickel foil 0.1 μm thick. This was then stretched on a ring holder to get a surface as flat as possible. The γ rays were recorded by a 35 cm^3 Ge(Li) coaxial detector at 0 degrees to the beam and operated in coincidence with the backscattered ^{40}Ar projectiles detected by a silicon ring counter. The recoiling ^{206}Pb nuclei were stopped at different distances from the target with a flat bismuth plunger. This distance, d, could be read to

±0.1 mil. Comparison of the relative intensities of the Doppler-shifted (s) and unshifted (u) transitions as a function of the distance between the target and the plunger allows determination of the mean life of the transition under study if the average recoil velocity is also accurately known. This velocity has been evaluated from the energy difference between the shifted and unshifted lines, ΔE, after correction for the effective solid angle at the Ge(Li) detector. That is given by the expression:

$$\frac{\Delta E}{E_0} = \frac{(1-\beta^2)^{1/2}}{\beta(1-\cos\theta_c)} \operatorname{Log}\left(\frac{(\beta+1)(1-\cos\theta_0)}{\beta\cos\theta_c - \cos\theta_0 + [(\cos\theta_0-\beta\cos\theta_c)^2 + (1-\beta^2)\sin^2\theta_0]^{1/2}}\right) - 1$$

where θ_c is the half-angle subtended by the counter, θ_0 is the angle between the axis of the counter and the direction of the recoiling nucleus, E_0 is the energy of the unshifted line, and $\beta = v/c$. The effective velocity so measured was $v = (0.0265\pm0.0003)\,c$.

3. Results

Figure 1 shows a few of the spectra obtained as a function of the stopping distance. The variation in the relative intensities of the shifted and unshifted peaks can be clearly seen.

A number of corrections had to be made to the experimental data. These are:

- Subtraction of the background. As can be seen, reasonably clean spectra were obtained by Coulomb excitation in coincidence with the backscattered particles. The background is flat on both sides of the peaks and the two peaks (u,s) are well separated (20.5 keV). The small number of accidental coincidences were first subtracted, and then the background was fitted by a third-order polynomial curve and subtracted from under the peaks. Errors coming from this analysis are shown with final results, Fig. 2.

- Variations in the solid angle of the gamma-ray counter caused by the movement of the plunger. This correction is quite small because of the short distances involved in moving the plunger relative to the target-Ge counter distances. The maximum effect, corresponding to the largest separation distance leads to a decrease of 0.4% in the unshifted-peak intensity.

- Variation in the counter efficiency for the shifted (higher energy) peak, compared with the unshifted one. This correction leads to an increase of 3% in the shifted-peak intensity as deduced by the measured efficiency curve.

- Correction of the shifted transition intensity for the change in the angular distribution and solid angle at the Ge(Li) counter due to the motion of the recoiling nucleus. The correction at 0 deg to the beam direction $\varepsilon(0)$ is added to the angular distribution

$W(\psi)_{\psi=0} = 1 + A_2Q_2 + A_4Q_4$ and has the value (to first order in v/c):

$$\varepsilon(0) \simeq \frac{2v}{c} \{(1-1/5\ A_2)Q_1 + (6/5\ A_2 - 2/3\ A_4)\ Q_3 + 5/3\ A_4\ Q_5\} \quad ,$$

where A_2, A_4 are the usual angular distribution coefficients, and Q_i ($i = 1$ to 5) are the finite geometry correction factors calculated for the given geometry. This correction yields a decrease in the shifted peak intensities of 7%.

4. Discussion

In the analysis, the feeding of the 2^+ state from higher states has been assumed negligible because of the very small probability of exciting the higher states in ^{206}Pb by the Coulomb excitation process with ^{40}Ar projectiles of the energy used. With this assumption, calculations start from the well known relation:

$$-\frac{dN}{dt} = \lambda N \quad ,$$

and the definitions:

$$\lambda = 1/\tau$$

$$I_s(\text{shifted}) = \int_0^T \left(-\frac{dN}{dt}\right) dt$$

$$I_u(\text{unshifted}) = \int_T^\infty \left(-\frac{dN}{dt}\right) dt$$

where T is the time after the excitation corresponding to the stopping distance, d.

If we assume no dependance on time for the angular distribution of the γ rays we have:

$$N = W(\psi)\; n_0 e^{-\lambda t} \quad ,$$

where $W(\psi)$ is the angular distribution and n_0, the number of counts at $t = 0$.

In this case we can write for $\psi = 0$ deg

$$I_s = W(0)\; n_0\; (1 - e^{-\lambda T})$$

$$I_u = W(0)\; n_0\; e^{-\lambda T} \quad ,$$

and

$$F = \frac{I_u}{I_u + I_s} = e^{-\lambda T} = e^{-\lambda \frac{d}{v}} \quad ,$$

where d is the stopping distance.

In fact, before integrating, the deorientation effect[9]) caused by the large hyperfine field acting on the recoiling nucleus in vacuum, must be taken into account. This is done by including attenuation coefficients in the angular distribution as defined:

$$G_k(t) = e^{-\frac{t}{\tau_k}} \quad (k = 2,4) \quad ,$$

where

$$\tau_k = \frac{1}{p_k\ \omega^2\ \tau_c}$$

τ_c is the correlation time, p_k is related to the nature of the hyperfine interaction, and ω is the average Larmor frequency due to the hyperfine field.

The angular distribution thus depends on time and can be written for $\psi = 0$ deg

$$W(0,t) = 1 + A_2Q_2G_2(t) + A_4Q_4G_4(t) \quad .$$

We can write now:

$$I_s = n_0\lambda \int_0^T W(0,t)\ e^{-\lambda t}\ dt$$

$$I_u = n_0\lambda\ W(0,T) \int_T^\infty e^{-\lambda t}\ dt \quad .$$

(In the second case the nucleus is no longer recoiling in vacuum, but stopped by the plunger, and it is assumed that the angular distribution remains unchanged during the short lifetime in the solid bismuth).

To determine W(0,t), the A_2 and A_4 coefficients have been calculated using the deBoer-Winther program[10]) for the case of projectiles scattered between 142 and 161 deg to the beam direction (ring geometry). The coefficients $G_2(t)$ and $G_4(t)$ have been evaluated by measuring the intensity of gamma rays at 45 deg and 90 deg to the beam direction in coincidence with back-scattered projectiles. The experimental ratio of the yields was compared with the theoretical one using the integral attenuation coefficients:

$$G_k(k = 2,4) = \lambda \int_0^\infty G_k(t)\, e^{-\lambda t}\, dt = \frac{\tau_k}{\tau + \tau_k} \quad .$$

We further assumed a magnetic dipole interaction[9]) to obtain a simple relation between G_2 and G_4 or $G_2(t)$ and $G_4(t)$ namely, $p_2 = 2$, $p_4 = \frac{20}{3}$. This permits the determination of τ_k from the comparison of the yield ratios with an approximate value for τ.

Finally, a least-square-fit program has been made to obtain the best value of the mean life, τ, from the corrected values of F(d) as a function of the distance. Figure 2 shows the corrected experimental data points for F(d) vs. the stopping distance and the line is the best-fit curve. We find:

$$\tau = (13.2 \pm 0.8) \text{ ps}$$

and using a value of $\alpha_T < 0.01$ for internal correction, calculated from ref. 11, we deduce:

$$B(E2,\, 0^+ \rightarrow 2^+) = (0.091 \pm 0.006)\ e^2 b^2 \quad .$$

5. Conclusion

The value of $B(E2, 0^+ \rightarrow 2^+)$ found is slightly smaller than those previously deduced by other methods, and we feel, more accurate, as is shown in Table I.

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Table 1.

Reference	B(E2, $0^+ \rightarrow 2^+$) (e^2b^2)
3	$0.11 \begin{cases} +0.02 \\ -0.04 \end{cases}$
	$0.16 \begin{cases} +0.02 \\ -0.06 \end{cases}$
4	0.115
5	0.13 ±0.05
6	0.108 ±0.010
Present work	0.091 ±0.006

Figure Captions

Fig. 1. Gamma spectra from the 2+ → 0+ transition (803 keV) in ^{206}Pb at different stopping distances. One can see the variation of the shifted and unshifted line intensities with distance.

Fig. 2. Plot of Log $\left(\frac{I_u}{I_u + I_s}\right)$ vs. the separation distance between the target and plunger. The symbols are the experimental points and the straight line is the best fit result.

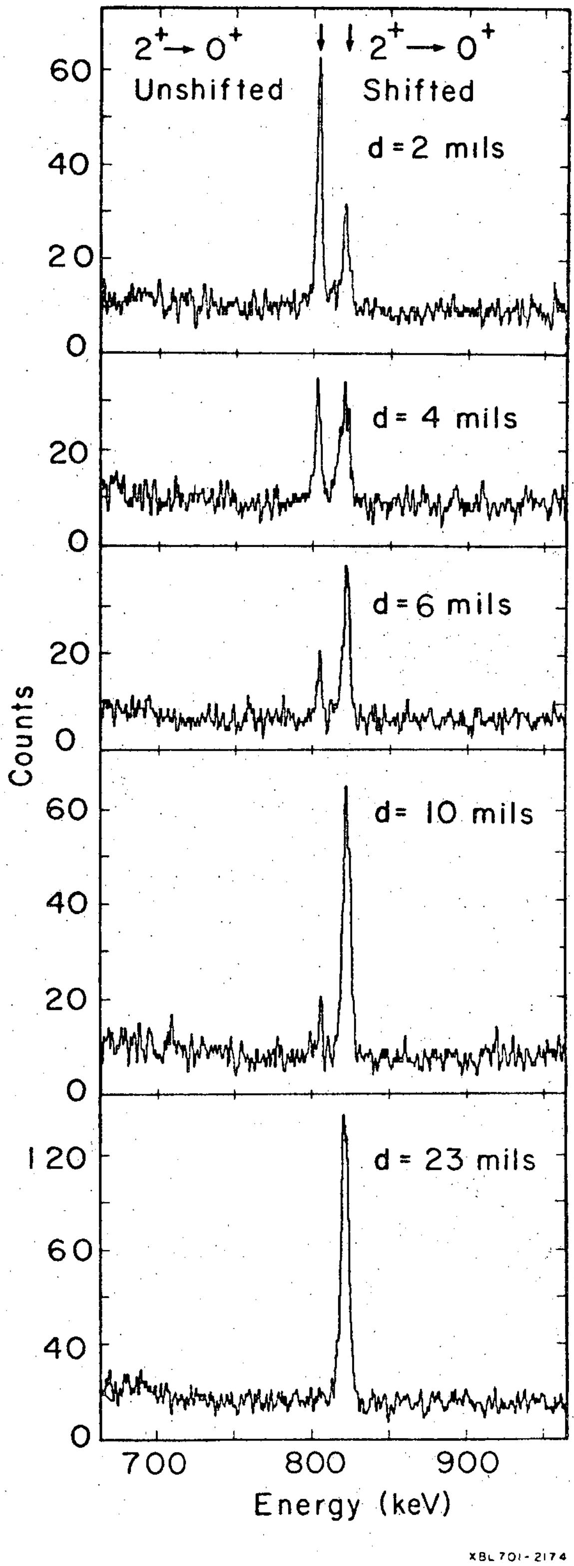
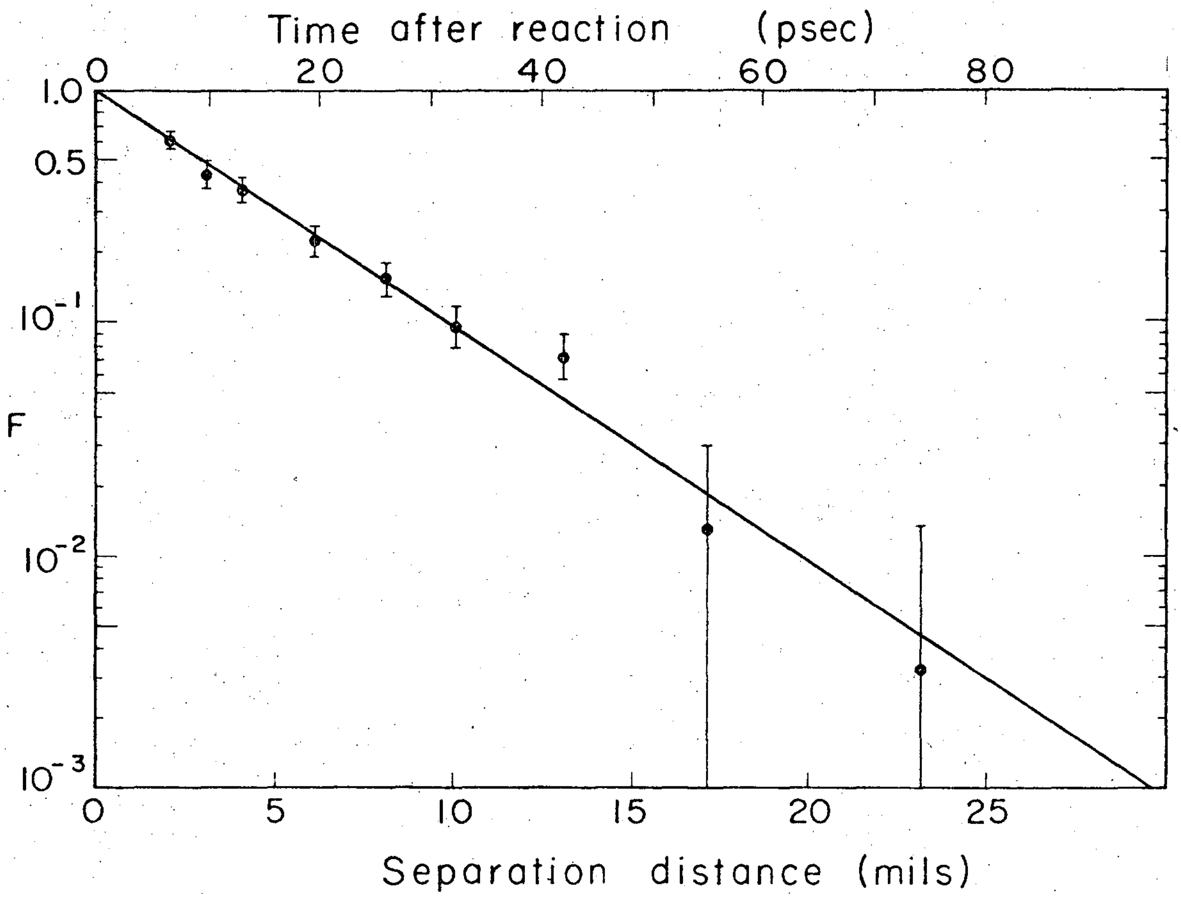

$2^+ \rightarrow 0^+$
Unshifted
$2^+ \rightarrow 0^+$
Shifted
d = 2 mils
d = 4 mils
d = 6 mils
d = 10 mils
d = 23 mils
Counts
0
20
40
60
120
700
800
900
Energy (keV)
XBL 701-2174

Fig. 1



XBL701-2176

Fig. 2

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