Title

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LIFETIME OF THE 2^3P_0 AND THE 2^3S_1 STATES OF HELIUMLIKE KRYPTON (Kr XXXV)*†

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ABSTRACT

The radiative decay $2^3S_1 - 1^1S_0$ has been observed in the two electron atom Kr XXXV. From the observed decay, the electric dipole transition rate $A_{E1}(2^3P_0)$ and the magnetic dipole transition rate $A_{M1}(2^3S_1)$ can be obtained. We find: $A_{E1}(2^3P_0)=(6.0 \pm 0.2) \times 10^8\ \text{sec}^{-1}$ and $A_{M1}(2^3S_1)=(5.0 \pm 1.5) \times 10^9\ \text{sec}^{-1}$. From the measured 2^3P_0 decay rate, a value of 43.65 ± 0.7 eV is inferred for the $2^3S_1 - 2^3P_0$ energy splitting.

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This letter reports a beam foil time-of-flight measurement of the radiative lifetime of the 2^3P_0 and 2^3S_1 states of 34 times ionized (heliumlike) krypton. Measurement of the 2^3P_0 lifetime may be interpreted to yield a value of the $2^3S_1 - 2^3P_0$ energy splitting which is of sufficient precision to be sensitive to the Lamb shift contribution, and contributions from higher-order relativistic effects. Measurement of the lifetime of the 2^3S_1 state in this system extends the range over which the magnetic dipole transition (M1) rate has been measured in heliumlike atoms[1-8] (He I to Kr XXXV) to over 13 orders of magnitude. To our knowledge this is the largest range of lifetime for which the theory of a radiative transition has been verified.

In heliumlike Kr the 2^3P_0 state decays to the 2^3S_1 state by a fully allowed electric dipole transition (E1) in about 1.7 ns. This is long compared to the approximately 0.2 ns lifetime of the 2^3S_1 state, and consequently the 2^3P_0 lifetime can be determined by observation of the $2^3S_1 \rightarrow 1^1S_0$ transition after sufficient time has elapsed to allow for the decay of the initial 2^3S_1 population. In the absence of hyperfine structure or external fields, the rate for E1 decay of the 2^3P_0 state to the 2^3S_1 state is give by[5] (in units $m = c = \hbar = 1$)

$$A_{E1}(2^3P_0) = \alpha\, k^3\, 12\, (Z\alpha)^{-2}\, [1 + 0.759\, Z^{-1} - 0.417\, (Z\alpha)^2]^2 \qquad (1)$$

where k is the $2^3S_1 - 2^3P_0$ energy splitting and α the fine structure constant.

To understand the magnitude of the various contributions to the $2^3S_1 - 2^3P_0$ energy splitting it should be noted that the 2^3P_0 state arises purely from the coupling of the $1s_{1/2}$ and $2p_{1/2}$ electrons and contains no $p_{3/2}$ as do the other 2p states. Similarly the 2^3S_1 state arises entirely from the coupling of the $1s_{1/2}$ and $2s_{1/2}$ electrons. Consequently, the 2^3S_1 - 2^3P_0 system is the analog of the hydrogenlike $2^2s_{1/2}$ - $2^2p_{1/2}$ system, and in the hydrogenic approximation (without Lamb shift) the states are degenerate. The actual energy splitting (see Table I) results mainly from three contributions: 1.) Coulomb interaction of the two electrons for which the leading (non relativistic) term is $\alpha(Z\alpha)$. 2.) Relativistic effects, such as the interaction of the spin-magnetic-dipole moments of the two electrons, whose leading terms are $\alpha(Z\alpha)^3$. 3.) Lamb shift. The Lamb shift, which accounts for 2×10^{-5} of the 2^3S_1 - 2^3P_0 energy splitting in neutral helium,[17] scales almost as fast as Z^4, and at Z=36 accounts for about 4% of the energy splitting. The presence of the Lamb shift decreases the decay rate by 12%.

The techniques and apparatus used to measure lifetimes in heliumlike Kr are essentially the same as used in measurements on heliumlike Ar, Ti, V and Fe.[3,5] Beams containing at least several percent heliumlike Kr as measured by magnetic deflection experiments were produced by passing the 714 MeV beams of Kr^{84} and Kr^{86} from the Berkeley SuperHILAC through 350 $\mu g/cm^2$ Be foil. Si(Li) x-ray detectors mounted downstream of the foil were used to observe the 13 keV x rays originating from decays in flight of the 2^3S_1 state. The x-ray detectors were calibrated against the known K_α and K_β x rays obtained by fluorescing compounds of Br, Sr, Mo, Cu, and Zn.

Identification of radiative decay from the 2^3S_1 state of heliumlike Kr is based upon several factors: 1.) identification of Kr^{+34} in the beam, 2.) observation of x rays, Fig. 1, originating in the beam with an energy corresponding to the 2^3S_1 - 1^1S_0 transition energy (see Table II), 3.) measurement of a double exponential decay consistent with the compound decay $2^3P_0 \rightarrow 2^3S_1 \rightarrow 1^1S_0$, 4.) absence of any known long lived states of Kr XXXI through Kr XXXVI with transition energies near 13 keV, 5.) similarity with spectra and decays obtained with lower Z beams.

Fig. 2 shows one of the eight decay curves used to determine the 2^3P_0 lifetime. In each case measurements were made over at least two decay lengths. Values of the lifetimes obtained by least-squares fits to the decay curves are shown in Fig. 3 along with calculated lifetimes which show the effects of including in the theory both relativistic corrections and Lamb shift. Our result for the 2^3P_0 lifetime, corrected for 1% time dialation is $(1.66 \pm 0.06) \times 10^{-9}$ sec. The quoted error is twice the standard deviation of the mean + 1% for uncertainty in the beam velocity. Possible sources of systematic error include deadtime in the detectors from gamma rays and neutrons, and cascades from very high excited states. Cascades from these states have not been observed in experiments at lower Z and there is no reason to expect them here. The gamma ray and neutron background is somewhat higher at Kr beam energies than those used at lower Z. Either effect would make the apparent lifetime longer than the true lifetime.

The value of the 2^3S_1 - 2^3P_0 energy splitting obtained by using Eq. 1 is 43.65 ± 0.7 ev where the error includes both the experimental error and a 1% uncertainty in Eq. 1. The calculated values of the $2^3S_1 - 2^3P_0$ splitting from Table II is 44.24 ev. Agreement between theory and experiment suggests that the sum of the uncalculated terms in the theory is not large compared to the experimental error.

Fig. 4 shows the decay curve used to determine the lifetime of the 2^3S_1 state. As there are cascades from the 2^3P_0 state present, the decay curve was fit to a double exponential in which the 2^3P_0 lifetime was held fixed. At small foil-detector separations most of the counts come from the decay of the initial population of the 2^3S_1 state and the extracted 2^3S_1 lifetime was found to be insensitive to the exact 2^3P_0 lifetime used. Again choosing $2\sigma + 1\%$ for the error, our measured 2^3S_1 lifetime in heliumlike Kr is $(2.0 \pm 0.6) \times 10^{-10}$ sec, in agreement with the theoretical value of 1.7×10^{-10} sec of Johnson and Lin.[18]

We would like to acknowledge helpful discussions with Dr. Peter Mohr on the theoretical aspects of this work. We thank the operators and staff of the Super-Hilac whose efforts make this work possible and we thank Douglas Macdonald for excellent engineering assistance.

TABLE I. CONTRIBUTIONS TO THE 2^3S_1 - 2^3P_0 ENERGY SPLITTING IN HELIUMLIKE KRYPTON

Contribution	Order	Value (ev)
Hydrogenic[a]	$(Z\alpha)^2$, $(Z\alpha)^4$, ...	0
One Photon Exchange (between bound electrons)		
Coulomb interaction (non rel.)[b]	$\alpha(Z\alpha)$	37.03
relativistic effects[c]	$\alpha(Z\alpha)^3$	9.66
relativistic effects[d]	$\alpha(Z\alpha)^5$	0.47
Two Photon Exchange (between bound electrons)		
Coulomb interaction (non rel.)[e]	$\alpha^2(Z\alpha)^0$	-0.70
relativistic effects[f,g]	$\alpha^2(Z\alpha)^2$	-0.50
Lamb Shift[h]		
one photon self energy	$\alpha(Z\alpha)^4 \ln(Z\alpha)^{-2}$, $\alpha(Z\alpha)^4$, ... (all)	-1.86
vacuum polarization	$\alpha(Z\alpha)^4$, $\alpha(Z\alpha)^5$, ...	0.18
nuclear size corr		-0.04
TOTAL		44.24

[a]Reference 9
[b]Reference 10
[c]Reference 11
[d]Reference 12
[e]Reference 13
[f]Reference 14
[g]Reference 15
[h]Reference 16

TABLE II. Kr XXXV $2^3S_1 - 1^1S_0$ ENERGY SEPARATION (keV)

Experiment	Observed x-ray	=	12.893	
	Relativistic Doppler shift correction	=	0.116	
	Peak uncertainty			0.010
	Calibrated uncertainty			0.010
	Alignment error[a] (1°)			0.030
			13.009 ± 0.033 (1σ)	
Theory	$Z\alpha$ expansion[b]		12.981	
	$(Z\alpha)^6$ Dirac hydrogenic		0.007	
	1s - 2s Lamb shift[c]		-0.011	
			12.977	
	Experiment - Theory	=	0.032 ± 0.033 (1σ)	

[a] Uncertainty in the angle between the beam and the x-ray detectors results in an energy uncertainty through the Doppler shift.

[b] Reference 11

[c] Reference 16

REFERENCES

†. Work supported by the United States Energy Research and Development Administration.

1. R. Marrus and R. W. Schmieder, Phys. Rev. Lett., 32A, 431 (1970); R. Marrus and R. W. Schmieder, Phys. Rev., A5, 1160 (1972).

2. H. W. Moos and J. R. Woodworth, Phys. Rev. Lett., 30, 775 (1973).

3. H. Gould, R. Marrus and R. W. Schmieder, Phys. Rev. Lett., 31, 504 (1973).

4. C. L. Cocke, B. Curnutte and R. Randall, Phys. Rev. Lett., 31, 507 (1973); C. L. Cocke, B. Curnutte, J. R. Macdonald and R. Randall, Phys. Rev., A9, 57 (1974).

5. H. Gould, R. Marrus and P. J. Mohr, Phys. Rev. Lett., 33, 676 (1974).

6. J. A. Bednar, C. L. Cocke, B. Curnutte and R. Randall, Phys. Rev. A11, 460 (1975).

7. J. R. Woodworth and H. W. Moos, Phys. Rev., A12, 2455 (1975).

8. H. Gould and R. Marrus, Bull. Am. Phys. Soc., 21, 84 (1976).

9. See, for example, H. A. Bethe and E. E. Salpeter, Quantum Mechanics of One- and Two-Electron Atoms (Springer - Verlag, Berlin, 1957).

10. See, for example, R. E. Knight and C. W. Scherr, Rev. Mod. Phys., 35, 431 (1963).

11. H. T. Doyle, in Advances in Atomic and Molecular Physics, edited by D. R. Bates and I. Esterman (Academic, New York, 1969) Vol. 5.

12. P. J. Mohr, private communication.

13. F. C. Sanders and C. W. Scherr, Phys. Rev., 181, 84 (1969).

14. P. J. Mohr, in Proceedings of the Fourth International Conference on Beam-Foil Spectroscopy (1975) (Plenum Press, to be published).

15. The sum of the nonrelativistic terms, and the sum of the leading one photon and two photon relativistic terms are in agreement with the corresponding terms of A. M. Ermolaev and M. Jones, J. Phys., 87, 199 (1974) and tables quoted therein.

16. P. J. Mohr, Phys. Rev. Lett., 34, 1050 (1975), also reference 14.

17. K. S. Suh and M. H. Zaidi, Proc. Roy. Soc., 291, 94 (1966); A. M. Ermolaev, Phys. Rev. Lett., 34, 380 (1975).

18. W. R. Johnson and C. Lin, Phys. Rev., A9, 1486 (1974).

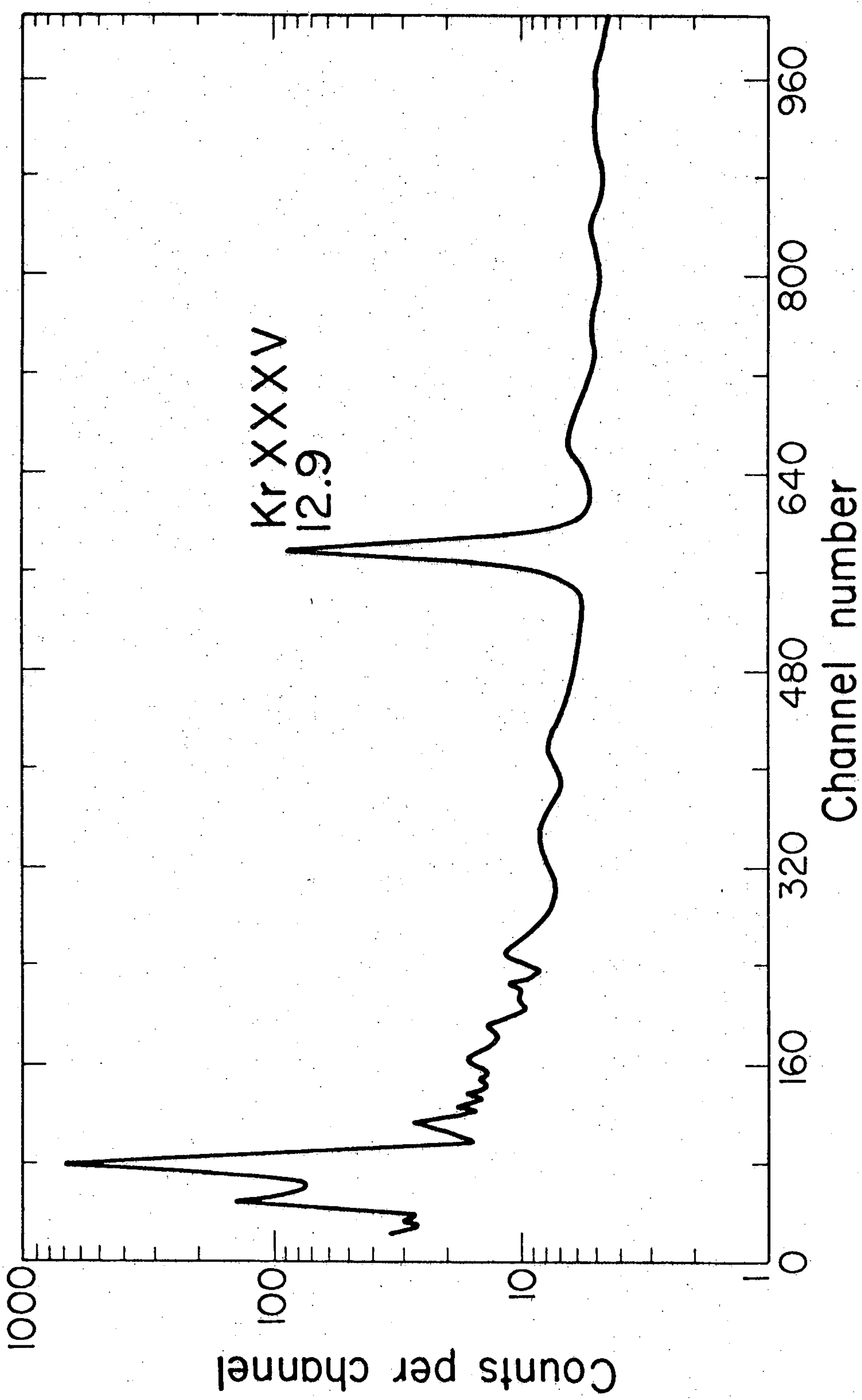
FIGURES

Fig. 1. Observed pulse height spectra with a foil-detector separation of 6 cm. The peak at channel 580 is the 12.89 keV x-rays from the decay in flight of the 2^3S_1 state of heliumlike Kr. The 300 ev linewidth is instrumental linewidth plus Doppler broadening. The origin of the low energy peaks has not been identified.

Fig. 2. Typical decay curve of $2^3P_0 \rightarrow 2^3S_1 \rightarrow 1^1S_0$ at large foil-detector separations. The error bars are the statistical error in each point.

Fig. 3. Measured 2^3P_0 lifetime as compared with theory (from Table I and Eq. 1). Error bars on individual measurements are error to least square fit of the decay curves only. Solid bar includes all error (see text). Horizontal lines represent theoretical lifetimes, showing various contributions to the theory.

Fig. 4. Decay curve of $2^3P_0 \rightarrow 2^3S_1 \rightarrow 1^1S_0$ at small foil-detector separations. The contributions from the decay of the initial 2^3S_1 population and from cascades from the 2^3P_0 state are plotted separately below.



XBL 7510-8597 A

Fig. 1

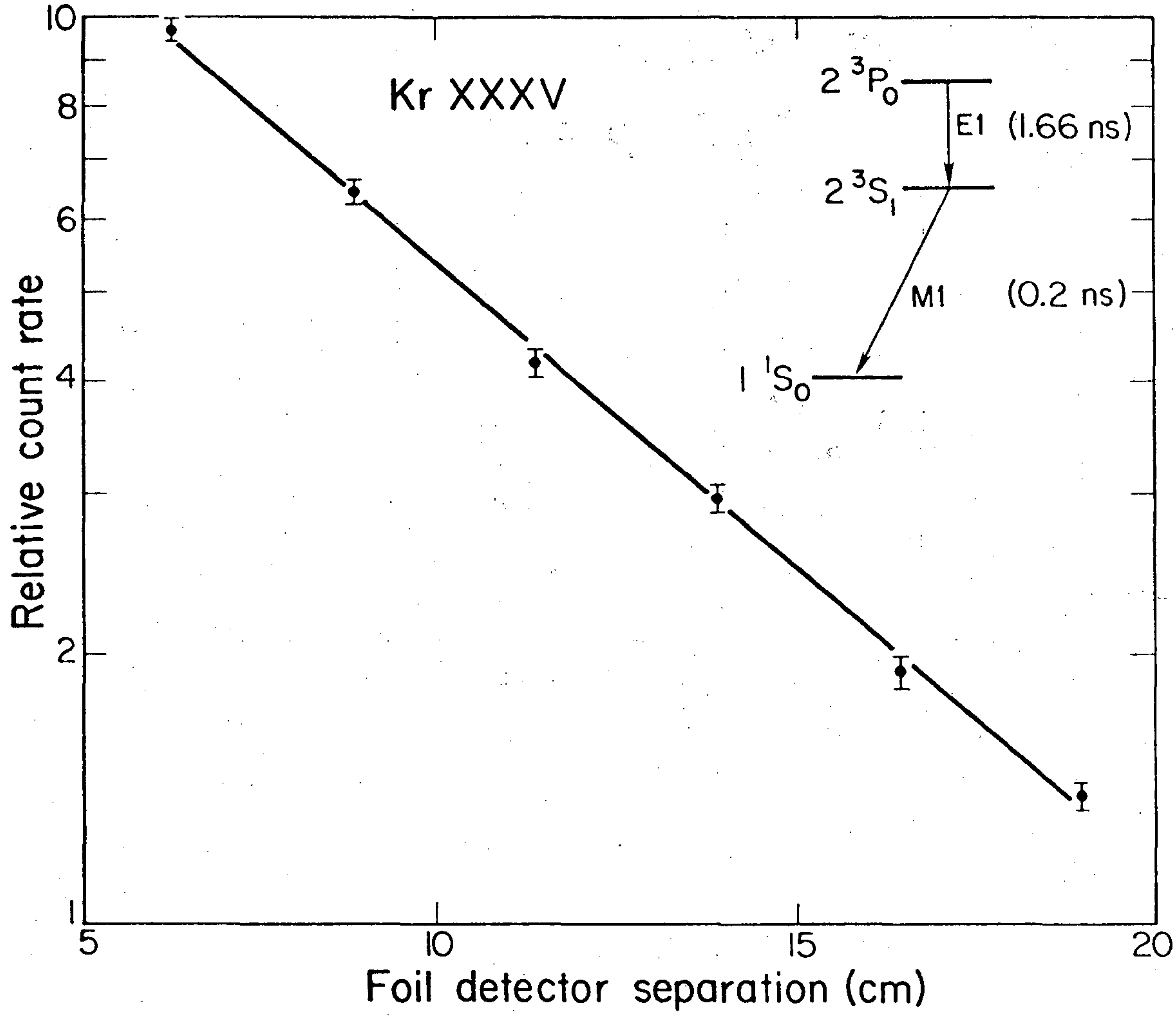


Fig. 2

XBL 759-3885 A

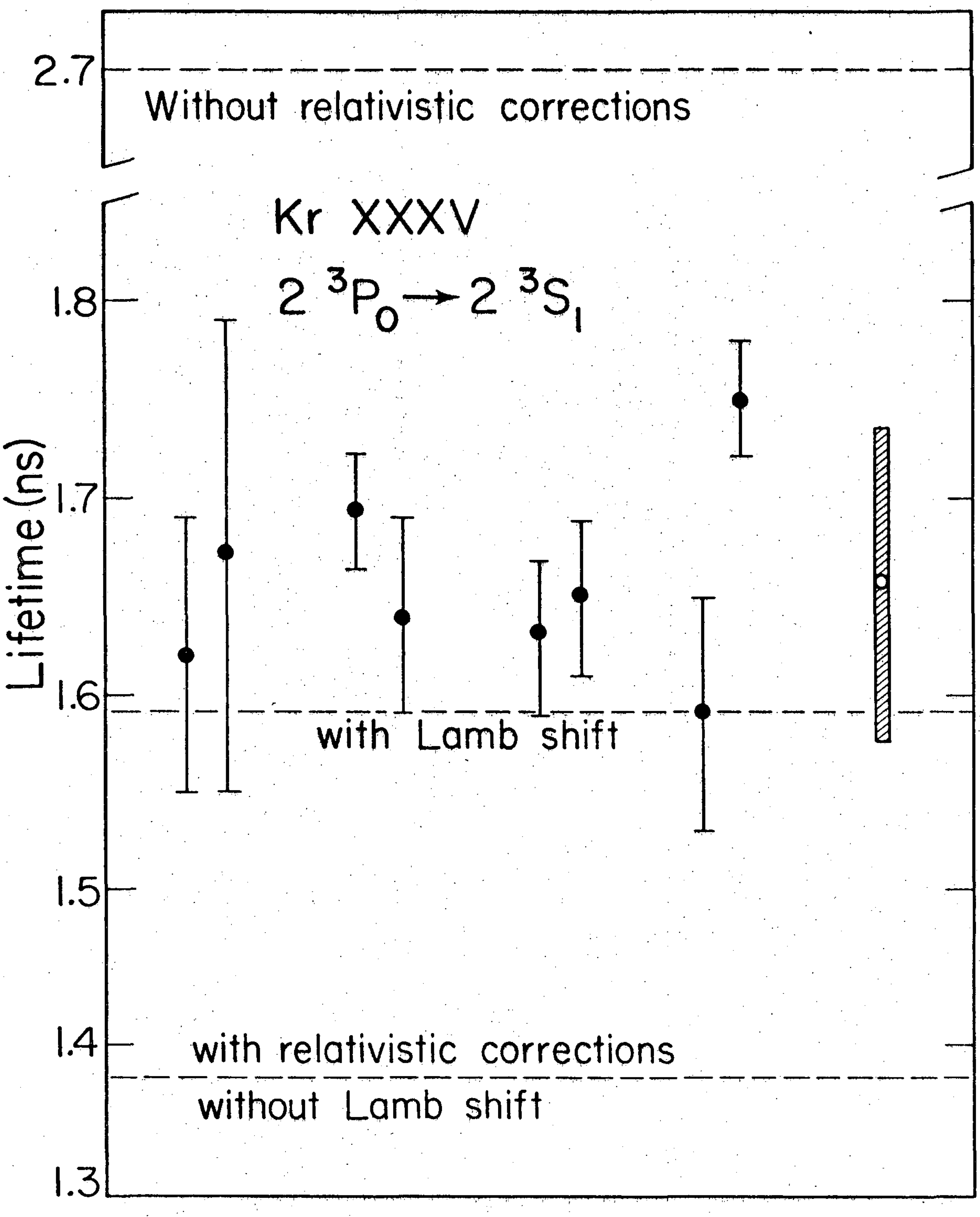


Fig. 3

XBL 759-4038 A

0 0 0 0 4 5 0 0 1 3 3

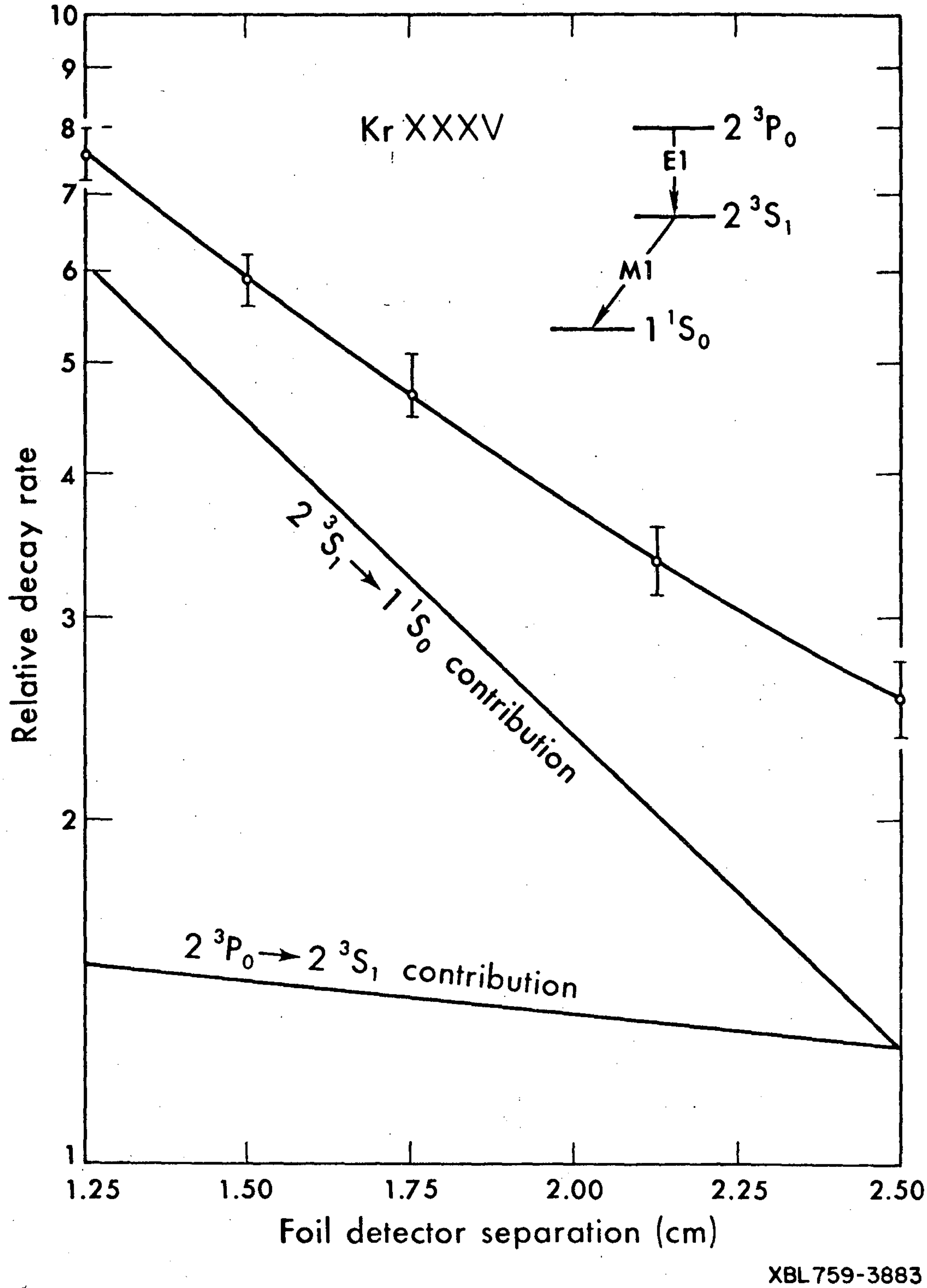


Fig. 4

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