Submitted to Physical Review Letters

LBL-2906
Preprint c.2

RADIATIVE DECAY OF THE 2^3S_1 AND 2^3P_2 STATES OF HELIUM-LIKE VANADIUM (Z = 23) AND IRON (Z = 26)

Harvey Gould, Richard Marrus,
and Peter J. Mohr

June 21, 1974

Prepared for the U. S. Atomic Energy Commission
under Contract W-7405-ENG-48

TWO-WEEK LOAN COPY

This is a Library Circulating Copy
which may be borrowed for two weeks.
For a personal retention copy, call
Tech. Info. Division, Ext. 5545

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY
340

LBL-2906 c.2

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

RADIATIVE DECAY OF THE 2^3S_1 AND 2^3P_2 STATES OF HELIUM-LIKE VANADIUM (Z = 23) AND IRON (Z = 26)†

Harvey Gould, Richard Marrus, and Peter J. Mohr

Department of Physics and Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

ABSTRACT

Lifetimes of the M1 decay $2^3S_1 \rightarrow 1^1S_0$ and of the decay $2^3P_2 \rightarrow 1^1S_0$ have been measured in the two-electron ions V^{+21} and Fe^{+24}. The measured lifetimes are $\tau(2^3S_1) = 16.9(7)$ nsec. for V^{+21} and $\tau(2^3S_1) = 4.8(6)$ nsec. for Fe^{+24}. The 2^3P_2 lifetimes are compared with a calculation that considers relativistic corrections and hyperfine structure effects. It is found that for V^{+21}, hyperfine effects contribute appreciably to the lifetime. For Fe^{+24} we obtain $\tau(2^3P_2) = 0.11(2)$ nsec.

The study of radiative decay from the 2^3S_1 and 2^3P_2 levels of the two-electron system offers an opportunity to test the theory of forbidden decay in a system where precise, unambiguous calculations of decay rates can be made. In this paper, we describe some measurements designed to extend existing experimental information on the rates of these decays to the two-electron atoms V^{+21} and Fe^{+24}. We develop a theory for the 2^3P_2 rates which take into account leading order relativistic corrections and hyperfine effects. Our results on vanadium show the first evidence for the influence of the hyperfine interaction on the radiative decay of an energy level belonging to the two-electron system.

Experimental work on the 2^3S_1 levels of the two-electron system has established the single-photon nature of the decay in Ar^{+16} (Ref. 1) and ordinary helium.[2] The theory of this decay has been examined by several authors[3] and detailed calculations of the rates have been made by Drake[4] and by Johnson and Lin[5] using somewhat different starting points. Measurements of this decay rate have been made on Ar^{+16}, Ti^{+20} (Ref. 6) and Cl^{+15} (Ref. 7). The measured rates in Cl and Ar differ from theory by several times the quoted error, whereas the result in Ti is in agreement. In order to establish the Z dependence of this discrepancy we report here measurements on V^{+21} and Fe^{+24}.

Interest in the 2^3P_2 levels centers mainly on the M2 decay mode to the 1^1S_0 ground level which has a rate comparable with the E1

rate to 2^3S_1 for ions with $Z \simeq 20$. The M2 decay was first observed in Ar^{+16} (Ref. 8) and rates have now been measured in S^{+14} (Ref. 9), Cl^{+15} (Ref. 10) and Ar^{+16} (Ref. 11). In this paper we present evidence indicating that the decay of this level is strongly influenced by the hyperfine interaction in V^{+21} and give results for Fe^{+24}.

The lifetimes were measured by the beam-foil time-of-flight method. Our apparatus has been described previously[6] and the details are not repeated here. The vanadium (Z = 23) and iron (Z = 26) ions were obtained from the SuperHILAC at an energy of 7.2 MeV/AMU. Excitation of the beams into the metastable states was done with a 50 $\mu gm/cm^2$ carbon foil. Decay curves are taken by varying the foil-detector separation. The total number of counts under the peak is integrated and normalized to the integrated beam current collected in a Faraday cup. This quantity is plotted vs. foil-detector separation. A sample decay curve is shown in Fig. 1.

Since the 2^3P_2 and 2^3S_1 energy separations are small compared with the detector resolution, the decay curves are composites, exhibiting fast components and slow components. The slow components are ascribed to the 2^3S_1 decay and the fast components to decay from 2^3P_2. As discussed below, the slow and fast components are probably composites of two or more exponentials as the result of hyperfine effects in V^{+21} and cascading effects in Fe^{+24}.

The isotope ^{51}V has a nuclear spin I = 7/2 and a magnetic moment $\mu = 5.15$ nm.[12] The resulting hyperfine structure (HFS)

influences our decay curves by admixing 2^3P_2 with 2^3P_1 and 2^1P_1. The 2^3P_2 level is split into five components with total angular momentum between F = 3/2 and F = 11/2 (Fig. 1). Because the hyperfine interaction is diagonal in F, the rates from both F = 3/2 and F = 11/2 are unaffected by hyperfine structure. However, the rates from F = 5/2, 7/2 and 9/2 will all be altered. Hence, the observed decay curve will be a composite of four exponentials weighted according to the initial populations of each of the hyperfine levels.

The most abundant stable iron isotope has zero spin and hyperfine effects are not present. Hence the decay of 2^3P_2 is exclusively by E1 decay to 2^3S_1 and M2 to 1^1S_0.

A problem arises in the interpretation of the 2^3S_1 decay due to cascading from 2^3P_0. The lifetime of 2^3P_0 is calculated to be τ = 2.7 nsec. which is close to that of 2^3S_1. Hence cascading effects from this level may be important. The shape of the resultant curve will depend upon the relative population $R \equiv \frac{N_0(2^3P_0)}{N_0(2^3S_1)}$ of the two states and the decay rates. It was found that the data could be fit to two exponentials for $0 \leq R \leq 0.8$. Varying the lifetimes of the two exponentials, we find that the "best fit" values for $\tau(2^3S_1)$ varied between 4.2 ns and 5.3 ns where 5.3 ns results from a single exponential fit (R = 0) and, hence, is an upper limit to the 2^3S_1 lifetime. Similarly, the values for $\tau(2^3P_0)$ varied between 1.3 ns and 3.3 ns. We note that the theoretical value of $\tau(2^3P_0)$ = 2.7 nsec corresponds to $\tau(2^3S_1)$ = 4.8 nsec. We have chosen to take the mean value as the experimental value and to take cascading into account by using an increased error.

In Fig. 1, an experimental decay curve is shown for the V^{+21} beam. The decay curve is fit by identifying the data points beyond 22 cm with the 2^3S_1 decay. These yield a lifetime $\tau(2^3S_1) = 16.9(7)$ nsec. When this decay is subtracted from the experimental curve it yields the points shown. These are fit to a composite decay curve constructed by assuming that each of the F states associated with 2^3P_2 has the theoretical lifetime shown in Table I. These lifetimes include effects due to hyperfine quenching. Moreover, the initial populations of the F states are taken as proportional to (2F + 1). The resultant fit to the experimental points is as shown and is seen to be quite good.

To calculate accurate theoretical rates for the 2^3P_2 level, the transition-matrix elements are evaluated to zeroth and first order in the quantities Z^{-1} and $(Z\alpha)^2$. The zeroth order term is the non-relativistic hydrogenic approximation. The term of order Z^{-1} is the first correction in the nonrelativistic Z - expansion of the matrix element. The leading relativistic correction, of order $(Z\alpha)^2$, is obtained by evaluating the relativistic transition operator between states formed from properly symmetrized products by hydrogenic Dirac wave functions.

For the M2 transition, the coefficient of Z^{-1} has been determined by Drake [13] from the Z-expansion calculation of Dalgarno and Parkinson.[14] Taking his result together with the leading relativistic and finite wavelength (retardation) corrections yields

$$A_{M2}(2^3P_2) = \alpha k^5 \frac{2^{15}}{5\cdot 3^{10}} (Z\alpha)^{-2} [1 + .147\, Z^{-1} - .640(Z\alpha)^2]^2 \qquad (1)$$

(in units where $m_e = c = \hbar = 1$) where k is the transition energy.

Because the nonrelativistic velocity form of the matrix element for $n \to n$ E1 transitions vanishes to lowest order in Z^{-1}, the evaluation of the E1 transition rate $2^3P_2 \to 2^3S_1$ is simplified by making the dipole approximation and converting the matrix element to the length form. The error in making this approximation is negligible due to the smallness of the transition energy: $\langle \vec{k}\cdot\vec{r} \rangle = 0(\alpha)$. The conversion to length form is valid relativistically and so relativistic corrections may be obtained as described above. For this transition matrix element, the coefficient of Z^{-1} has been obtained by Cohen and Dalgarno.[15] We thus have

$$A_{E1}(2^3P_2) = \alpha k^3\ 12(Z\alpha)^{-2}[1 + .759\ Z^{-1} - .167\ (Z\alpha)^2]^2 \qquad (2)$$

The transition probability for the E1 decay $2^3P_0 \to 2^3S_1$, obtained as for the 2^3P_2 decay, is given by

$$A_{E1}(2^3P_0) = \alpha k^3\ 12(Z\alpha)^{-2}[1 + .759\ Z^{-1} - .417\ (Z\alpha)^2]^2 \qquad (3)$$

We note that the theoretical uncertainty in the expressions for the transition rates listed above is expected to be of the order of 1% or less for Z in the range 10-40.

In the case of vanadium, which has a non-zero nuclear spin, the 2^3P_2 and 2^3P_0 states undergo an E1 transition to the 1^1S_0 state due to hyperfine mixing.[16] An estimate of the transition rate is obtained in the following way. Nonrelativistic intermediate coupling wave functions are taken as the unperturbed basis. The hyperfine interaction

which is diagonal in F = J + I, is treated in first-order perturbation theory. Only the effect of mixing of the 2^3P_2 and 2^3P_0 states with the nearby 2^3P_1 and 2^1P_1 states is included. The dipole transition operator then has a non-vanishing matrix element between the perturbed 2^3P_2 and 2^3P_0 states and the 1^1S_0 state which is proportional to the dipole matrix element between the LS coupled 2^1P_1 state and the 1^1S_0 state. The latter is evaluated with the aid of the Z-expansion of Dalgarno and Parkinson.[14] The hyperfine matrix elements are approximated by evaluating the contact interaction term between hydrogenic product wave functions. Energy differences are evaluated by means of the Z expansion of the nonrelativistic energies,[17] together with the Z expansion of the order α^4 corrections.[18] The transition rates thus obtained are added to the rates discussed above and the resulting values for the lifetime of the 2^3P_2 state are listed in Table I.

In Fig. 2 we compare all of the measured decay rates of 2^3P_2 with the corresponding theoretical rates. Agreement is seen to be very good over a wide range of Z. For vanadium, the theoretical rate includes the contribution from hyperfine quenching. It is seen that the experimental and theoretical rates would be in serious disagreement without contributions from this mechanism. We take this as very strong evidence that hyperfine quenching is indeed present.

In Fig. 3 we compare the measured 2^3S_1 decay rates with the calculated rates. Agreement between theory and experiment is satisfactory for Z = 22, 23, 26, but puzzling discrepancies exist at Z = 17 and 18.

We are indebted to Al Ghiorso and the staff of the SuperHILAC.

for their enthusiastic support of this work. The development of the vanadium and iron beams was a vital product of this support. Doug MacDonald gave valuable engineering support. One of us (P.J.M.) gratefully acknowledges helpful conversations with Professors Charles Schwartz and Eyvind H. Wichmann.

REFERENCES

† Work supported by the U. S. Atomic Energy Commission.

1 R. Marrus and R. W. Schmieder, Phys. Lett., 32A, 431 (1970).

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

3 G. Feinberg and J. Sucher, Phys. Rev. Lett. 26, 681 (1971); H. R. Griem, Astrophys. J. 156, 1103 (1969); I. L. Beigman and V. I. Safronova, Zh. Eksp. Teor. Phys. 60, 2045 (1971) [Sov. Phys. JETP 33, 1102 (1971)]; S. Feneuille and E. Koenig, Comptes Renues Acad. Sc. Paris 274, 46 (1972); G. W. F. Drake, Phys. Rev. A 5, 1979 (1972).

4 G. W. F. Drake, Phys. Rev. A3, 908 (1971).

5 W. R. Johnson and C. Lin, Phys. Rev. A 9, 1486 (1974).

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

7 C. L. Cocke, B. Curnutte and R. Randall, Phys. Rev. Lett 31, 508 (1973).

8 R. Marrus and R. W. Schmieder, Phys. Rev. Lett. 25, 1689 (1970).

9 C. L. Cocke, B. Curnutte and R. Randall, Phys. Rev. A 9, 1823 (1974).

10 C. L. Cocke, B. Curnutte, J. R. MacDonald and R. Randall, Phys. Rev. A 9, 57 (1974).

11 R. Marrus and R. W. Schmieder, Phys. Rev. A 5, 1160 (1972).

12 W. F. Ramsey, Molecular Beams, Oxford University Press, p. 173, (1963).

13 G. W. F. Drake, Astrophys. J. 158, 1199 (1969).

14 A. Dalgarno and E. M. Parkinson, Proc. Roy. Soc. A 301, 253 (1967).

15 M. Cohen and A. Dalgarno, Proc. Roy. Soc. A 293, 359 (1966).

16 A discussion of the history and calculations of this effect is given in R. H. Garstang, J. Opt. Soc. Am. 52, 845 (1962).

17 R. E. Knight and C. W. Sherr, Rev. Mod. Phys. 35, 431 (1963).

18 H. T. Doyle, Adv. At. Mol. Phys. 5, 337 (1969).

Table I. Theoretical transition rates and lifetime of the 2^3P_2 state in helium-like ions.

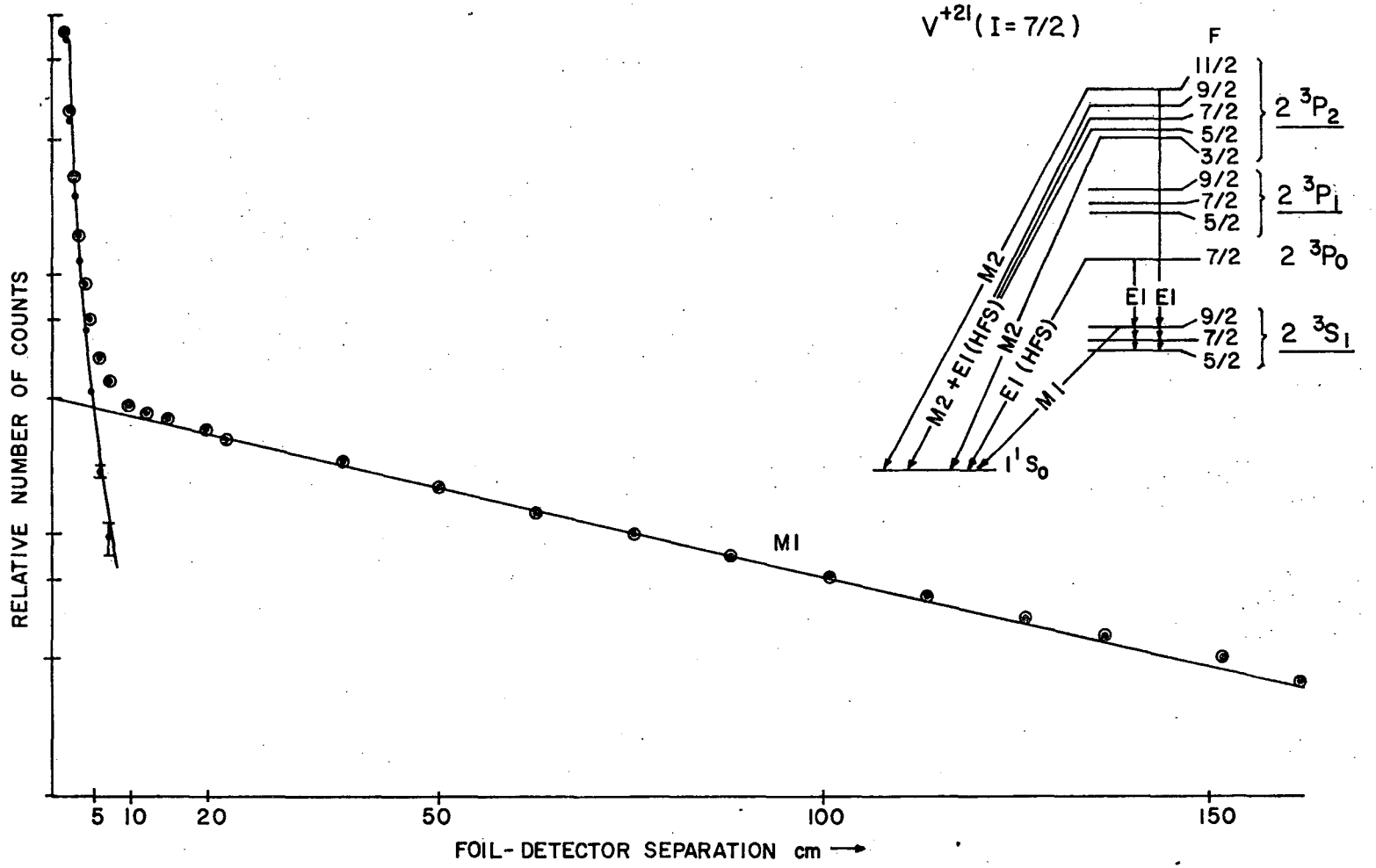
Z	A_{E1} ($nsec^{-1}$)	A_{M2} ($nsec^{-1}$)	F	A_{E1}^{HFS} ($nsec^{-1}$)	τ (nsec)
16	.259	.117			2.66
17	.301	.194	All	<.007	≃2.01
18	.352	.312			1.51
22	.687	1.64			.429
23	.820	2.37	3/2	0	.313
			5/2	.99	.239
			7/2	1.75	.202
			9/2	1.69	.205
			11/2	0	.313
26	1.43	6.50			.126

FIGURE CAPTIONS

Figure 1. Sample decay curve obtained with V^{+21} beam. The points beyond 22 cm are fit to a single exponential and ascribed to decay of the 2^3S_1 level. The near points are fit to a composite of four exponentials as described in the text and are ascribed to decay of the 2^3P_2 level.

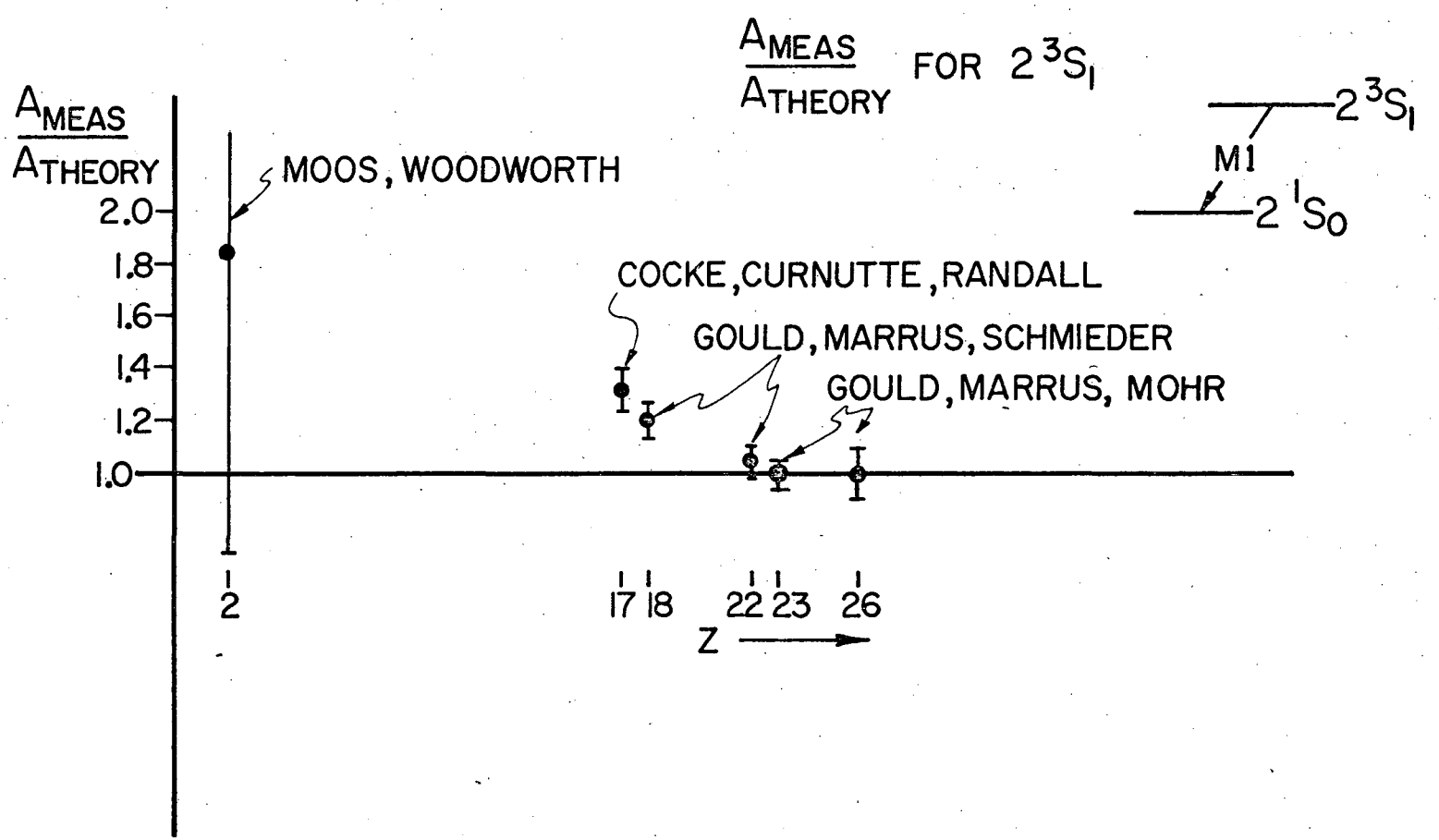
Figure 2. Comparison between measured and calculated decay rates for the 2^3S_1 level.

Figure 3. Comparison between measured and calculated M2 rates for decay from the 2^3P_2 level. The point at $Z = 23$ labelled "without HFS" is obtained by making a best fit to our vanadium data using a single exponential.



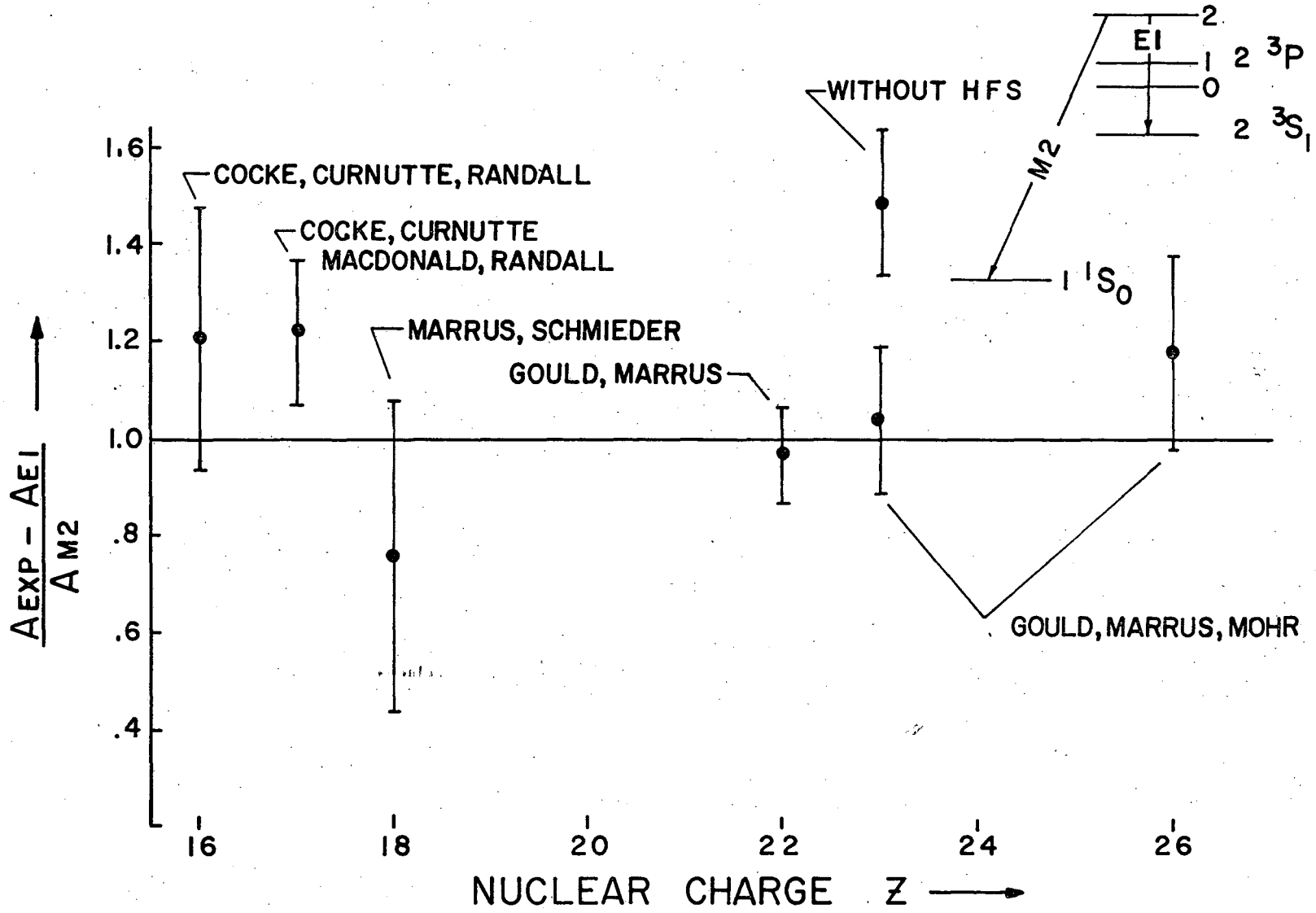
XBL 746-1022

Fig. 1



XBL 742-295

Fig. 2



XBL 746-1021

Fig. 3

LEGAL NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

TECHNICAL INFORMATION DIVISION
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720