where we have taken $\alpha^{-1} = 137.036\,08$.

Combining this result with previous calculations[1,5] we obtain

$$\nu_{\text{theor}} = 2.034\,04 \times 10^5 \text{ MHz} \quad (8)$$

for the ground-state positronium hyperfine interval, which is to be compared with the experimental value[6]

$$\nu_{\text{expt}} = 2.033\,96(5) \times 10^5 \text{ MHz}.$$

One observes the theoretical result is now slightly more than 1 standard deviation above the experimental value. Considering the estimate for uncalculated diagrams in Ref. 5, the agreement between theory and experiment seems quite reasonable.[7]

I wish to thank Professor A. Peterman for checking this calculation.

*Chercheur Associé au Centre National de la Recherche Scientifique.

[1]R. Karplus and A. Klein, Phys. Rev. 87, 848 (1952).

[2]D. A. Owen and W. W. Repko, Phys. Rev. A 5, 1570 (1972). The present paper uses the Bjorken and Drell metric and in this respect differs from this reference.

[3]G. Källén and A. Sabry, Kgl. Dan. Vidensk. Selsk., Mat.-Fys. Medd. 29, No. 17 (1955); B. E. Lautrup and E. de Rafael, Phys. Rev. 174, 1835 (1968).

[4]After the completion of this work, I learned that the same result had been obtained, independently, by R. Barbieri, P. Christillin, and E. Remiddi.

[5]T. Fulton, D. A. Owen, and W. W. Repko, Phys. Rev. A 4, 1802 (1971).

[6]E. R. Carlson, V. W. Hughes, M. L. Lewis, and I. Lindgren, Phys. Rev. Lett. 29, 1069 (1972).

[7]This is, of course, assuming that none of the other three-photon diagrams contribute to order $\alpha^6 \ln\alpha^{-1}$. Although arguments exist which suggest that this is the case, no definitive statement concerning their contribution can be made until there is further investigation. Furthermore, it would be useful to calculate all relevant diagrams to order α^6 as this could bring the agreement between theory and experiment even closer. Estimates to this order have recently been discussed by T. Fulton (to be published) showing that this is quite possible.

High-Resolution Study of Fluorine Metastable X-Ray Emitters*

Patrick Richard, R. L. Kauffman, F. F. Hopkins, C. W. Woods, and K. A. Jamison
Kansas State University, Manhattan, Kansas 66506
(Received 20 February 1973)

A crystal spectrometer is used to study foil-excited fluorine beam x rays. The transitions from 2^1P and 2^3P to 1^1S_0 He-like fluorine states and the transitions from $^2P°(1)$ and $^4P°(1)$ to $1^2S_{1/2}$ Li-like fluorine states are observed. Lifetimes of 0.537 ± 0.02 and 2.000 ± 0.025 nsec are measured and identified with the 2^3P_1 and either the $2^4P_{3/2}°(1)$ or $2^4P_{1/2}°(1)$ decays, respectively.

In this paper we report measurements of F beam x rays with sufficient resolution to observe separately singlet and triplet He-like states as well as doublet and quartet Li-like states. The F x rays are measured after passing through a thin C foil and the intensities recorded as a function of time of flight. Lifetimes of two metastable states are determined from these measurements. Allowed transitions are also seen far downstream from the C foil which implies the existence of long-lived cascades.

The first lifetime determination of x-ray–emitting metastable states was performed by Sellin, Donnally, and Fan[1] who, with the use of a proportional counter, measured the lifetimes of the 1^1S_0-2^3P_1 intercombination transitions in N^{+5} and O^{+6} obtained from a tandem Van de Graaff accelerator. Sellin *et al.*[2] later repeated the oxygen measurement with a crystal spectrometer and within the statistics of the experiment observed only the triplet intercombination line downstream from the foil. In the first experiment the exponential decay curves contained a long-lived component whereas in the later experiment no such component was observed. Schmieder and Marrus,[3-5] with the use of a Si(Li) detector, have measured the 1^1S_0-2^3S_1 $M1$, 1^1S_0-2^3P_2 $M2$, and the 1^1S_0-2^1S_0 double $E1$ lifetimes of He-like Ar^{+16} as well as the $1^2S_{1/2}$-$2^2S_{1/2}$ double $E1$ lifetime of He-like Ar^{+17} obtained from the heavy-ion linear accelerator at the University of California, Berkeley. Cocke, Curnutte, and Macdonald[6] have also recently measured x-ray metastable states of Cl with the use of a Si(Li) detector.

The present experiment was performed with the Kansas State University tandem Van de Graaff accelerator. A beam-foil apparatus equipped with a curved crystal vacuum spectrometer has been set up to make these measurements. The spectrometer views the beam at 90° to the beam direction. A rubidium acid phthlate crystal and a flow proportional counter with a 2.0-μm Makrofol foil[7] were used. The detector was operated at 2000 V and with 10% methane–90% argon gas at a flow rate of 5 l/hr. A 20-μg/cm^2 C foil was used to excite the fluorine beam which was run at three energies of 12, 15, and 22 MeV. Because of a small observed Doppler shift, the spectra were calibrated at each bombarding energy. The number of x rays from the residual gas in the beam line was found to be negligible. This was accomplished by removing the C foil and looking for x rays from a F^{+9}, F^{+8}, F^{+7}, and a F^{+6} beam.

The x-ray energy calibration was established by identifying several lines in the He-like and H-like F spectrum. The two points used in the calibration are the He-like transitions $(1s)^2\,{}^1S$-$(1s)$-$(3p)\,{}^1P$ and $(1s)^2\,{}^1S$-$(1s)(2p)\,{}^1P$ at 857.5 and 737.7 eV, respectively, as measured by Tyrén.[8] This calibration leads to very good agreement between our measured energies for the $1s$-$2p$, $1s$-$3p$, $1s$-$4p$, and $1s$-$5p$ H-like transitions and the calculated energies for these transitions by Garcia and Mack.[9]

Figure 1 contains the F foil-excited beam x-ray spectra in the 40-eV interval between 710 and 750 eV with the C foil at 0.0, 1.0, 4.0, and 10.0 cm upstream from the spectrometer. The lower spectrum, taken with the spectrometer viewing the C foil directly, contains the four peaks of interest with energies of 715.1, 724.8, 731.1, and 737.7 eV.

The two peaks at 737.7 and 731.1 eV are the x-ray transitions from the singlet P and the triplet P states, respectively, of the two-electron configuration $(1s)(2p)$ to the 1^1S_0 $(1s)^2$ ground state of the He-like fluorine. Both of these transitions are seen downstream from the foil. The intensity as a function of foil position for these two states is given in Fig. 2. The lifetimes τ are obtained from the decay curves by a best least-squares fit with

$$N = N_1 \exp(-X/v\tau_1) + N_2 \exp(-X/v\tau_2),$$

where v is the beam velocity, X is the foil position, and N is the number of counts at position X. From the fit to the 2^3P decay we obtain $\tau_1 = 0.537 \pm 0.020$ nsec and $\tau_2 = 4.9 \pm 1.7$ nsec.

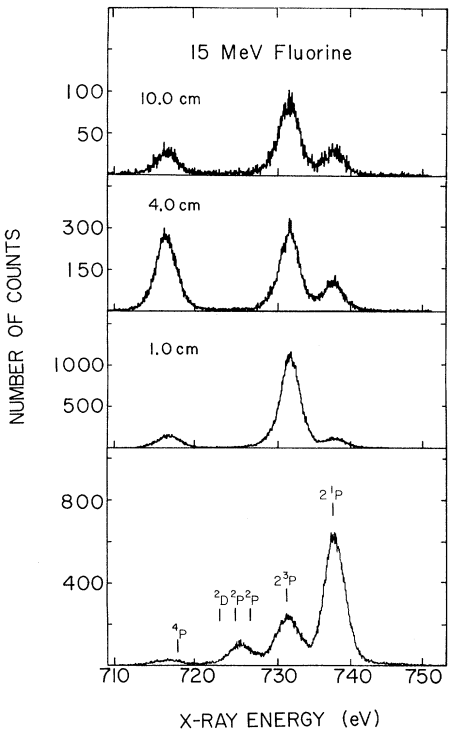

FIG. 1. F x-ray spectra for various upstream foil positions. Bottom spectrum is for a direct look at the carbon foil. Other positions are indicated in upper left-hand corner of each spectrum. The spectra shown here are not all for the same amount of integrated beam.

The fine structure of the 1^1S_0-2^3P_J transition cannot be resolved into the $J=0$, 1, and 2 components in the present experiment; however only the 2^3P_1 and 2^3P_2 states have ground-state decay branches. The 2^3P_1 state has two radiative branches. One branch is to the 1^1S_0 ground state with a calculated transition rate[10] of 1.85×10^9 sec^{-1} and the other branch is to the 2^3S_1 state with a calculated transition rate[11] of 0.09×10^9 sec^{-1}. The dominant decay is thus the 1^1S_0-2^3P_1 intercombination transition and the calculated 2^3P_1 lifetime is 0.52 nsec. This is in excellent agreement with our experimentally determined lifetime of 0.537 $\pm$ 0.020 nsec which is the fast component of the 2^3P decay curve. The 2^3P_2 state also has two radiative branches. One branch is to the 1^1S_0 which goes by an $M2$ transition with a calculated transition rate[12] of 9.02×10^5 sec^{-1} and the other branch is to the 2^3S_1 which goes by an $E1$ transition with a calculated transition rate of 0.09×10^9 sec^{-1}. The lifetime of the 2^3P_2 state is 11 nsec; however, the $E1$ branch is a factor of 100 greater than the $M2$ branch. The experimentally observed

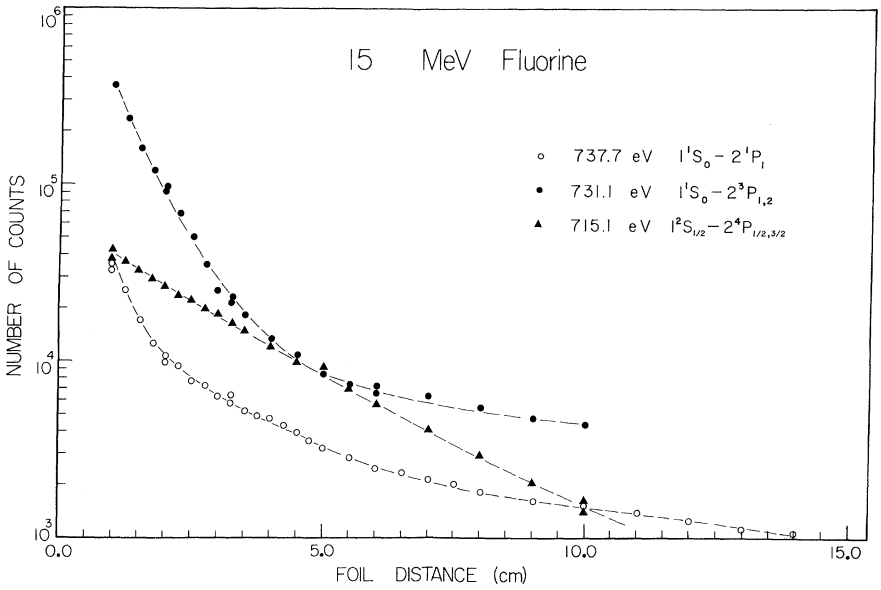

FIG. 2. Decay curves for the three peaks observed downstream from the C foil. The $2^3P_{1,2}$ curve contains two components with lifetimes of $\tau_1 = 0.537 \pm 0.02$ nsec and $\tau_2 = 4.9 \pm 1.7$ nsec. The $2^4P_{1/2,3/2}$ curve contains one component with a lifetime of 2.000 ± 0.025 nsec.

long component of 2^3P decay may thus, in part, be due to the 2^3P_2 $M2$ decay but does not give good agreement with the expected lifetime. This may be due to the fact that the decay curve spans less than one expected lifetime of the 2^3P_2 state. The long-lived component could also be due in part to cascading through the 2^3P_1 state.

The 1^1S_0-2^1P_1 fully allowed $E1$ transition has a lifetime of 1.79×10^{-4} nsec so that only cascading through the 2^1P_1 state can be leading to the observed decay curve. The curve was fit with a two-component decay and yielded values of $\tau_1 = 0.41 \pm 0.02$ nsec and $\tau_2 = 3.61 \pm 2.1$ nsec. The origin of the cascades is not known from the present results. The decay curve can also be fit with a three-component decay.

The two peaks at 715.1 and 724.8 eV in Fig. 1 can be tentatively identified as the transition from the Li-like quartet and doublet states, respectively, of the three-electron configuration $(1s)(2s)(2p)$ to the $1^2S_{1/2}$ $(1s)^2(2s)$ ground state of the Li-like fluorine. This identification is based on the favorable comparison with calculated energies of the three-electron system[13] and on the experimental observation that the intensities of these two transitions relative to the two He-like transitions vary with bombarding energy as predicted by charge equilibrium data.[14] The $^4P^\circ$ decay curve is fit with a single component with lifetime $\tau = 2.000 \pm 0.025$ nsec. The $^4P_J{}^\circ$ state has three fine-structure components for $J = \frac{1}{2}$, $\frac{3}{2}$, and $\frac{5}{2}$ which cannot be resolved in the present experiment. Unlike the ^3P He-like state, the ^4P Li-like states have radiative branches only to the ground state and can decay by autoionization. Sellin *et al.*[15] have recently studied these autoionizing states in a beam-foil arrangement. The presently observed radiative decay with a 2-nsec lifetime could be assigned to the $1^2S_{1/2}$-$2^4P_{3/2}{}^\circ(1)$ or $1^2S_{1/2}$-$2^4P_{1/2}{}^0(1)$ transition. No calculations of the lifetime are available at this time.

In summary it is shown that it is quite fruitful to study metastable x-ray emission with a high-resolution crystal spectrometer. In the case of a fluorine beam many lines can be seen downstream from a C foil. The 1^1S_0-2^3P_1 transition has a measured lifetime of 0.537 ± 0.020 nsec which agrees quite well with the theoretical calculations of Drake and Dalgarno[10] and confirms the recent lifetime measurement (0.536 ± 0.03 nsec) of this state by Mowat *et al.*,[16] who use a Si(Li) detector and assume that all the intensity in the spectrum is from the 1^1S_0-2^3P_1 transition. The data of Mowat *et al.* show a slow systematic increase in lifetime as the beam energy is lowered. This can possibly be explained by the variation in the relative population of the $^3P_1$ and $^4P^\circ(1)$ states as a function of beam energy. The $^4P^\circ(1)$ state is observed to have a radiative decay to the $1^2S_{1/2}$ Li-like ground state with a lifetime

of 2.00 ± 0.025 nsec. This state is similar to the 2^3P_1 state with the additional coupling of a $2s$ electron. Finally it is observed that the allowed $E1$ 1^1S_0-2^1P_1 transition is seen downstream from the C foil which implies the existence of long-lived cascades.

The authors wish to thank Professor I. A. Sellin, Professor J. R. Macdonald, Professor M. D. Brown, and Professor C. L. Cocke for stimulating discussions regarding this study. The authors also wish to thank Professor Sellin for communicating fluorine measurements prior to publication.

*Work supported in part by the U.S. Atomic Energy Commission and in part by the Research Corporation.

[1]I. A. Sellin, B. L. Donnally, and C. Y. Fan, Phys. Rev. Lett. 21, 717 (1968).

[2]I. A. Sellin, M. D. Brown, W. W. Smith, and B. L. Donnally, Phys. Rev. A 2, 1189 (1970).

[3]R. W. Schmieder and R. Marrus, Phys. Rev. Lett. 25, 1245 (1970).

[4]R. Marrus and R. W. Schmieder, Phys. Rev. Lett. 25, 1689 (1970).

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

[6]C. L. Cocke, B. Curnutte, and J. R. Macdonald, Phys. Rev. Lett. 28, 1233 (1972).

[7]Siemens Corporation, Karlsruhe, Germany.

[8]F. Tyrén, Nova Acta Regiae Soc. Sci. Upsal. 12, 1 (1940).

[9]J. D. Garcia, J. E. Mack, J. Opt. Soc. Amer. 55, 654 (1965).

[10]G. W. F. Drake and A. Dalgarno, Astrophys. J. 157, 459 (1969); R. C. Elton, Astrophys. J. 148, 573 (1967).

[11]W. L. Wiese, M. W. Smith, and B. M. Miles, *Atomic Transition Probabilities*, U.S. National Bureau of Standards, National Standards Reference Data Series–22 (U.S. GPO, Washington, D.C., 1969).

[12]G. W. F. Drake, Astrophys. J. 158, 1199 (1969).

[13]E. Holøien and S. Geltman, Phys. Rev. 153, 81 (1967).

[14]J. B. Marion and F. C. Young, *Nuclear Reaction Analysis* (North-Holland, Amsterdam, 1968), p. 44.

[15]I. A. Sellin, D. J. Pegg, M. Brown, W. W. Smith, and B. Donnally, Phys. Rev. Lett. 27, 1108 (1971).

[16]J. R. Mowat, I. A. Sellin, R. S. Peterson, D. J. Pegg, M. D. Brown, and J. R. Macdonald (to be published).

Theory of Giant Transmission Electron Spin Resonance in Ion-Implanted Films*

M. B. Walker

Department of Physics and Scarborough College, University of Toronto, Toronto, Ontario M5S 1A7, Canada

(Received 12 December 1972)

A theoretical model is proposed which gives a qualitative explanation of the dominant features of the recent experiments of Monod, Hurdequint, Janossy, Obert, and Chaumount. In particular, the origin of the large enhancement factors is explained, and the spectrum observed in the implanted alloys is related to the spectra observed in the pure metal, and in a homogeneous magnetic alloy similar to the implanted layer.

Monod, Hurdequint, Janossy, Obert, and Chaumont[1] have recently shown that manganese implantation of copper films leads to a large enhancement (e.g., by a factor of approximately 2500) of the copper transmission electron spin resonance (TESR). They point out that the implantation technique thus has potentially important application in exploring TESR in a large number of metals in which TESR has not yet been observed. This paper presents a theoretical model suitable for interpreting results of experiments on implanted films. It is hoped that the existence of such a theoretical model will encourage experimenters to make use of the implantation technique in future experiments.

Monod *et al.*[1] advanced no theory to explain their results, but clearly outlined the features of the experiment which would have to be explained by a theoretical model. These features are the following: (1) The TESR for samples implanted on one side is independent of which side is excited by the microwaves. (2) The TESR intensity is enhanced by a large factor which is squared for double-sided implantation. (3) The g factor is characteristic of pure copper metal. (4) The intensity, as well as the linewidth, decreases with increasing temperature at low temperatures. (5) The diffusion coefficient seems to remain close to that of copper, as evidenced by the high temperature falloff of the signal. (6) The TESR is independent of the magnetic field orientation of the sample. (7) The background