PHYSICAL REVIEW A VOLUME 27, NUMBER 1 JANUARY 1983

Measurement of the transition probability of the $2s^2\ ^1S_0$-$2s3p\ ^3P_1^o$ intercombination line in Ne VII

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(Received 30 July 1982)

The lifetimes of the $2s3p\ ^3P_{0,1,2}^o$ levels in Ne VII have been measured by the observation of transitions to the $2s3s\ ^3S_1$ level with the use of the beam-foil excitation method. The results are $\tau(^3P_J^o)=1.7(1)$, 1.0(1), and 1.9(1) nsec for the $J=0$, 1, and 2 levels, respectively. The smaller value for $J=1$ is due to a J-allowed decay channel to $2s^2\ ^1S_0$, and implies a transition probability of $4.3(6)\times 10^8$ sec^{-1} for this intercombination line.

I. INTRODUCTION

The transition probabilities for the $2s^2\ ^1S_0$-$2snp\ ^3P_1^o$ intercombination lines of the Be isoelectronic sequence are an interesting subject for theoretical study because they are electric dipole ($E1$) forbidden in pure LS coupling, but become $E1$ allowed when spin-orbit interaction and other relativistic effects cause mixing between $2snp\ ^3P_1^o$ and the $^1P_1^o$ series. This intercombination ($\Delta S\neq 0$) transition is the only energetically allowed decay from the $n=2$ level. However, the long lifetime of this state in all but very high stages of ionization (high-Z ions) precludes time-of-flight lifetime measurements.

The transition wavelength of the $n=3$ intercombination line, on the other hand, is an order of magnitude shorter than that of the $n=2$ line. This enhances the $n=3$ transition probability by three orders of magnitude over that of the $n=2$, making it more convenient for time-of-flight studies of lower ionization species. It was recently pointed out by Engström *et al.*[1] that the intercombination transition probability for the $n=3$ level can be accurately determined for these lower stages of ionization by differential lifetime measurements. The $2s3p\ ^3P_J^o$ levels all have spin-allowed decay channels to $2s3s\ ^3S_1$. But the lifetimes have a strong J dependence, caused principally by the additional intercombination decay channel to the ground state that is accessible to the $J=1$ level. It is forbidden to the $J=0$ and 2 levels by J selection rules.

Engström *et al.*[1] measured the individual lifetimes of the three N IV, O V, and F VI $n=3$ states and deduced from them transition probabilities for the ground-state intercombination lines, assuming that the J dependence of the lifetimes in each of these ions arose mainly from that transition. They substantiated this assumption with preliminary multiconfiguration calculations of transition rates for the various decay channels. Hibbert[2] subsequently confirmed their results by more detailed calculations, and he went on to predict the corresponding intersystem transition probability in Ne VII.

A number of theoretical calculations of this transition probability are also available for much higher members of this sequence.[3–7] These calculations indicate that the lower stages of ionization are affected by configuration interaction, whereas for the higher ionization stages, intermediate coupling causes the singlet/triplet classification to be misleading. Precise experimental measurements can do much to elucidate the inherent theoretical complications. This paper reports an extension of the measurements of Engström *et al.* to Ne VII and compares the results with the calculations of Hibbert and others.

II. EXPERIMENTAL ARRANGEMENTS

The measurements were made using the 5 MV ANL Dynamitron accelerator. Ne^{1+} and Ne^{2+} ions were formed in an rf-field ion source, accelerated through various potentials of 1.0–3.5 MV, and momentum analyzed to obtain ion energies of 1.0–7.0 MeV.

The monoenergetic ions were directed through carbon foils with areal densities in the range 4.4–5.3 μg/cm^2, where the ions became further ionized and excited. The resulting photon emission was analyzed with a McPherson model 225 1-m, normal-incidence, vuv monochromator equipped with a 250-nm blaze grating and was detected using a photomultiplier tube.

Decay-curve measurements were performed by translating the foil along the beam in successive equal increments by a stepping motor. Photons emitted from the beam were counted for each foil position until a prescribed quantity of charge had accumulated in a Faraday cup. The procedure was controlled by an on-line PDP 11/45 computer.

Energy loss in the foil was determined using the electronic stopping power tables of Northcliffe and Schilling,[8] and the foil-emergent velocities were computed. (Nuclear stopping power is negligible at these energies.) Uncertainties in the beam energy are expected to be less than 1%.

III. RESULTS

A spectral scan of the region of interest at an incident ion energy of 6 MeV is shown in Fig. 1. The monochromator was refocused for the moving light source by an appropriate translation of the grating.[9] The $2s3s\ ^3S_1$-$2s3p\ ^3P^o_{2,1,0}$ transitions at 1981.974, 1992.060, and 1997.345 Å (Ref. 10) were well resolved.

Decay curves for the three lines of the multiplet are shown in Fig. 2. The 6-MeV ion velocity here was 7.56 mm/nsec. The $J=1$ line is clearly shorter lived, as a result of its intercombination transition to the ground state. The decay curves were corrected on a channel-by-channel basis for dark counts (typically 0.1 sec^{-1}) using the measured integration time (which did not vary more than a few percent over the decay curves).

Statistically weighted chi-square fits to one and two exponentials with a constant background were attempted for each of the decay curves, but, similar to the results of Engström *et al.*,[1] the best results (in terms of fit convergence and resultant chi-square) were usually obtained with a single exponential and a constant background. This is consistent with the fact that the branching ratios for the cascades into the $2s3p\ ^3P$ levels are expected to be much smaller than to the $2s2p\ ^3P$ levels.

Our lifetime results are summarized in Table I, along with a number of calculations from theory. The theoretical values were obtained by combining transition probabilities from a number of sources that are summarized in Table II. The intercombination transition rate of $4.3(6)\times 10^8\ \mathrm{sec}^{-1}$ is arrived at by finding the difference in reciprocal lifetimes between the $J=1$ level value and an average of the $J=0$ and $J=2$ level results, as discussed below.

As an illustration of the technique, Fig. 3 displays, for a 6-MeV run, the logarithm of the ratio of the intensity of the 1982 Å ($J=2$) line to that of the 1992 Å ($J=1$) line with residual background removed, as a function of distance from the foil. Both decay curves were measured under closely similar conditions. Neglecting cascade effects and other exit channels, the semilogarithmic slope of this curve is proportional to the transition probability of the $2s^2\ ^1S_0$-$2s3p\ ^3P_1$ intercombination line.

IV. DISCUSSION

Because of configuration interaction and intermediate coupling, no energetically allowed transition from $2s3p\ ^3P$ can automatically be ruled out. All three fine-structure levels can $E1$ decay to $2s3s\ ^3S$ and to $2p^2\ ^3P$, and also $M1$ or $E2$ decay to $2s2p\ ^3P$, but $2s3p\ ^3P_1$ can in addition $E1$ decay to $2s^2\ ^1S$,

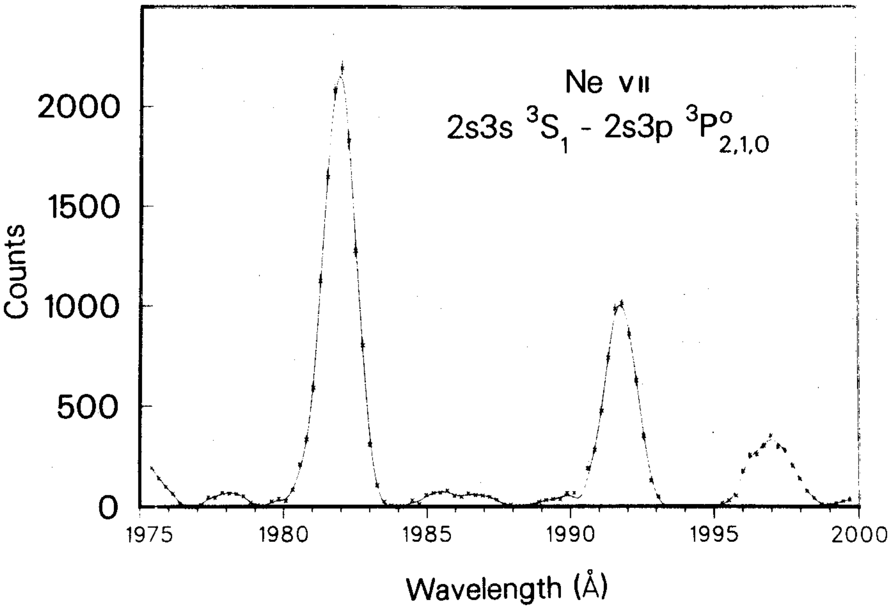

FIG. 1. Spectral scan at 6-MeV incident ion energy of the $2s3s\ ^3S_1$-$2s3p\ ^3P^o_{2,1,0}$ transitions in Ne VII at 1981.974, 1992.060, and 1997.345 Å. (The curve is drawn to aid the eye.)

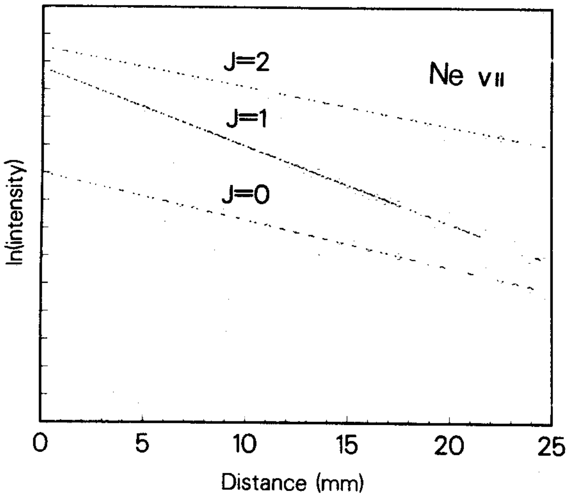

FIG. 2. Schematic plot of the decay curves of the $2s3p\,^3P^o_J$ lines. Each set of data has been scaled independently (*y* translated) for presentation. A constant residual background, as fit independently for each curve, has been subtracted from the data.

TABLE I. Lifetimes for the $2s3p\,^3P^o_J$ levels.[a]

	τ(nsec)			
J	Measured	Theoretical		
2	1.9(1)	2.35,[b]	1.56,[c]	1.64[d]
1	1.0(1)	1.43,[b,e]	1.09,[c,e]	1.13[d,e]
0	1.7(1)	2.35,[b]	1.56,[c]	1.64[d]

[a] The nonrelativistic calculations do not consider fine-structure splittings among the J values. The $J=0$ lifetimes should be longer than $J=2$ lifetimes by about 2%, due to the ω^3 dependence of transition rates.

[b] Nussbaumer (Ref. 11).

[c] Hummer and Norcross (Ref. 12): 11 configurations.

[d] Hummer and Norcross (Ref. 12): 16 configurations.

[e] Hibbert (Ref. 13).

$2p^2\,^1S$, and $2p^2\,^1D$. However, states having equal J among these may be heavily mixed, and the LS labeling could be misleading. For example, Sampson *et al.*[6] find that when they include configuration mixing between $2s3p$, $2p3s$, and $2p3d$, the computed transition probabilities depart dramatically and sensitively from the values obtained when only singlet-triplet mixing within the $2s3p$ configuration is included. They compute that the lowest energy state of the complex switches from being predominantly $2s3p\,^1P^o_1$ at $Z=14$ to being predominantly $2s3p\,^3P^o_1$ at $Z=18$. It is known that the triplet lies below the singlet for the early members of this sequence. The spin-allowed one-electron $2s3s\,^3S$-$2s3p\,^3P$ transition has been computed by several authors[11-13] with the inclusion of configuration interaction. The $2s3p\,^3P^o_2$ state can also decay to ground by an $M2$ decay, but this is expected to be of much lower transition probability.

Considering the complexities of the atomic states involved, the lifetimes of the $J=0$ and the $J=2$ levels could differ by more than the $\approx 2\%$ expected from the ω^3 dependence of the transition rates. Our results indicate the $J=0$ lifetime to be perhaps 10% shorter than the $J=2$ lifetime. In the absence of detailed theoretical calculations of the various transition decay rates for these states, in order to obtain the intercombination decay rate, we have taken the simple average of their lifetimes [1.8(1) nsec] for comparison with the $J=1$ lifetime. The uncertainty in this intercombination rate [$4.3(6)\times 10^8$ sec^{-1}] is primarily due to the uncertainty in our $J=1$ lifetime value, not in the difference of the $J=0$ and $J=2$ results.

Direct observation of the $2s3p$ intercombination line to the ground state is difficult because of its proximity to the corresponding singlet-singlet transition at 97.502 Å.[14] The $2s3s\,^3S$-$2s3p\,^3P$ wavelengths

TABLE II. Multiplet transition probabilities.

Transition	Transition probability (10^8 sec^{-1})
$2s^2\,^1S^e$-$2s3p\,^3P^o$	2.754[a]
$2p^2\,^3P$-$2s3p\,^3P^o$	2.17,[b] 4.25,[c] 3.97[d]
$2p^2\,^1D$-$2s3p\,^3P^o$	None available
$2p^2\,^1S$-$2s3p\,^3P^o$	None available
$2s3s\,^3S$-$2s3p\,^3P^o$	2.09,[b] 2.13,[c], 2.11,[d] 2.10[e]
$2s3s\,^1S$-$2s3p\,^3P^o$	None available
$2s2p\,^3P^o$-$2s3p\,^3P^o$	None available ($M1$,$E2$)
$2s2p\,^1P^o$-$2s3p\,^3P^o$	None available ($M1$,$E2$)

[a] Hibbert (Ref. 2).

[b] Nussbaumer (Ref. 11).

[c] Hummer and Norcross (Ref. 12): 11 configurations.

[d] Hummer and Norcross (Ref. 12): 16 configurations.

[e] Hibbert (Ref. 13).

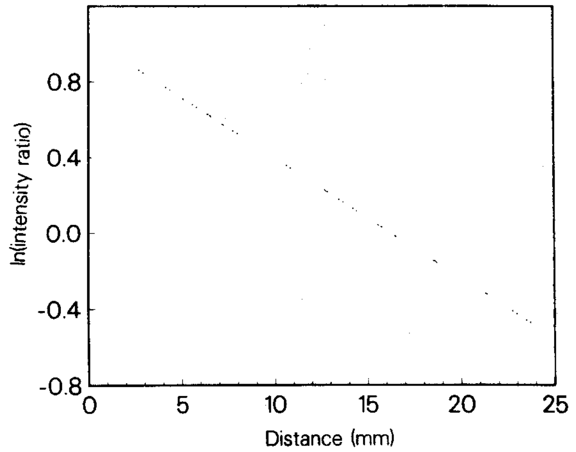

FIG. 3. Plot of the logarithm of the ${}^3P_1^o$:${}^3P_2^o$ decay curve intensity (count) ratio. A constant residual background, as fit independently for each curve, has been subtracted from the data.

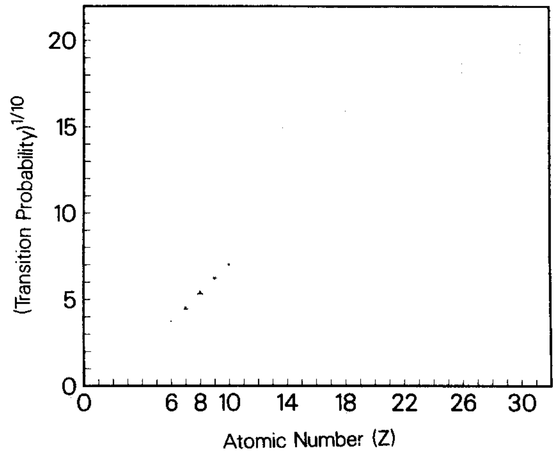

FIG. 4. Plot of the $2s^2\,{}^1S$-$2s3p\,{}^3P$ intercombination transition probability (sec^{-1}), along the isoelectronic sequence, to the $\frac{1}{10}$ power. ○ denotes this work; × denotes data from Ref. 1; + indicates theoretical values from Ref. 2; and ◇ indicates theoretical values from Ref. 6.

of Bockasten *et al.*[9] can be connected to the $2s2p\,{}^3P$-$2s3s\,{}^3S$ wavelength of Hermansdorfer[15] and to the $2s^2\,{}^1S$-$2s2p\,{}^3P$ wavelength of Ridgeley and Burton[16] using the $2s2p\,{}^3P$ fine-structure separations of Bockasten *et al.*[9] to infer an intercombination wavelength of 97.22 Å. This transition appears to be present as an unresolved shoulder to the singlet-singlet transition in the fast-ion spectra of Barrette.[17] We have observed similar features in our grazing-incidence spectra using a McPherson 247 monochromator.

Hibbert[2] predicted an intercombination transition rate of 2.754×10^8 sec^{-1} for the $2s^2\,{}^1S_0$-$2s3p\,{}^3P_1$ transition in Ne VII. Figure 4 compares the result of our measurement with the isoelectronic calculations of Hibbert[2] and of Sampson *et al.*,[6] as well as with the previous measurements of Engström *et al.*[1] The ordinate is the intercombination transition probability raised to the $\frac{1}{10}$ power, following the approximate Z^{10} scaling observed to govern the corresponding $1s^2\,{}^1S_0$-$1s\,2p\,{}^3P_1$ intercombination line in the helium isoelectronic sequence at low Z.[18] The theoretical calculations have an approximate linear variation on this plot, but the low-Z and high-Z trends are quite different. Our result for Ne VII is larger than the calculated value of Hibbert but well below the extrapolated trend of the calculated values of Sampson *et al.* Measurements for values of $Z=11$—16 are needed to determine the behavior in this domain.

ACKNOWLEDGMENTS

We are grateful to Professor I. Martinson, Dr. K. T. Cheng, Dr. L. S. Goodman, Professor D. G. Ellis, Professor W. R. Johnson, and Professor D. H. Sampson for valuable discussions, to Dr. H. G. Berry for placing his experimental facilities at our disposal, and to P. Arcuni and W. Ray for assistance during the measurements. The work was performed under the auspices of the U.S. Department of Energy, Office of Basic Energy Sciences under Contract No. W-31-109-Eng-38 (J.E.H. and R.L.B.) and Contract No. DE-AS-05-80ER10676 (L.J.C.), and the U.S. National Science Foundation, Grant No. PHY81-11727 (A.E.L.).

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