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# Neon $K\alpha$, $K\beta$ satellite structure induced by 80-MeV argon-ion impact*

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High-resolution (full width at half-maximum ~ 3 eV) neon $K$ x-ray spectra obtained from 80-MeV argon-ion bombardment are presented for two narrow ranges of the projectile charge state ($q = \sim 6$, $\sim 14$). Production of the various satellite lines is found to depend on the projectile charge state. When the projectile is $\text{Ar}^{14+}$, the target is at least 6 times ionized, and a significant fraction (> 20%) of the observed radiation comes from hydrogenlike and heliumlike ions. We comment on the reliability of vacancy-production cross sections deduced from measured x-ray intensities.

## I. INTRODUCTION

Recent experiments have shown that heavy-ion–induced $K$ x-ray yields from light-gas targets depend upon the charge state of the projectile. This effect, which occurs even at projectile energies as high as 1–4 MeV/amu has been observed for numerous target-projectile combinations in Si(Li)-detector spectra[1–3] and in spectra taken with a bent-crystal spectrometer.[4,5] We report here high-resolution neon spectra, produced in collisions with 80-MeV argon ions, which can be compared with earlier, low-resolution Si(Li)-detector data for the same collision system.[2] We find that highly ionized target states are produced in these collisions. After correction for energy-dependent window absorption factors and configuration-dependent fluorescence yields, we find there still remains a projectile charge-state dependence in the total vacancy-production cross section.

## II. EXPERIMENTAL RESULTS

Details of experimental technique and apparatus have been discussed previously.[4,5] An 80-MeV argon 6+ beam was produced by the Oak Ridge isochronous cyclotron at ORNL. The beam was sent through a 2.5-cm-long, 0.2-Torr neon-gas target from 2 cm of which the emission of neon x rays was observed. Dispersion of the x rays was accomplished by a rubidium acid phthalate (RAP) crystal ($2d$ spacing, 26.12 Å). At this target density stripping of the projectile can occur prior to a $K$-shell ionizing collision. Neither charge-changing cross sections nor charge-state distributions are known for such high-velocity argon ions in dilute (less than equilibrium thickness) gases. Extrapolating lower-energy data[6] we estimate that the incident 6+ beam is charge-stripped approximately 2 units in the gas region. Thus a significant portion of the beam is probably actually in charge state 7+ or 8+. To obtain higher charge states the beam was stripped by a thin C foil placed directly in front of the gas cell. Charge states 13+ through 16+ comprise 90% of the foil-stripped beam, the mean charge being near 14+.

Spectra produced by the 80-MeV beam are presented in Fig. 1 for projectile charge states in the regions near 6+ and 14+. The dominant lines produced by the "6+" Ar beam are $2p \rightarrow 1s$ transitions in He-like, Li-like, Be-like, and B-like states with single $K$-shell vacancies. These assignments are based on a comparison of measured and calculated[7–9] energies, as indicated in Table I. As pointed out by Cocke *et al.*,[10] term splittings within the same configuration can be as large as satellite spacings themselves. Hence these assignments are reasonable, but not unique. The dominant lines produced by the "14+" Ar beam are $2p$-$1s$ transitions in He-like, Li-like, and Be-like ions. No evidence for a B-like line is seen for this charge-state beam, nor is there any evidence of x rays from neon ions with more than four electrons. Three prominent high-energy lines, not seen with the "6+" projectile, are produced by the "14+" projectile. Two of these (one heliumlike, the other hydrogenlike) arise from configurations with two $K$-shell vacancies. The third is a doubly excited, lithiumlike line. Again, the assignments are made on the basis of the measured energies. They agree with the measurements of Peacock *et al.*[11] on neon ions excited in a dense, high-temperature plasma. Decays from the $J=0$, 1, 2 levels of the $(2s2p)^{3,1}P^o$ and $(2p^2)$, ${}^3P^e$, ${}^1D^e$, ${}^1S^e$ terms are not resolved in our spectrum. The designation ${}^3P_2$ is suggested by Peacock *et al.*, merely because it would be the strongest line if the levels were statistically

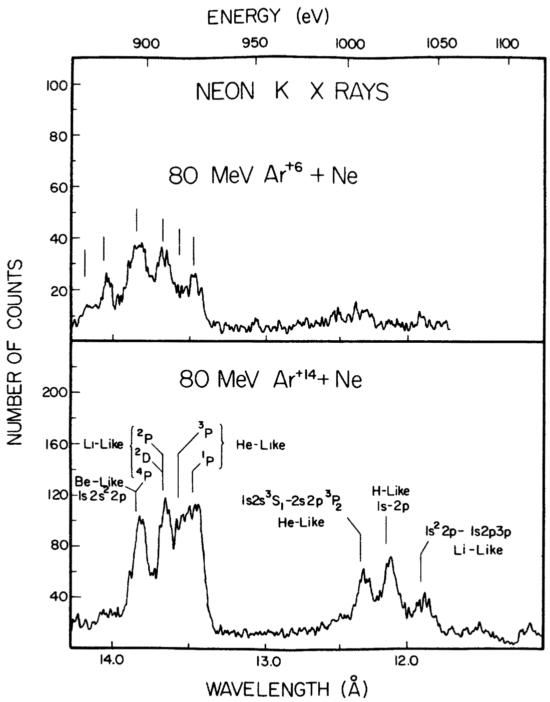

FIG. 1. Neon $K\alpha$,$K\beta$ spectra produced by 80-MeV argon bombardment. The vertical lines locate energies of several transitions either observed or computed by other workers: $1s2s^22p$ (Be-like), Ref. 7; $^2P$, $^2D$, $^4P$ (Li-like), Ref. 12; $^{3,1}P$ (He-like), Ref. 11; $2p$ (H-like), Ref. 8; $1s2p3p$ (Li-like), Ref. 11. The "6+" beam is really an undetermined mixture of states 6+ through 8+, and the "14+" beam is a foil-averaged, equilibrium distribution. More than 30 h of cyclotron time (beam currents typically ~10 nA) were required to accumulate these spectra. The 850-eV line from singly ionized neon was not produced with detectable intensity.

populated. It should be pointed out that these terms usually autoionize (fluorescence yield[7] = 0.0998), as do the $^2D^e$ and $^2S^e$ terms of the lithiumlike configuration $1s2p3p$. Hartree-Fock and perturbation-theory calculations[12] indicate an overlap of the berylliumlike configuration $(1s2s^22p)$ and the lithiumlike terms $(1s2p^2)\,^4P^e$ and $(1s2s2p)\,^4P^o$ (see Fig. 1). The line is most likely Be-like, since the $^1P_0^o$ state of that configuration can radiatively decay, whereas the lithiumlike quartets usually autoionize since they are metastable against $E1$ decay.

A summary of satellite line identifications, energies, fluorescence yields $\omega_K$, and relative intensities $R_n$ is given in Table I. The average fluorescence yields $\omega_n$ for each satellite were obtained from

$$\omega_n^{-1} = \sum_i w_i\, \omega_i^{-1},$$

where the sum runs over all unresolved configurations within a given line, and individual configurations are assigned weights $w_i$ according to the number of states within the configuration that have open $E1$ decay channels. The fluorescence yield $\omega_i$ for each configuration has been computed by Bhalla *et al.*[7] The centroids and relative intensities of each distinct component were obtained by least-squares fits of the spectra with Gaussian peaks. The listed errors are those given by the fitting program. The data were corrected for crystal reflectivity and proportional-counter quantum efficiency (including window absorption and gas response) prior to fitting.

## III. DISCUSSION

The average fluorescence yields $\omega_n$ and relative intensities $R_n$ listed in Table I can be used to derive an effective fluorescence yield $\bar{\omega}_k$ for neon excited in these collisions:

$$\bar{\omega}_k^{-1} = \sum_n R_n\, \omega_n^{-1}.$$

Thus, we find, for projectiles $Ar^{6+}$ and $Ar^{14+}$, $\bar{\omega}_k(6) = 0.049 = 3\omega_0$ and[13] $\bar{\omega}_k(14) = 0.094 = 6\omega_0$, where $\omega_0 = 0.018$ is the fluorescence yield[14] of the configuration $(1s2s^22p^6)$. The reader is reminded that the argument "6" ("14") here refers to a mixture of projectile charge states 6, 7, and 8 (13, 14, 15, 16). These values are useful for estimating the total vacancy-production cross sections from x-ray yields measured with relatively low-resolution Si(Li) detectors.[2] Using the energies and relative intensities obtained in this experiment a better estimate of the energy-dependent window-transmission factor can be made. The corrected window transmission for the detector used is found to be 0.13 (0.16) for spectra taken with projectile charge "6+" ("14+"). In the earlier work[3] with neon targets the transmission was assumed to be 0.1. These two systematic effects alone would lead to an increase in the total x-ray yield of a factor $2\frac{1}{2}$ when the projectile charge state is raised from 6+ to 14+. The actual yield increased by a factor of 20. We conclude that these systematic effects, while significant, only account for about 10% of the measured yield increase, the rest of which is probably due to changes in the vacancy-production cross section itself. Assuming that these systematic corrections vary slowly in the neighborhoods of 6+ and 14+, the adjusted total vacancy-production cross sections are

$$\sigma_I(6) = 1.7\ \text{Mb}, \quad \sigma_I(14) = 14\ \text{Mb}.$$

An over-all uncertainty of a factor of ~2 is assigned to these numbers to allow for possible error in the absolute value of the Si(Li) window

TABLE I. Summary of observations (all energies in eV).

| | | | | | | | Present work | $R_n$ | |
|---|---|---|---|---|---|---|---|---|---|
| Line | Configuration | $\omega_k$ [a] | $\omega_n$ | $E_{\mathrm{calc}}$ [a] | $E_{\mathrm{calc}}$ [b] | $E_{\mathrm{meas}}$ [c] | $E$ | $q$ = "6" | $q$ = "14" |
| | $1s2s^22p^3$ | 0.0189 | | 869.0 | | | | | |
| $KL^3$ | $1s2s2p^4$ | 0.0250 | 0.023 | 868.9 | 869.5 | | 875 | 0.052(8) | 0.000 |
| | $1s2s^02p^5$ | 0.0256 | | 869.2 | | | | | |
| | $1s2s^22p^2$ | 0.0196 | | 879.0 | | | | | |
| $KL^4$ | $1s2s2p^3$ | 0.0313 | 0.029 | 878.5 | 879.4 | | 882 | 0.19(2) | 0.029(3) |
| | $1s2s^02p^4$ | 0.0319 | | 878.3 | | | | | |
| | $1s2s^22p$ | 0.0164 | | 890.7 | | | | | |
| $KL^5$ | $1s2s2p^2$ | 0.0445 | 0.042 | 889.7 | 890.9 | | 897 | 0.29(1) | 0.19(1) |
| | $1s2s^02p^3$ | 0.0447 | | 889.0 | | | | | |
| | $1s2s^22p^0$ | 0.0000 | | | | | | | |
| $KL^6$ | $1s2s2p$ | 0.0843 | 0.083 | 902.6 | 902.3 | 908.1 | 909 | 0.20(1) | 0.17(2) |
| | $1s2s^02p^2$ | 0.0823 | | 901.6 | | 904.4 | | | |
| | $1s2s2p^0$ | 0.0000 | 0 | | | | | | |
| $KL^7$ | $1s2s^02p$ | 1.000 | 1 | 914.4 | 914.9 | 915.1 | 920 | 0.17(2) | 0.28(1) |
| | $1s2p3p$ [d] | 1.000 | 1 | | | 1041.5 | 1044 | 0.013(5) | 0.062(10) |
| $K^2L^5$ | $1s^02s^22p$ | 0.0198 | 0.020 | 997.4 | | | 995 | 0.030(6) | 0.030(4) |
| $K^2L^6$ | $1s^02s2p$ | 0.0998 | 0.10 | 1007.6 | | 1007.8 | 1011 | 0.046(6) | 0.11(1) |
| | $1s^02s^02p^2$ | | | | | 1003.6 | | | |
| $K^2L^7$ | $1s^02s^02p$ | 1 | 1 | 1021.8 [e] | | | 1025 | 0.006(6) | 0.13(1) |

[a] C. P. Bhalla, N. O. Folland, and M. A. Hein, Phys. Rev. A 8, 649 (1973), except for $K^2L^7$.

[b] Lewis L. House, Astrophys. J. Suppl. Ser. 18, 21 (1969).

[c] N. J. Peacock, R. J. Speer, and M. G. Hobby, J. Phys. B 2, 798 (1969).

[d] This state is observed by a $3p$-$1s$ transition.

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

transmission (see Ref. 3).

Some comments are in order regarding the reliability of vacancy-production cross sections derived from x-ray cross sections using configuration-averaged fluorescence yields. Reference 10 points out that x rays from different initial charge states can overlap (even with 3-eV resolution) owing to large term splittings in some configurations. Three other considerations are (i) the influence of metastable states on fluorescence yields, (ii) branching and feeding of single-vacancy states by double-vacancy states, and (iii) electron capture by recoiling, metastable ions.

First, fluorescence yields computed by Bhalla *et al.*[7] are defined as

$$\omega_k = \Gamma_x/(\Gamma_A + \Gamma_x).$$

The total $2p$-$1s$ x-ray decay rate $\Gamma_x$ includes only *allowed* $E1$ decays from all possible states of a given configuration. Likewise the total Auger decay rate $\Gamma_A$ includes only *allowed* Coulomb-autoionization decays from all possible states in the configuration. However, in so far as spin-orbit induced autoionization decays have been ignored, the fluorescence yield is, in general, overestimated. For example, the fluorescence yield computed for the configuration $1s2p^3$ (a component of $KL^5$) includes the radiative decay of 35 of the 40 possible states formed (${}^5S_2^o$ being metastable), but the Auger decay of only 12 of them. (${}^{3,1}D^o$ and ${}^{5,3}S^o$ are metastable against Coulomb autoionization.) Spin-orbit mixing of the 16 states in the $(1s2p^3)$, ${}^3D_{2,1}^o$, ${}^1D_2^o$, and ${}^3S_1^o$ levels with the autoionizing states in the $(1s2p^3)\,{}^3P_{2,1}^o$ levels will tend to make the true fluorescence yield smaller than the calculated value of 0.0447. However, by assuming a rather large 10% mixing (e.g., assuming ${}^3D_2^o$ is composed of 90%-pure ${}^3D_2^o$ and 10%-pure ${}^3P_2^o$) we estimate that the fluorescence yield drops by only ~10% to 0.0396. The neglect of metastable states in the computation of $\omega_k$ means that this parameter cannot be used to estimate the production rate of metastable vacancies from total x-ray yields. The fluorescence yields of states that are metastable against both $E1$ decay and Coulomb autoionization are completely unknown. Some atoms in these states do, eventually, radiate and thereby contribute to the total x-ray yield.

Second, observation of a given spectral line does not, of course, necessarily reveal the location of the original vacancy. For example, the double-vacancy $(2p^2)\,{}^1S_0^e$ can decay to the single-vacancy level $(1s2p)\,{}^1P_1^o$, which can then decay to the $(1s^2)\,{}^1S_0^e$ ground state. Both steps are evident in the observed spectra. Such cascades make it difficult, if not impossible, to infer the number of direct collision-induced single-vacancy states when significant double-vacancy production also occurs.

Finally, we have considered the possibility that a recoiling metastable target ion can capture an electron before the original vacancy decays. We estimate that such captures, which change the identity of the collision-induced vacancy, are negligible at the target densities used here whenever the lifetime of the recoiling metastable state is shorter than $10^{-8}$ sec.

## IV. CONCLUSION

We have resolved the satellite structure of neon $K$ x rays excited in collisions with fast, highly ionized argon ions and determined the relative satellite intensities. An average of configuration-dependent fluorescence yields computed by Bhalla *et al.* serves as an estimate of the fluorescence yield for each satellite line. These average fluorescence yields were combined with the experimentally determined relative intensities to deduce the effective fluorescence yield that is needed to convert total x-ray cross sections measured previously with a Si(Li) detector into total ionization cross sections. We find that the ionization cross section thereby crudely estimated, increases by a factor of ~8 when the projectile charge is increased from 6+ to 14+.

*Added Note*: Since the submission of this paper a Letter[15] appeared reporting direct measurements of neon fluorescence yields for similar collision systems (50-MeV $\mathrm{Cl}^{q+}$ on neon, $5 \leq q \leq 15$). The authors of that Letter conclude, as we do, that the projectile-charge-state–dependent $K$ x-ray cross section is due in part to an increase in target fluorescence yield, but that a significant part of the dependence is a result of an increasing target $K$-shell ionization cross section. The effective fluorescence yields measured by Burch *et al.* are larger than the weighted averages estimated above, even though there is no discrepancy between the two experimental results with regard to the fraction of x-ray transitions from states having $\omega_k = 1$.

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[1] James R. Macdonald, Loren Winters, Matt. D. Brown, Tang Chiao, and Louis D. Ellsworth, Phys. Rev. Lett. 29, 1291 (1972); Loren M. Winters, James R. Macdonald, Matt D. Brown, Tang Chiao, Louis D. Ellsworth, and E. W. Pettus, Phys. Rev. A 8, 1835 (1973).

[2] J. Richard Mowat, I. A. Sellin, D. J. Pegg, R. S. Peterson, Matt D. Brown, and James R. Macdonald, Phys. Rev. Lett. 30, 1289 (1973).

[3] J. Richard Mowat, I. A. Sellin, P. M. Griffin, D. J. Pegg, and R. S. Peterson, Phys. Rev. A 9, 644 (1974).

[4] Robert L. Kauffman, Forrest Hopkins, C. W. Woods, and Patrick Richard, Phys. Rev. Lett. 31, 621 (1973).

[5] M. D. Brown, J. R. Macdonald, Patrick Richard, J. R. Mowat, and I. A. Sellin, Phys. Rev. A 9, 1470 (1974).

[6] H. D. Betz, Rev. Mod. Phys. 44, 465 (1972).

[7] C. P. Bhalla, N. O. Folland, and M. A. Hein, Phys. Rev. A 8, 649 (1973).

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

[9] Lewis L. House, Astrophys. J. Suppl. Ser. 18, 21 (1969).

[10] C. L. Cocke, B. Curnutte, and R. Randall, Phys. Rev. A 9, 1823 (1974); see also Robert L. Kauffman, C. W. Woods, K. A. Jamison, and Patrick Richard (unpublished).

[11] N. J. Peacock, R. J. Speer, and M. G. Hobby, J. Phys. B 2, 798 (1969).

[12] Hugh P. Summers, Astrophys. J. 179, L45 (1973).

[13] In computing this average the value $\omega_n$ $(1s2p)$ was taken to be unity. Since half of the states of this configuration are metastable against $E1$ decay and probably recoil out of the field of view before decaying, it may be more appropriate to use $\omega_k = 0.5$, even though the state does not autoionize. However, the effective value $\omega_k$ (14) is remarkably insensitive to the choice of $\omega_n$ for this configuration.

[14] Walter Bambynek, Bernd Crasemann, R. W. Fink, H. U. Freund, Hans Mark, C. D. Swift, R. E. Price, and P. Venugopala Rao, Rev. Mod. Phys. 44, 716 (1972).

[15] D. Burch, N. Stolterfoht, D. Schneider, H. Wieman, and J. S. Risley, Phys. Rev. Lett. 32, 1151 (1974).