Delayed emission of $2p$-$1s$ and $3p$-$1s$ x rays from 40-MeV neon ions following beam-foil excitation

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The decay curves for the delayed emission of $2p$-$1s$ and $3p$-$1s$ transitions in 40-MeV He- and H-like Ne projectiles excited by passage through a thin carbon foil have been measured. The decay curves, when compared to theoretical calculations, indicate that the l distribution is uniform in the high-n Rydberg states. Various structural features in the delayed x-ray emission spectra of 40-MeV Ne and 48-MeV Mg ions have also been examined.

I. INTRODUCTION

The beam-foil technique has long been used as a convenient way to produce and study highly stripped ions. As a fast-moving ion passes through a thin foil, the electrons in its outer shells are quickly stripped away. At the same time, electrons from the foil are continuously being captured and lost so that when the ion finally emerges from the back surface of the foil it may be in any one of a large number of possible excited states.

Some fraction of the ions passing through a thin foil end up with an electron in a Rydberg state of high principal quantum number ($n > 100$) as is evidenced by the existence of long-lived components in the decay curves of np-$1s$ x-ray transitions.[1–4] In order to characterize the mechanism for the population of high-n Rydberg states via the beam-foil interaction, several recent investigations have focused on the nature of the distribution of Rydberg states with respect to the angular momentum quantum number.[5–8] It has been pointed out, for example, that capture of electrons into Rydberg states at the back surface or in the last few layers of the foil should lead to a predominately low-l population.[7] The observation of a very low intensity of delayed Ly-β lines relative to the delayed Ly-α intensity in foil-excited 127-MeV sulfur ions by Rothermel *et al.*[8] has been interpreted to mean that most of the initial Rydberg states have large angular momentum quantum numbers. Thus, it would appear that last-layer electron capture may not be the principal mechanism for populating high-n Rydberg states.

Betz *et al.*[7] have performed cascade calculations for a variety of assumed excited-state distributions, $N(n,l)$, of 40-MeV oxygen ions emerging from foils. These calculations indicate that the predicted decay curves and the relative intensities of various np-$1s$ lines in the He- and H-like spectra should be sensitive to $N(n,l)$ and, therefore, measurements of the decay curves for individual lines would provide further information concerning the actual distribution of Rydberg electrons. In the present work, the decay curves for delayed emission of $2p$-$1s$ x rays from H- and He-like neon and of $3p$-$1s$ x rays from H-like neon were measured for the purpose of assessing the l distribution at a significantly lower Z than sulfur. In addition, several structural features in the K x-ray spectra of foil-excited neon and magnesium ions were examined.

II. EXPERIMENTAL PROCEDURE

A beam of 40-MeV Ne^{2+} ions was extracted from the Texas A&M cyclotron and directed onto a 50-μg/cm^2 carbon foil mounted on a target slide which could be moved along the beam axis as shown in Fig. 1. The Ne K x rays emitted at 90° to the beam direction were analyzed with a 12.7-cm Johansson-type curved-crystal spectrometer employing a rubidium-acid-phthalate (RAP) crystal. The viewing region of the spectrometer was restricted to a 2-mm length of the beam path by an adjustable slit assembly. Line intensities were extracted from the spectra by means of a least-squares program which used a linear function to represent the flat background and Voigt functions to represent the x-ray peaks.

Presented in Fig. 2 are Ne K x-ray spectra taken at distances of 0, 2.3, and 9.1 mm behind the foil. These spectra have been normalized to the same total integrated charge collected from the carbon foil. The $1s2p(2\,^3P_1)$–$1s^2(1\,^1S_0)$ transition is spin-forbidden (a metastable intercombination line) and has a lifetime of 1.85×10^{-10} sec[9], whereas the $1s2p(^1P)$–$1s^2(^1S)$, $2p(^2P)$–$1s(^2S)$, and $3p(^2P)$–$1s(^2S)$ transitions are dipole allowed with lifetimes of 1.13×10^{-13},[9] 1.59×10^{-13},[10] and 5.98×10^{-13} sec,[11] respectively. It is apparent that

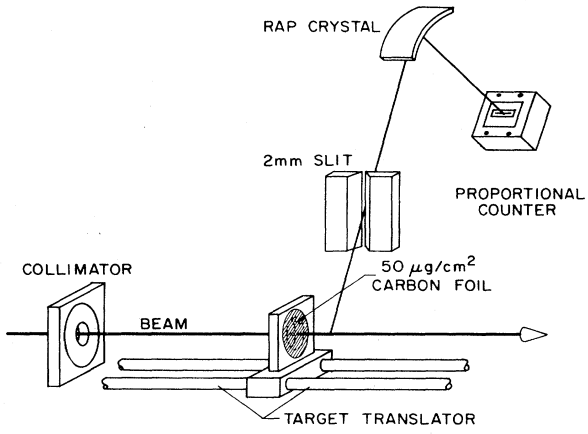

FIG. 1. Schematic diagram of the experimental configuration.

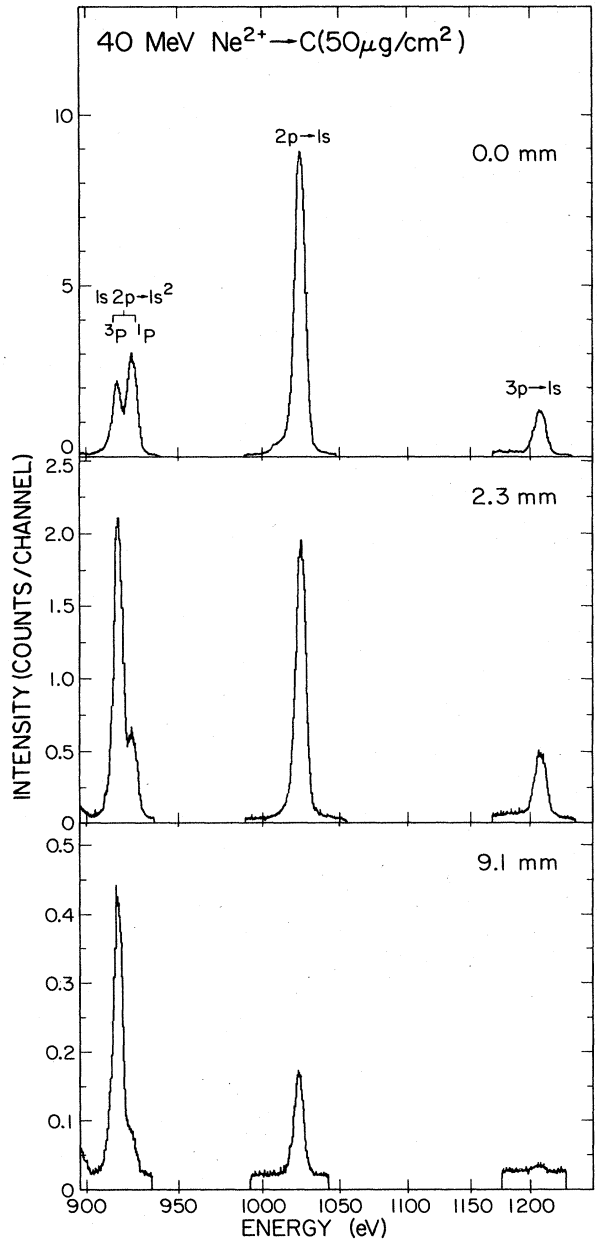

FIG. 2. K x-ray spectra of 40-MeV foil-excited Ne ions taken at various distances behind the carbon foil.

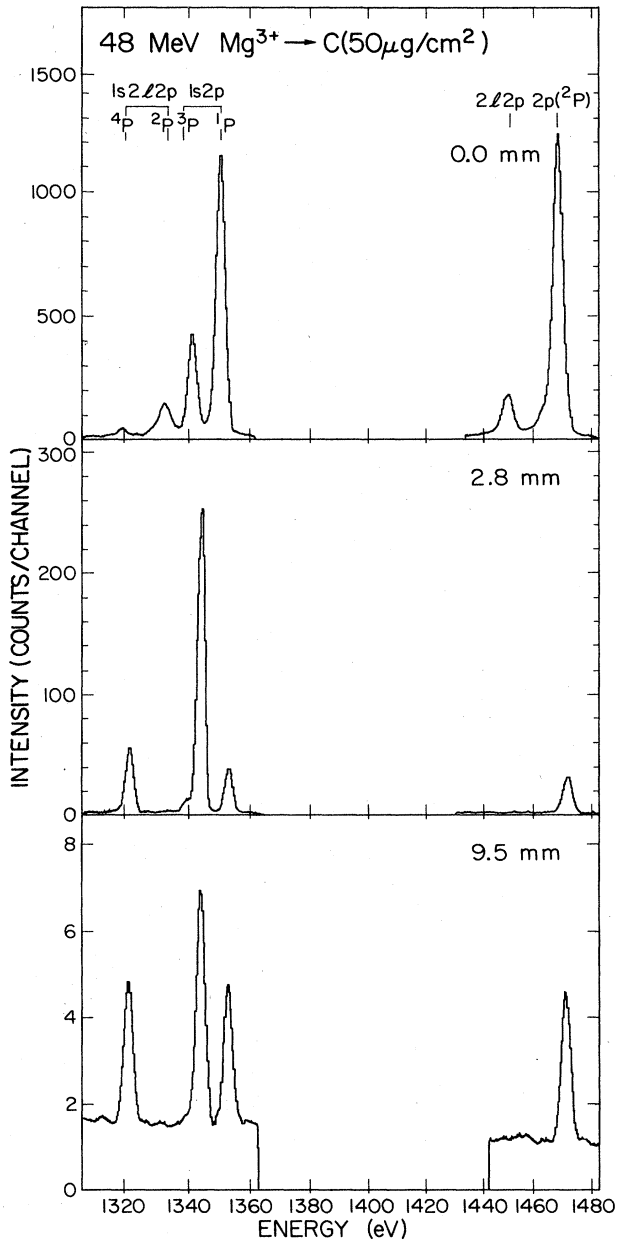

FIG. 3. K x-ray spectra of 48-MeV foil-excited Mg ions taken at various distances behind the carbon foil.

even at 1 cm (i.e., 0.5 nsec) behind the foil, considerable intensity is still detected for the short-lived transitions indicating that electrons are cascading from very high-n levels.

Similar measurements were performed at three foil positions for magnesium $K\alpha$ x rays using a beam of 48-MeV Mg^{3+} incident on a 50-$\mu g/cm^2$ carbon foil. The magnesium spectra are shown in Fig. 3. The lifetimes of the magnesium $1s2p(^3P)$, $1s2p(^1P)$, and $2p(^2P)$ states are 2.92×10^{-11},[9] 5.13×10^{-14},[9] and 2.88×10^{-13} sec,[11] respectively.

III. RESULTS AND DISCUSSION

Presented in Fig. 4 are the intensities of the neon delayed $1s2p(^1P)$—$1s^2(^1S)$, $2p$-$1s$, and $3p$-$1s$ transitions as a function of the distance behind the foil. Previous measurements[3] and calculations[7] have shown that the decay curves can be described by a power law, $I=ct^{-b}$, where c and b are constants for a given line. The decay curves for the $1s2p(^1P)$—$1s^2$ and $2p$-$1s$ transitions are well represented by the power law with b equal to 1.35 and 1.44, respectively. Previous measurements[3,12] of the decay

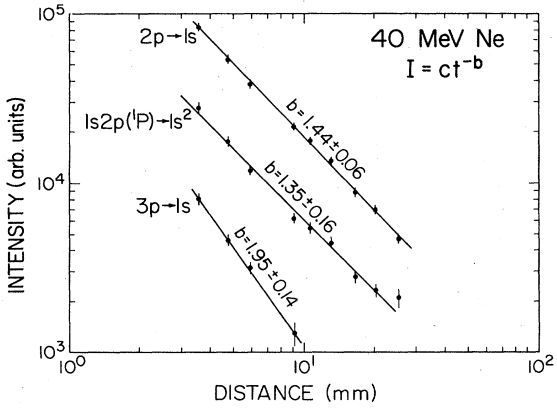

FIG. 4. Measured decay curves for the indicated lines of 40-MeV foil-excited Ne ions. The solid lines are power-law fits to the experimental data.

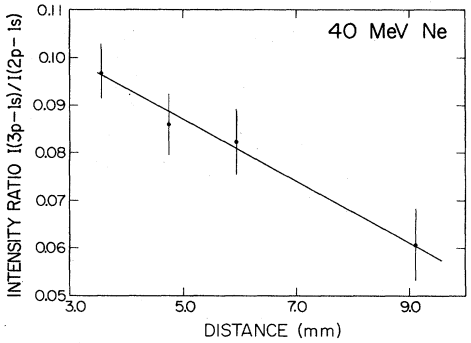

FIG. 5. The measured dependence of the intensity ratio $I(3p\text{-}1s)/I(2p\text{-}1s)$ on the distance behind the foil for 40-MeV foil-excited Ne ions.

curves for these transitions in He- and H-like oxygen and fluorine yielded $b=1.5$, while a more recent low-resolution study[13] gave $b=1.40$ and 1.44, respectively, for the $2p$-$1s$ transition in H-like oxygen and fluorine.

The model calculations of the decay curves for $2p$-$1s$ transitions by Betz *et al.*[7] were carried out for the hypothetical cases: (1) electron capture using the l dependence predicted by the first Born approximation (i.e., predominantly low l states), (2) only s states populated, (3) all l states uniformly populated, and (4) only yrast states ($l=n-1$) populated. Cases (1) and (2) yielded decay curves characterized by $b=1.8$, while cases (3) and (4) yielded decay curves characterized by $b=1.33$. It appears, therefore, that cases (3) and (4) represent the present experimental results better than do the other two cases.

The decay curve for the H-like neon $3p$-$1s$ transition in the present work (Fig. 4) is characterized by a power law with $b=1.95$; a value which is considerably larger than those observed for the $2p$-$1s$ transitions. This may be attributable to the fact that electrons cascading down from high-n Rydberg states must feed the $2p$ and $3p$ states through different channels. The high angular momentum yrast states would be expected to feed the $2p$ state through a strong sequential yrast cascade, whereas the non-yrast states would feed both the $2p$ and $3p$ states through direct and sequential cascades.

The intensity ratio $I(3p\text{-}1s)/I(2p\text{-}1s)$ for 40-MeV H-like neon is shown in Fig. 5 as a function of the distance behind the exciting foil. Both the absolute value of this ratio and its dependence on the distance from the foil give fairly good agreement with the case-(3) model calculation of Betz *et al.*,[7] which assumes the l states are uniformly populated (see Fig. 5 of Ref. 7). The intensity ratio $I(3p\text{-}1s)/I(2p\text{-}1s)$ for 16-MeV O projectiles and 127-MeV S projectiles excited by thin carbon foils can be obtained from the measurements of Braithwaite *et al.*[3] and of Betz *et al.*,[13] respectively. For oxygen, the value of this ratio is 0.5 and it does not appear to depend on the distance from the foil, which by comparison with the model calculations[7] implies that only low-angular-momentum states are populated. For sulfur, the intensity ratio changes with the distance from the foil in accordance with our findings, for neon, but, as was mentioned above, the absolute magnitude of this ratio (0.027—0.019) implies a high-l distribution.

Considering the different possible mechanisms proposed[8] for populating Rydberg states in the projectile upon exiting the foil (capture of electrons from the last few atomic layers of the foil, Coulomb capture of cusp electrons, radiative capture of continuum electrons), it is difficult to predict what kind of an l distribution should predominate. The present results for neon suggest that the different l states within a given n manifold are populated uniformly. However, the situation is far from clear at this point and more systematic studies of delayed x-ray emission as a function of projectile Z and energy will be required to unify the apparently conflicting results obtained for the few systems studied thus far. It is likely that several different mechanisms are important in determining the population distribution of high-n Rydberg states. Also a redistribution of the initial n,l population via Stark mixing in the electric field at the foil surface may occur, thereby complicating the picture.

Besides the overall intensity variations, the spectra presented in Figs. 2 and 3 show interesting structure changes as a function of distance from the foil. For example, the ratio of the intensities of the He-like $(1s2p)^3P_1$—$(1s^2)^1S$ and $(1s2p)^1P$—$(1s^2)^1S$ lines [hereafter referred to as the $I(^3P)/I(^1P)$ ratio] changes from a value which is much less than one in the prompt spectrum to a value that is much greater than one in the delayed spectra. At distances comparable to the mean decay length of the $^3P_1$ state (3.6 mm for neon and 0.6 mm for magnesium), the enhancement of the ^3P intensity over the ^1P intensity mainly reflects the fact that the ^3P line still has a substantial contribution from the decay of states populated by direct excitation at the foil, while the ^1P contribution arises only from cascading. It was found, however, that even at large distances from the foil, where the direct excitation contribution is negligible, the $I(^3P)/I(^1P)$ ratio is still much larger than the value of 0.97 expected for a statistical population of these states. The $I(^3P)/I(^1P)$ ratios at large foil distances are 1.5 and 1.6 for 40-MeV neon and 48-MeV magnesium, respectively. The cause of this

effect is most likely associated with the fact that a triplet state to a singlet state transition is forbidden by dipole selection rules. Thus, anytime the high-n Rydberg electron, in combination with the $1s$ electron, forms a ^3P state during the cascade process, the branching ratio for a direct transition to the ^1S ground state will be very much smaller than that for the corresponding transition from a ^1P state. The net effect will be to produce an enhanced population of the $2\,^3P$ state, since proportionally more ^1P states than ^3P states will decay to the ground state at each stage of the cascade. A more quantitative study of the different possible cascade channels will be necessary to find out how the $I(^3P)/I(^1P)$ ratio relates to the initial $N(n,l)$ distribution of Rydberg states.

Another important difference between the prompt and delayed spectra is the absence of the $1s\,2l2p-1s^22l$ and $2l2l-1s2l$ lines in the latter. The missing $1s2p2p-1s^22p$ and $2p2p-1s\,2p$ lines simply reflect the fact that the $1s\,2p$ or $2p$ cores decay before a high-n Rydberg electron has time to cascade down to the $2l$ level. The $1s\,2s(^3S)$ and $2s$ cores, on the other hand, have very long lifetimes, but even so, there is no evidence of the $1s\,2s\,2p-1s^22p$ and $2s2p-1s2p$ lines in the delayed spectra. Also, the disappearance of the $2pnl-1snl$ satellite lines is quite evident in both the Ne and Mg spectra. These spectator-electron satellites cause unresolvable shoulders on the low-energy tails of the $2p$-$1s$ lines in the prompt spectra and hinder the precise determination of the $2p$-$1s$ transition wavelength in Lamb-shift measurements.[14] Their absence in the delayed spectra suggests that higher precision might be obtainable (at the expense of intensity) by performing such measurements at a well-defined position behind the exciting foil.

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[1]J. Pálinkás, G. J. Pedrazzini, D. A. Church, R. A. Kenefick, C. A. Fulton, R. L. Watson, and D.-W. Wang, Phys. Rev. A **31**, 598 (1985).

[2]R. J. Maurer, R. L. Watson, O. Benka, J. M. Sanders, and D. M. Oldham, Nucl. Instrum. Methods **202**, 193 (1982).

[3]W. J. Braithwaite, D. L. Matthews, and C. F. Moore, Phys. Rev. A **11**, 465 (1975).

[4]I. A. Armour, J. D. Silver, and E. Traber, J. Phys. B **14**, 3563 (1981).

[5]H.-D. Betz, D. Roschenthaler, and J. Rothermel, Phys. Rev. Lett. **50**, 34 (1984).

[6]E. P. Kanter, D. Schneider, and Z. Vagner, Phys. Rev. A **28**, 1193 (1983).

[7]H. D. Betz, J. Rothermel, and F. Bell, Nucl. Instrum. Methods **170**, 243 (1980).

[8]J. Rothermel, H.-D. Betz, F. Bell, and V. Zacek, Nucl. Instrum. Methods **194**, 341 (1982).

[9]C. D. Lin, W. R. Johnson, and A. Dalgarno, Phys. Rev. A **15**, 1 (1977); **15**, 154 (1977).

[10]L. A. Vainshtein and U. I. Safronova, At. Data Nucl. Data Tables **21**, 49 (1978).

[11]K. Omidvar, At. Data Nucl. Data Tables **28**, 215 (1983).

[12]P. Richard, Phys. Lett. **45A**, 13 (1973).

[13]A. P. Georgiadis, L. von Gerdtell, G. Dehmelt, D. Strāter, R. N. Ahmad-Bitar, and P. von Brentano, Z. Phys. A **300**, 277 (1983).

[14]J. P. Briand, *X-Ray and Atomic Inner-Shell Physics—1982 (International Conference, University of Oregon)*, edited by Bernd Crasemann (AIP, New York, 1982), p. 271.