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Nonstatistical enhancement of the $1s2s2p\ ^4P$ state in electron transfer in 0.5–1.0-MeV/u $C^{4,5+}$ + He and Ne collisions

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Nonstatistical enhancements for formation of the metastable $1s2s2p\ ^4P$ state compared to the similarly configured $1s2s2p\ ^2P_-$ and $1s2s2p\ ^2P_+$ states are observed following single electron transfer to $C^{4+}(1s2s\ ^3S)$ and double electron transfer to $C^{5+}(1s)$ ions, respectively. Previously, similar enhancements were observed in the population of the ^4P metastable state resulting from electron transfer in ~1 MeV/u $F^{7,8+}$+He and Ne collisions [J. A. Tanis *et al.*, Phys. Rev. Lett. **92**, 133201 (2004)]. The enhancements were attributed to a dynamical Pauli exchange mechanism involving projectile and target electrons having the same spin alignment. Recently, it was suggested that the enhancement might be due to cascade effects following electron transfer to states with $n>3$. To further understand the observed enhancement of the ^4P state, new investigations of Auger emission spectra in collisions of 0.5–1 MeV/u $C^{4,5+}$ with He and Ne targets have been conducted. Experimental ratios of the resulting ^4P intensities to the sum of the $^2P_-$ and $^2P_+$ intensities for the collision systems studied give values three to four times larger than expected based solely on spin statistics for single transfer to $C^{4+}(1s2s\ ^3S)$ and double transfer to $C^{5+}(1s)$. Theoretical calculations suggest that about half of the observed enhancement is caused by cascade effects.

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I. INTRODUCTION

Previously, anomalously large Auger emission intensities were observed for the $1s2s2p\ ^4P$ state compared to the similarly configured $1s2s2p\ ^2P_-$ and $1s2s2p\ ^2P_+$ states in electron transfer interactions involving 1.1 MeV/u collisions of He-like and H-like F ions with He and Ne targets [1]. Enhancement of the measured ^4P intensities were evaluated from the ratio $R={}^4P/({}^2P_-+{}^2P_+)$, for which a value of 2 is expected based on spin statistics [2]. Determination of the actual formation probability for R required corrections for geometrical factors due to the long lifetimes of the ^4P state ($J=5/2,3/2,1/2$), which have values in the range 10^{-9} s $<t<10^{-7}$ s in F^{6+} [3]. The resulting large ^4P intensities, which could not be explained on the basis of spin statistics, were attributed to a dynamical Pauli exchange mechanism involving projectile and target electrons having the same spin alignment in the electron transfer interaction. Notably, large enhancements of the $2p^53s3p\ ^4D$ state have also been observed by Hutton *et al.* [4] for single and double capture to Ne-like and F-like ions, respectively, of Si, Ar, Sc, Ti, Fe, and Cu in low velocity (0.2–0.4 a.u.) collisions with He targets. However, formation of the $2p^53s3p\ ^4D$ state due to Pauli exchange effects was not considered in that work, and, in fact, no specific mechanism for enhancement of the ^4D state was identified.

Recently, it has been suggested that the ^4P intensity might be significantly enhanced due to cascade effects following electron transfer to states with $n>3$ [5], thereby eliminating the need to invoke a dynamic mechanism such as Pauli exchange. A limitation of the earlier measurements for 1.1 MeV/u $F^{7,8+}$ ions [1] was the fact that the single transfer measurements were conducted only for the mixed-state beam $F^{7+}(1s^2+1s2s\ ^3S)$ formed by post-stripping accelerated F ions of lower charge states. Thus, it was not clear what fraction of the observed ^4P intensity was due solely to single transfer to the metastable $1s2s\ ^3S$ beam component. However, single transfer to F^{7+} and double transfer to F^{8+} gave similar values for the ratio R, suggesting similar mechanisms for the formation of the $1s2s2p\ ^4P$.

To shed light on these conflicting interpretations, and to gain further insight into the origin of the observed ^4P enhancement, new experimental and theoretical studies have been undertaken for 0.5–1.0 MeV/u $C^{4,5+}$ ions colliding with He and Ne targets. In the present work, Auger spectra for single transfer to incident C^{4+} ions were collected for both ground-state $C^{4+}(1s^2)$ and mixed-state $C^{4+}(1s^2+1s2s\ ^3S)$ beams. In this way, the measured spectra for the mixed-state beam could be corrected for the ground-state contribution to give the $1s2l2l'$ intensities due solely to the $C^{4+}(1s2s\ ^3S)$ component. Again, as in Ref. [1], the intensity ratio $R={}^4P({}^2P_-+{}^2P_+)$ for incident He-like and H-like ions was found to exceed significantly the value expected based on spin statistics, and, furthermore, R was found not to vary significantly over the velocity range of the present measurements. The effect of electron cascading on the measured value of R is considered by theoretical calculations, which indicate that cascade feeding due to capture into $n\geqslant 3$ levels does indeed play an important role, but explains only about half of the observed enhancement.

II. EXPERIMENTAL PROCEDURE

The measurements were made at Western Michigan University using the 6 MV tandem Van de Graaff accelerator.

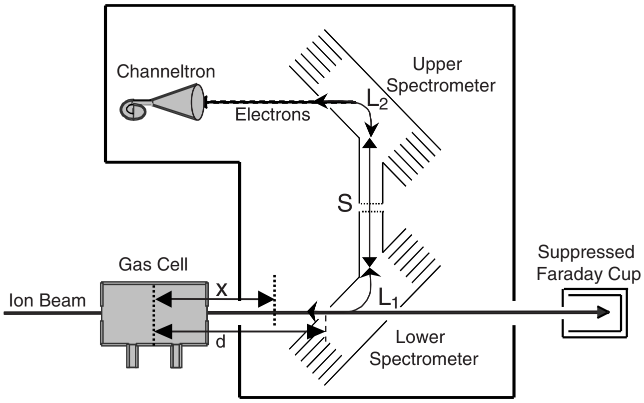

FIG. 1. Experimental configuration of gas cell interaction region and parallel-plate spectrometer.

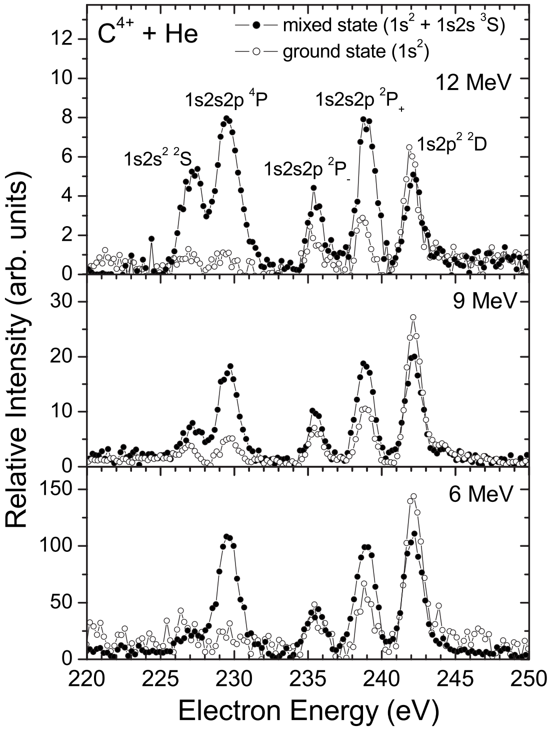

FIG. 2. Measured zero-degree Auger emission spectra following single electron transfer to mixed-state $C^{4+}(1s^2+1s2s\,^3S)$ and ground-state $C^{4+}(1s^2)$ in 6, 9, and 12 MeV collisions with He. The ejected electron energy has been transformed to the rest frame of the projectile and the electron yield has been normalized to the incident beam current.

Beams of C^{4+} and C^{5+} ions were accelerated to energies of 6, 9, and 12 MeV (0.5, 0.75, and 1.0 MeV/u, respectively), collimated, and directed into a scattering chamber with a differentially pumped gas cell that contained targets of He or Ne atoms. Beam intensities on target ranged from 1–100 nA depending on the incident energy and charge state, while target gas pressures ranging from 10–80 mTorr were chosen to ensure single collision conditions (depending on energy, charge state, and target gas). Single collision conditions were checked prior to each measurement by determining the total charged-changed fraction of the incident ions and keeping this value less than about 5%. Auger electrons emitted along the beam direction (i.e., at zero degrees) from excited-state $1s2l2l'$ configurations in C^{3+} ions were energy analyzed with a high-resolution two-stage parallel-plate spectrometer located ~10 cm downstream from the target cell. High resolution was achieved by retarding electrons emerging from the first stage of the spectrometer to a pass energy of 100 eV prior to entering the second stage. Analyzed electrons were counted with a channel electron multiplier (CEM) and normalized to the incident beam current, which was collected in a Faraday cup. A diagram of the interaction region and spectrometer is shown in Fig. 1.

For single transfer to incident C^{4+}, spectra were collected for both the ground-state ($1s^2$) beam, formed directly by gas-stripping C^- ions at the relatively low energy encountered at the terminal of the accelerator, and for the mixed-state ($1s^2+1s2s\,^3S$) beam, which was produced by post-stripping accelerated C^{3+} following energy and charge-state analysis. For C^{4+} produced directly by gas stripping at the accelerator terminal essentially all of the ions are expected to be in the $1s^2$ ground state [6], while the post-stripped beam is expected to contain a $1s2s\,^3S$ metastable component of ~10–30 % [7]. From the spectra obtained for the ground- and mixed-state beams it was possible to determine the $1s2l2l'$ Auger intensities resulting solely from electron transfer to the metastable $C^{4+}(1s2s\,^3S)$ beam component. The procedure for doing this will be described below. For double capture to C^{5+}, only post-stripped ions were used since there are no long-lived excited states for H-like C^{5+} ions.

III. RESULTS AND ANALYSIS

Figures 2 and 3 show the electron spectra obtained for the mixed-state and ground-state C^{4+} beams for He and Ne targets, respectively, for each of the collision energies investigated. Figure 4 shows the corresponding spectra for $C^{5+}(1s)$+Ne. For C^{5+}+He, negligible intensity was observed for $1s2l2l'$ autoionizing transitions, in agreement with our earlier results for F^{8+}+He [1]. This is due to the fact that double transfer from He targets to H-like ions in the studied energy range is very unlikely. The energy scale of the spectra in Figs. 2–4 has been transformed to the rest frame of the projectile, and the electron yields for the ground and mixed states (Figs. 2 and 3) have been normalized to the beam current so the relative contributions of the various Auger lines for each collision energy can be directly compared. The spectra show five Auger lines with significant and varying intensities: $1s2s^2\,^2S$, $1s2s2p\,^4P$, $1s(2s2p\,^3P)\,^2P_-$, $1s(2s2p\,^1P)\,^2P_+$, and $1s2p^2\,^2D$, in order of increasing ejected electron energy.

In this work we are interested in the formation probability of the $1s2s2p\,^4P$ state compared to the similarly configured $1s(2s2p\,^3P)\,^2P_-$ and $1s(2s2p\,^1P)\,^2P_+$ states, i.e., the ratio $R={}^4P/({}^2P_-+{}^2P_+)$. To accurately determine the formation probabilities of these states two significant corrections are necessary. In the case of incident C^{4+} ions, the beam can contain contributions from both the $1s^2$ ground state and the

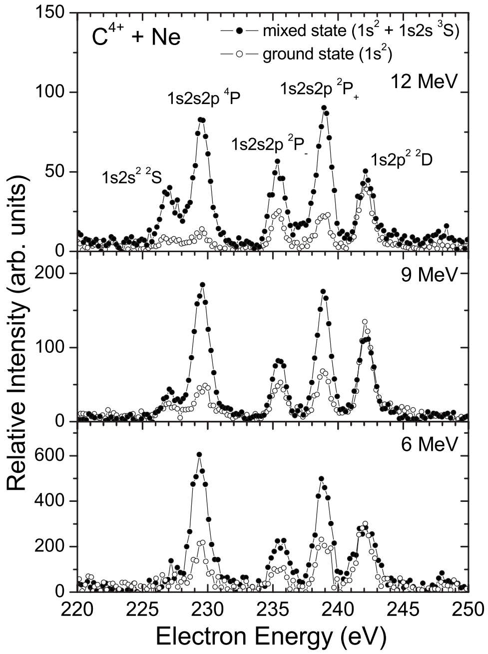

FIG. 3. Measured zero-degree Auger emission spectra following single electron transfer to mixed-state $C^{4+}(1s^2+1s2s\,^3S)$ and ground-state $C^{4+}(1s^2)$ in 6, 9, and 12 MeV collisions with Ne. The ejected electron energy has been transformed to the rest frame of the projectile and the electron yield has been normalized to the incident beam current.

$1s2s\,^3S$ metastable state. Hence, the ground-state contribution must be subtracted in order to determine the Auger intensities due solely to the $1s2s\,^3S$ beam component. A second important correction, for both C^{4+} and C^{5+}, arises from the long lifetime of the ^4P causing its observed intensity to be significantly altered from its true production intensity compared to that of the $^2P_-$ and $^2P_+$ states. These corrections will be considered separately.

A. Ground-state correction for C^{4+} beam

In the case of a mixed state $C^{4+}(1s^2+1s2s\,^3S)$ beam, the ^4P state can be formed from single electron transfer to the $1s2s\,^3S$ state, or by a two-electron process involving single transfer accompanied by K-shell excitation (with a spin flip) from the $1s^2$ ground state. The two-electron mechanism is small, however, in the present collision velocity range, compared to single capture to the $1s2s\,^3S$ state, especially for the He target [8]. The dominance of ^4P formation from single transfer to the $1s2s\,^3S$ state can be seen from the data of Fig. 2, which shows that the $1s^2$ ground-state beam gives rise to only a small ^4P intensity. Furthermore, these data indicate the purity of the C^{4+} ground-state beam, since an appreciable metastable component in this beam would result in formation of the ^4P state. On the other hand, the $^2P_+$ state, and to a lesser extent the $^2P_-$ state, can be formed from the $1s^2$ ground state by resonant transfer excitation (RTE) [9,10], in which electron transfer is accompanied by simultaneous electronic excitation ($1s \rightarrow 2l$). Both of these latter states are also formed with significant probability from the $1s2s\,^3S$ state by single transfer (see Figs. 2 and 3).

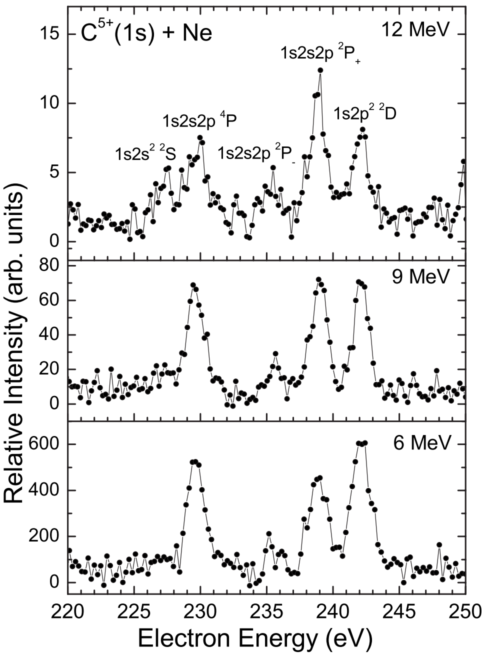

FIG. 4. Measured zero-degree Auger emission spectra following double electron transfer to $C^{5+}(1s)$ in 6, 9, and 12 MeV collisions with Ne. For He targets double transfer was too small to be observable.

To prepare a beam with a $1s2s\,^3S$ component requires stripping accelerated C ions of lower charge state, in the present case C^{3+}, a process that results in a mixed-state $C^{4+}(1s^2+1s2s\,^3S)$ beam. Hence, to determine accurately the ratio of the ^4P intensity to the sum of the $^2P_-$ and $^2P_+$ intensities formed solely from the $1s2s\,^3S$ state the data collected for the mixed-state beam must be corrected for the contributions from the ground state. A nearly pure $1s^2$ ground-state beam is produced by stripping accelerated C^- ions directly to C^{4+} at the much lower energy encountered at the terminal of the tandem accelerator, a technique used by Zamkov *et al.* [6] to produce pure ground-state beams of $B^{3+}(1s^2)$. It is noted that these corrections were not made in Ref. [1], in which it was assumed that the ^4P, $^2P_-$, and $^2P_+$ states were all formed primarily from the $1s2s\,^3S$ metastable component of the mixed-state F^{7+} beam.

As noted above, the $1s2s\,^2S$ metastable state fraction in the mixed-state beam is expected to vary from 10% to 30% [7]. To determine the metastable fraction for a given C^{4+} beam energy, we compare the relative intensities of the ^2D states obtained for the $C^{4+}(1s^2)$ and $C^{4+}(1s^2+1s2s\,^3S)$ beams, using a method similar to that described in Refs. [11,12]. Production of the ^2D state occurs primarily from the $1s^2$ ground state by RTE in the present 0.5–1.0 MeV/u energy range, with a maximum probability occurring at about 0.75 MeV/u [9], while ^2D production from $1s2s\,^3S$ metastable ions by the two-electron process of L-shell excitation accompanied by capture is small in this range [8]. Thus, the ^2D intensity observed for the mixed-state $C^{4+}(1s^2+1s2s\,^3S)$ beam in Fig. 2 can be attributed almost entirely to the $1s^2$

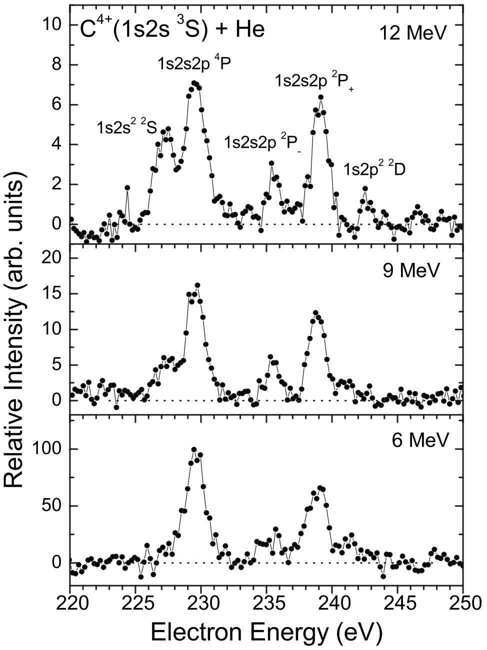

FIG. 5. Measured Auger emission spectra for single transfer to metastable $C^{4+}(1s2s\ ^3S)$ in He after correction for the contribution due to ground-state $C^{4+}(1s^2)$ using the data of Fig. 2.

ground-state component. Notably, for the spectra of Fig. 2 only the ground-state ^2D intensity is greater than its corresponding intensity for the mixed-state when normalized to the same beam current, providing further verification that the ^2D is produced only from the ground state. In the case of the Ne target, the latter is not quite true because independent two-electron excitation and single transfer events occur with higher probability for this higher Z target.

Thus, to correct the mixed-state spectra for the ground-state contribution, and consequently to determine the metastable $1s2s\ ^3S$ beam fraction, the ground-state ^2D intensity can be normalized to the corresponding mixed-state ^2D intensity. This procedure assumes that all of the ^2D intensity in the mixed-state beam is due to the ground-state component, and therefore the resulting normalization factor gives an upper limit to the ground-state fraction present in the mixed-state beam (and a corresponding lower limit to the metastable fraction). A secondary correction is obtained by comparing the underlying backgrounds of the two spectra after normalizing the ^2D intensities. These backgrounds should be nearly the same, and so the correction factor can be adjusted for any remaining discrepancy. These latter background adjustments amounted to changes of less than 5% in the values obtained for the metastable fraction. Using this technique, the $1s^2$ ground-state contributions to the mixed-state beams for 6, 9, and 12 MeV C were found to be 73%, 75%, and 75%, respectively, corresponding to $1s2s\ ^3S$ metastable fractions of 27%, 25%, and 25%. In Figs. 5 and 6, the spectra shown are those obtained after subtracting the ground-state contributions. The same ground-state percentages obtained for the He target were used to correct the Ne spectra, since the same incident beams were used for each target.

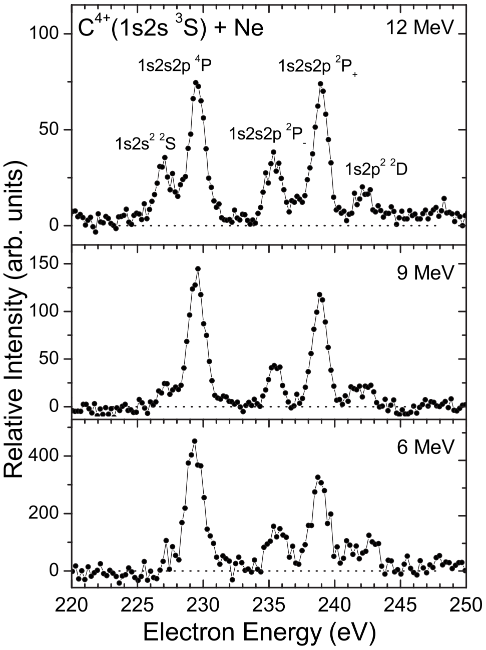

FIG. 6. Measured Auger emission spectra for single transfer to metastable $C^{4+}(1s2s\ ^3S)$ in Ne after correction for the contribution due to ground-state $C^{4+}(1s^2)$ using the data of Fig. 3.

B. Intensity correction due to the $1s2s2p\ ^4P$ lifetime

As noted earlier, the long lifetime of the ^4P state causes the observed intensity to be altered from the true production intensity due to in-flight decays from the target region to the electron spectrometer. Carbon ions in the ^4P state have lifetimes $(J=5/2,3/2,1/2)$ in the range $10^{-9}\ \mathrm{s}<t<10^{-7}\ \mathrm{s}$, whereas ^2P lifetimes are in the range $10^{-14}\ \mathrm{s}<t<10^{-13}\ \mathrm{s}$ [3]. Hence, lifetime effects are negligible for the ^2P states since the decays all take place in the target region, but must be taken into account for the ^4P state in order to obtain an accurate value for the ratio $^4P/(^2P_-+^2P_+)$. There are two competing effects: Ions in the ^4P state that decay in flight between the gas cell and the spectrometer have an increasing solid angle while approaching the spectrometer causing an increase in the observed intensity. On the other hand, ^4P ions that decay after passing through the spectrometer are lost to detection resulting in a reduction of the observed intensity. Correction factors for each beam energy were calculated by considering the ratio of the expected true intensity to the observed intensity, $N_{\mathrm{true}}/N_{\mathrm{obs}}$, where the number of events in each case decreases exponentially modified by a solid angle function, $\Omega(x)$ [13]. Integrating over the distance from the gas cell to the spectrometer gives the expected observed events N_{obs}; integrating over the entire beam path length to infinity gives the expected total number of true events N_{true}. The ratio was then used to determine the correction factors to be applied to the observed intensity for the ^4P state, giving values of 7.3, 8.8, and 10.2, respectively for C^{4+} at 6, 9, and 12 MeV. For further details of the computation of the correction factors, see the Appendix.

IV. DISCUSSION

By applying the above lifetime correction factors to the measured ^4P intensity in Figs. 4–6, the ratio $^4P/(^2P_-+^2P_+)$

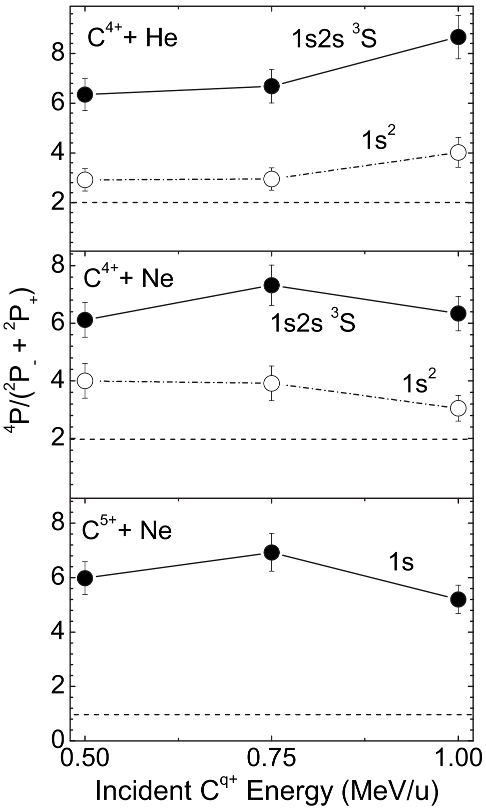

FIG. 7. Measured ratios of the $1s2s2p\ ^4P$ intensities to the sum of the $1s2s2p\ ^2P_-$ and $1s2s2p\ ^2P_+$ intensities as a function of the incident projectile energy for the indicated collision systems. The observed ^4P intensities were corrected for lifetime effects and, in the case of single transfer to $C^{4+}(1s2s\ ^3S)$, contributions from the $C^{4+}(1s^2)$ ground state (see the text). The horizontal dashed lines represent the values expected for $^4P/(^2P_-+^2P_+)$ from spin statistics: two for single capture to $C^{4+}(1s2s\ ^3S)$ and one for double capture to $C^{5+}(1s)$ (see the text).

can be calculated giving values in the range ~6–8 for both single capture to $C^{4+}(1s2s\ ^3S)$ and double capture to $C^{5+}(1s)$ as shown in Fig. 7. The single capture ratios are seen to be nearly the same for the He and Ne targets, and the single and double capture ratios for Ne are similar as well (double transfer was not observed for the He target). Notably, for single capture the ratio exceeds substantially the expected value of two based on spin statistics. It is seen that the ratio for single capture to the $C^{4+}(1s^2)$ ground state ranges from 3–4, exceeding the statistical value of two as well. In all cases, the ratios do not exhibit a significant dependence on the incident beam energy in the range investigated.

Based solely on spin statistics, the ratio $^4P/(^2P_-+^2P_+)$ should give a value of 2 independent of its production mechanism. For the case of single capture to the $1s2s\ ^3s$ initial state it was demonstrated that the direct transition probabilities do indeed give this value [2]. For double capture to $C^{5+}(1s)$ a similar reasoning as in Ref. [2] yields an expected value of one if the contributions from both $(1s2s\ ^1S)2p\ ^2P$ and $(1s2s\ ^3S)2p\ ^2P$ terms are included in the denominator. Hence, in both cases the experimentally determined ratios exceed substantially the value expected from spin statistics. The fact that the ratio gives comparable values for single and double capture suggests that similar mechanisms are responsible for producing the ^4P state.

To explain the apparent nonstatistical enhancement of the ^4P state intensity, in addition to the Pauli exchange mechanism proposed in our earlier work [1], it has been suggested that cascading following electron transfer to $(1s2\ s\ ^3S)nl\ ^4L$ states with $n \geqslant 3$ can lead to ^4P enhancement [5]. In such a scenario, capture to an $nl\ ^4L$ state is followed by successive prompt radiative transitions with $\Delta l = 1$ until the captured electron reaches the $1s2s2p\ ^4P$ from which it cannot decay radiatively, and which has a long Auger lifetime as well. Calculations have been carried out to estimate the magnitude of this cascading contribution. While a discussion of the details of these calculations is beyond the scope of the present work and will be presented elsewhere, the results are summarized here.

Briefly, capture calculations for C^{4+}+He on the single-particle level have been performed by using the two-center extension of the nonperturbative basis generator method [14,15]. This method has proven to give reliable results in the impact energy regime of interest, in which the projectile velocity is larger than the average orbital velocity of the electrons in the He ground state. In this region capture is often described in terms of a velocity matching mechanism, also known as kinematic capture, which occurs due to an overlap between electronic target and projectile states in momentum space. Similar to previous studies and in line with perturbative analyses our single-particle capture cross sections decrease with increasing principal quantum number n of the final states as n^{-3} [16–18].

Final-state populations for correctly coupled three-particle states of C^{3+} have been obtained from the single-particle solutions with the assumption that the initial projectile electrons are frozen in the $1s2s$ configuration. The $E1$ transition rates have been calculated for all relevant states with $n=3$, 4, and 5 [19,20], and the dynamical rate equations solved for the corresponding subsets of three-particle states using the above-mentioned three-particle populations as initial conditions. To facilitate the analysis the decay rates of the $1s2s2p\ ^2P_-$, $1s2s2p\ ^2P_+$, and $1s2s2p\ ^4P$ states have been set equal to zero, and the rate equations have been propagated in time until their populations do not change further. Total cross sections have been calculated from these probabilities by integration over the impact parameter, and their ratio compared with the experimental data assuming isotropy of the Auger electron emission [18].

The results of these calculations are compared with the experimental ratio for single transfer in $C^{4+}(1s2s\ ^3S)$+He collisions in Fig. 8. Clearly, cascading effects are not negligible and become more significant if capture is allowed into shells with increasing n. The calculated cross sections for the production of the $1s2s2p\ ^2P_-$, $1s2s2p\ ^2P_+$, and $1s2s2p\ ^4P$ states are also roughly consistent with the n^{-3} scaling rule for capture such that an extrapolation to $n \rightarrow \infty$ appears reasonable. The resulting ratio is also included in the figure. It is seen that only about half of the observed enhancement is obtained in this way. We note that the results shown are based on rates calculated in the length gauge. In the Coulomb gauge a somewhat smaller ratio was obtained, which

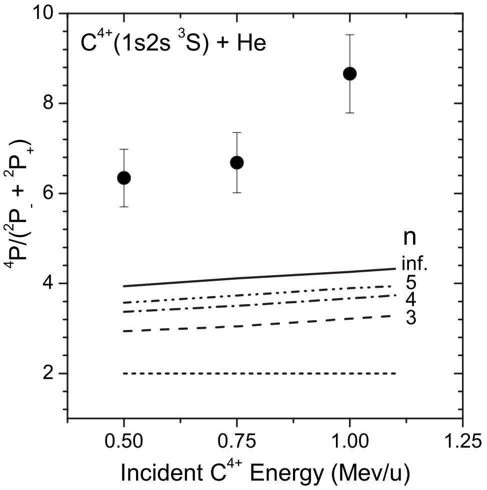

FIG. 8. Calculated and measured ratios of the $1s2s2p\ ^4P$ intensities to the sum of the $1s2s2p\ ^2P_-$ and $1s2s2p\ ^2P_+$ intensities as a function of the incident projectile energy for single transfer in $C^{4+}(1s2s\ ^3S)$+He collisions. Dashed line: calculation including cascades from all relevant states up to $n=3$; dash-dotted line: calculation including cascades from all relevant states up to $n=4$; dash-dot-dot line: calculation including cascades from all relevant states up to $n=5$; and full line: extrapolation to $n\rightarrow\infty$ (see the text). The observed ^4P intensities were corrected for contributions from the $C^{4+}(1s^2)$ ground state and for lifetime effects (see the text). The horizontal short dashed line at $^4P/(^2P_-+^2P_+)=2$ represents the value expected from spin statistics.

supports the conclusion that cascading effects are not sufficient to explain the experimental ratio.

Although there currently exist no calculations to evaluate whether a dynamical Pauli exchange of like aligned electrons [1] can explain the remainder of the observed enhancement of ^4P, we would argue that the present results are consistent with such an interpretation. In this mechanism, for single capture to $1s2s\ ^3S$ it was proposed [1] that an incoming target electron with the same spin alignment as the projectile $1s$ electron gives rise to an exchange interaction such that one of them is transferred to $2p$ to form the $1s(2s2p\ ^3P)\ ^4P$ state, since both electrons cannot occupy $1s$ due to the Pauli exclusion principle (see Fig. 2 of Ref. [1]). Hence, by means of this exchange, the ^4P state is enhanced beyond the intensity expected for direct transfer of an aligned target electron to the $2p$ orbital. In the case of two-electron transfer to $C^{5+}(1s)$, a double exchange mechanism was suggested in which target electrons of like spin interact with the single similarly aligned projectile $1s$ electron, resulting in promotion of one electron to $2s$ and the other to $2p$ to form the ^4P state (see Fig. 3 of Ref. [1]). A quantitative calculation to determine the effect of Pauli exchange is clearly needed to verify this proposed mechanism, however.

V. CONCLUSION

Nonstatistical enhancements have been observed for formation of the metastable $1s2s2p\ ^4P$ state compared to the similarly configured $1s2s2p\ ^2P_-$ and $1s2s2p\ ^2P_+$ states in single electron transfer to $C^{4+}(1s2\ ^3S)$ and double electron transfer to $C^{5+}(1s)$, respectively. After correcting for the ground-state contributions to the mixed-state $C^{4+}(1s^2+1s2s\ ^3S)$ beam, and then taking into account corrections for in-flight decays of the ^4P state due to its long lifetime, the $^4P/(^2P_-+^2P_+)$ ratio gave values of ~6–8. For single transfer to $C^{4+}(1s2s\ ^3S)$, these values are three to four times larger than expected based solely on spin statistics. In the case of double transfer to $C^{5+}(1s)$, similar ratios were found.

To explain the observed enhancement of the ^4P state, two mechanisms were considered. According to our present calculations cascading effects following electron transfer to states with $n\geqslant 3$, especially associated with single transfer to $C^{4+}(1s2s\ ^3S)$, account for about half of the increased population of the ^4P state. Consequently, Pauli exchange during electron transfer of similarly aligned target and projectile electrons, as originally proposed in Ref. [1], is still deemed to be a viable mechanism for selectively populating the ^4P state. Nevertheless, quantitative calculations are needed to better assess its significance.

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APPENDIX: COMPUTATION OF CORRECTION FACTORS TO THE (1*s*2*s*2*p*) ^4P INTENSITY

Due to the long lifetime of the $1s2s2p\ ^4P$ state, its measured intensity must be corrected for in-flight decays along the path from interaction region to spectrometer entrance. The correction factors were calculated by determining the ratio of the events seen by the spectrometer to the total events that occurred, taking into account the solid angle for detection as viewed from the reference frame of the projectile [13]. The expected true number of events is given by $N_{\text{true}}=-N_0/\nu\tau\int_0^\infty e^{-x/\nu\tau}\Omega_0 dx$, where N_0 is the initial number of ions, Ω_0 is the solid angle given by $\Omega_0=(A/\sqrt{2})/D(D+L)$, A is the area of the slit, $D=S+d$, $L=L_1+L_2$ (see Fig. 1), ν =ion velocity, and τ=ion lifetime. For those ions which are detected, the effective solid angle depends on the distance x traveled between the gas cell and spectrometer entrance before the decay occurs. The ions which decay after the spectrometer entrance are lost to detection, leading to the actual number of events observed $N_{\text{obs}}=-N_0/\nu\tau\int_0^d e^{-x/\nu\tau}\Omega(x)dx$, where $\Omega(x)$ is the effective solid angle given by $\Omega(x)=(A/\sqrt{2})/(D-x)(D+L-x)$, and D and L are as defined above. The correction factors were obtained by performing the integrations for the specific spectrometer geometry, and then taking the ratio $N_{\text{true}}/N_{\text{obs}}$ for each energy and each ^4P substate ($J=5/2,3/2,1/2$) lifetime [3]. The values obtained for the individual substates were then weighted statistically giving values of 7.3, 8.8, and 10.2, respectively, for C^{4+} at 6, 9, and 12 MeV.

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