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Experimental Evidence for Interference Effect in *K*-Shell–Vacancy Sharing

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The impact-parameter dependence of K-shell–vacancy sharing has been investigated with collisions of H-like S (S^{15+}) on Ar. An oscillation of the vacany-sharing ratio with impact parameter has been found which is due to the interference of components of the vacancy-sharing amplitude on incoming and outgoing parts of the collision.

In this note we present experimental evidence of an oscillatory structure in the impact-parameter dependence of the ratio of K-x-ray intensities measured with H-like S(15+) on Ar. This structure is interpreted as interference of contributions to the $2p\sigma$-$1s\sigma$ radial coupling amplitude from the incoming and outgoing parts of the collision. This is the first time that such an interference effect in the transition amplitude between atomic inner shells has been observed in energetic heavy-ion–atom collisions.

It is well established[1] that in nearly symmetric heavy-ion–atom collisions the K shell of the heavier collision partner is predominantly excited by $2p\sigma$-$1s\sigma$ radial coupling. In the theoretical calculations[2-5] of this $2p\sigma$-$1s\sigma$ coupling, the so-called K-shell–vacancy sharing, two approaches have been used: *ab initio* calculations and semiempirical formulations based on a simplified model of Demkov.[6] Such a semiempirical formulation[1] can well describe the ratio of total cross sections for K-shell excitation in heavy and light collision partners. Also the observed dependence of the vacancy-sharing ratio on impact parameter[7] was described reasonably well by the semiempirical formulation[3] of Briggs.

For the case where a K vacancy is already present on the incoming part of the collision, the $2p\sigma$-$1s\sigma$ radial coupling may occur on the incoming part as well as on the outgoing part of the collision. These two couplings have a certain phase relation for a fixed trajectory which gives an interference term in the transition amplitude. The phase difference between the two couplings is changed by varying the impact parameter b and an oscillatory structure in the b dependence of the vacancy-sharing ratio should be observed. Such an interference effect has been predicted by Briggs[3] both in a semiempirical formulation and in an *ab initio* calculation for O on Ne for this so-called two-passage vacancy sharing.

The experimental evidence of such an interference structure observed in the present work is a strong evidence for the existence of a definite phase relation between the coupling on incoming and outgoing parts of swift heavy-ion collisions. The interference structure provides a powerful tool for studying quasimolecular wave functions and dynamical couplings for the theoretical models of the $2p\sigma$-$1s\sigma$ vacancy-sharing process.

For an experimental test of this two-passage vacancy-sharing process a 32-MeV H-like S-beam (S^{15+}) was prepared by poststripping and selecting charge state 15+ by the switching magnet at the model EN tandem Van de Graaff accelerator of the Max-Planck-Institut für Kernphysik in Heidelberg. After being collimated to a size of 1 mm^2 with an angular divergency 0.01°, the beam hit a well-localized (≲2-mm) windowless Ar gas target of about 0.05 $\mu g/cm^2$ thickness to keep charge exchange below 10%. The particles scattered in the angular region from 0.06° to 0.4° were detected simultaneously by a position-sensitive parallel-plate avalanche detector[8]

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in coincidence with the emitted x rays. These characteristic x rays of S and Ar were detected at 90° relative to the beam direction by a Si(Li) detector. The data were recorded by a standard fast-slow coincidence technique in event mode. The spectra were corrected for random background (the ratio of true to random was 10:1).

A true coincidence x-ray spectrum for $b = 4170$ fm is plotted in Fig. 1(a). The dominating line in the spectrum is the S $K\alpha$ line. The Ar $K\alpha$ line is not well resolved from the S $K\beta$ line and at the high-energy end of the spectrum lies the Ar $K\beta$ line. For determination of the total number of S and Ar characteristic x rays a "Gauss-fit" procedure was performed, using the knowledge[9,10] about line positions, linewidths, and $K\alpha/K\beta$ intensity ratios. Another true coincidence spectrum at $b = 3750$ fm is plotted in Fig. 1(b). Here the Ar K lines have disappeared almost completely whereas the S K lines remained approximately with the same strength.

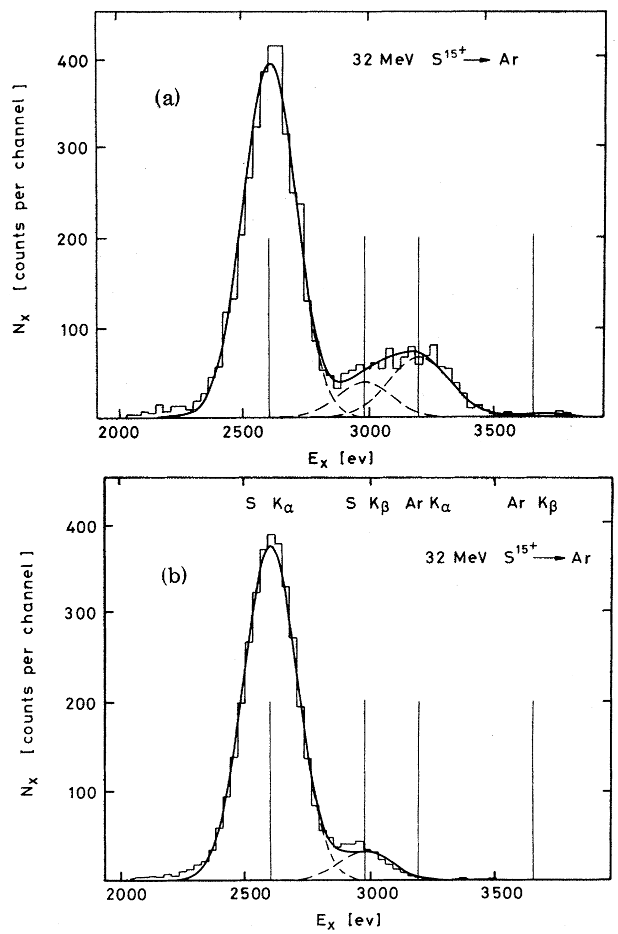

FIG. 1. True coincidence x-ray spectra for impact parameter (a) $b = 4170$ fm and (b) $b = 3750$ fm.

The vacancy-sharing ratio as a function of impact parameter is obtained by $P_{vs}(b) = P_K{}^{Ar}(b)/P_K{}^{S}(b)$, where $P_K{}^{Ar}$ and $P_K{}^{S}$ are the K-excitation probabilities of Ar and S, respectively. These probabilities are found from the measured Ar and S true coincidences corrected for Si(Li)-detector efficiency and fluorescence yield. The correction for detector efficiency is only about 10% for Ar and 20% for S. For determination of the vacancy-sharing ratio only the ratio of the S and Ar fluorescence yields is important and this ratio has been found[10] for the lower charge states of the S-Ar collision system to depend only weakly on incoming charge state. By assuming that capture into the outer shells of S^{15+} occurs with a very high probability it might be justified to use the ratio of S and Ar neutral-atom fluorescence yields here. This ratio should be the lower limit and has a very large uncertainty (up to a factor 10) in the direction of higher values.

The experimental result of $P_{vs}(b)$, which is plotted in Fig. 2, shows a clear oscillatory feature in comparison to a completely flat vacancy-sharing ratio measured with S^{5+} and S^{11+} on Ar (Ref. 11) (Fig. 2, dashed line), where no K vacancy initially is present. We assume from the result with S^{5+} and S^{11+} that the oscillation structure of S^{15+} is not produced by an impact-parameter-dependent fluorescence yield.

The prediction of the semiempirical formulation[3] for the two-passage vacancy sharing as a function of impact parameter is also presented in Fig. 2 (solid line). Qualitatively a similar

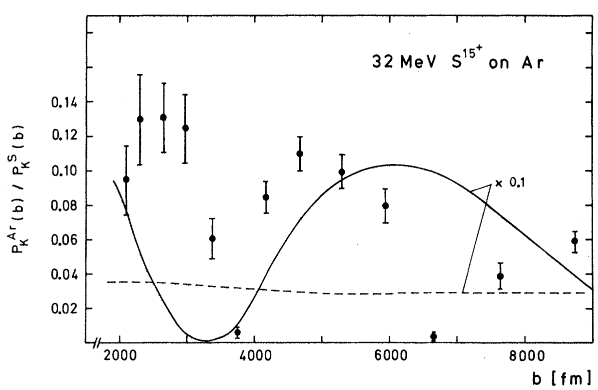

FIG. 2. Experimentally determined vacancy-sharing ratio $p_{vs}(b)$ (with a K-shell vacancy initially present) in dependence on impact parameter b. The dashed line represents the vacancy-sharing ratio of S^{5+} and S^{11+} on Ar and the full line the prediction of the semiempirical formula (see text).

structure is found, but the oscillations do not agree well in phase or in height. For the disagreement in height the above-mentioned uncertainty in the fluorescence yield is a likely cause.

In the semiempirical formulation the energy splitting between the $2p\sigma$-$1s\sigma$ orbitals is kept constant and is taken as the difference of the K-shell binding energies. These are obtained here in the same way as outlined in Ref. 10. The impact-parameter dependence is introduced by the dependence of the coupling element on the internuclear separation. No better agreement, however, can be obtained by varying the Ar and S binding energies within reasonable limits. For the case of O on Ne a similar discrepancy in $P_{vs}(b)$ is found by Briggs[3] between the semiempirical formula and his result of an *ab initio* calculation. In particular a smaller wavelength of the oscillations was found with the *ab initio* calculation. The discrepancy between the present experiment and the semiempirical formula demonstrates the need for *ab initio* calculations on the basis of quasimolecular wave functions for the S-Ar system.

The pronounced interference pattern observed in this experiment shows that all competing processes which occur during such violent heavy-ion collisions, such as outer-shell ionization and capture, and radial and rotational coupling to higher-lying orbitals (especially $2p\pi - 2p\sigma$), do not destroy the well-defined phase relation in the amplitude between the $2p\sigma$-$1s\sigma$ radial coupling contributions on incoming and outgoing parts of the collision. Also it should be noticed, that the impact velocity (1 MeV/N) is comparable with the $1s$-electron velocity, in which case the electrons are not adiabatic; so it may be surprising that the phase relation between the two couplings is conserved.

In spite of the quantitative disagreement of our data with the semiempirical formula we conclude that the experimental result of a strong oscillatory structure shows an interference of the $2p\sigma$-$1s\sigma$ radial coupling amplitudes. This strong interference effect should provide a test for *ab-initio* calculations using quasimolecular wave functions and dynamical couplings.

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Additional Sidebands in Cooperative Resonance Fluorescence

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Fluorescent spectra for two, three, four, and five atoms in a volume of dimension less than the resonant wavelength have been obtained numerically. For high laser intensities, resonances displaced from line center by twice the Rabi frequency are found in addition to the usual Stark sidebands.

Single-atom resonance fluorescence has been extensively studied in recent years.[1,2] Considerable interest is now directed towards the fluorescence from cooperative atomic systems.[3-8] In the present communication we consider two or more identical two-level atoms set in a volume of dimension less than the resonant wavelength. Intense laser radiation coherently drives this

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