Initial Tests of Possible Second-Born–Term Source of Asymmetry in Forward Electron Ejection by Fast Bare Nuclei

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(Received 11 August 1980)

The shapes of continuum capture cusps arising from ejection of target electrons by 15–18 a.u. velocity Ar^{18+} nuclei traversing He, Ne, and Ar are investigated. Observed asymmetries are compared to the second-Born-term asymmetry conjecture by Shakeshaft and Spruch, and to the alternative, first-Born-term asymmetry counter-conjecture by Chan and Eichler. Present evidence favors the former conjecture.

PACS numbers: 34.70.+e

To date, no unambiguous experimental tests of the relative importance of second and higher Born amplitudes compared to first Born amplitudes exist for any charge-transfer process, even at asymptotically high (though nonrelativistic) ion velocities v. It has often been suggested that the Born series of an exchange amplitude which includes charge transfer diverges. Because the Born series may be an *asymptotic* series, the question of which terms are dominant at high velocities becomes important. For radiationless electron capture by protons in hydrogen, for example, the Born series is dominated at high velocities ($\gtrsim$ 20 a.u.) by the *second* Born term[1,2] (which scales as $\sim v^{-11}$) as opposed to the first Born term ($\sim v^{-12}$). In general it is not clear to what extent the second Born term improves the first Born calculation, or even that either provides a good approximation, especially since alternative scattering calculations, e.g., approximate Faddeev-Watson scattering theory approaches, yield somewhat different predictions[3] for the asymptotic velocity dependence.

A potentially important step forward was made recently by Shakeshaft and Spruch.[4] They hinted that the asymmetry found in the velocity spectrum of electrons captured to continuum (ECC) states by bare ions traversing gases[5] might be the first experimental indication of the importance of the second Born term, even though the impact velocities were appreciably below that required to assure dominance in total cross section. In the first Born approximation the shape of the cusplike peak observed in the ECC velocity distribution is centered at $v_e = v$ and is symmetric about v, owing to a $\sim v^{-2l}$ dependence for ejected-electron partial waves. However, for the second Born term all partial waves are thought to have comparable importance. The first Born term depends only on the magnitude of the vector $(\vec{v}_e - \vec{v})$, implying an isotropic velocity distribution in the rest frame of the projectile characteristic of s-wave continuum states. Theoretically the asymmetry arises entirely[4] from second Born terms, for which the differential cross section $d\sigma/dv_e$ is asymmetric under the transformation $(\vec{v}_e - \vec{v}) \rightarrow -(\vec{v}_e - \vec{v})$.

A counter-conjecture concerning the origin of the observed asymmetry is provided by Chan and Eichler,[6] who note that retention of terms linear in $\Delta v_e/v = (|\vec{v}_e - \vec{v}|)/v$ beyond those incorporated in the first-Born–Brinkham-Kramers (BK) approach originally used by Dettmann, Harrison, and Lucas[6] produces a similar asymmetry. However, predictions of Refs. 4 and 6 concerning the projectile Z and v dependence of both shape and yield are very different, as is the predicted shape of the corresponding cusps (note the extremely sheer drop of the high velocity edge for the second Born cusp depicted in Fig. 1, curve B). Earlier attempts within the BK approximation by Chiu *et al.*[6] to improve upon the approximations made by Dettmann, Harrison, and Lucas even gave an asymmetry opposite in sign to what is

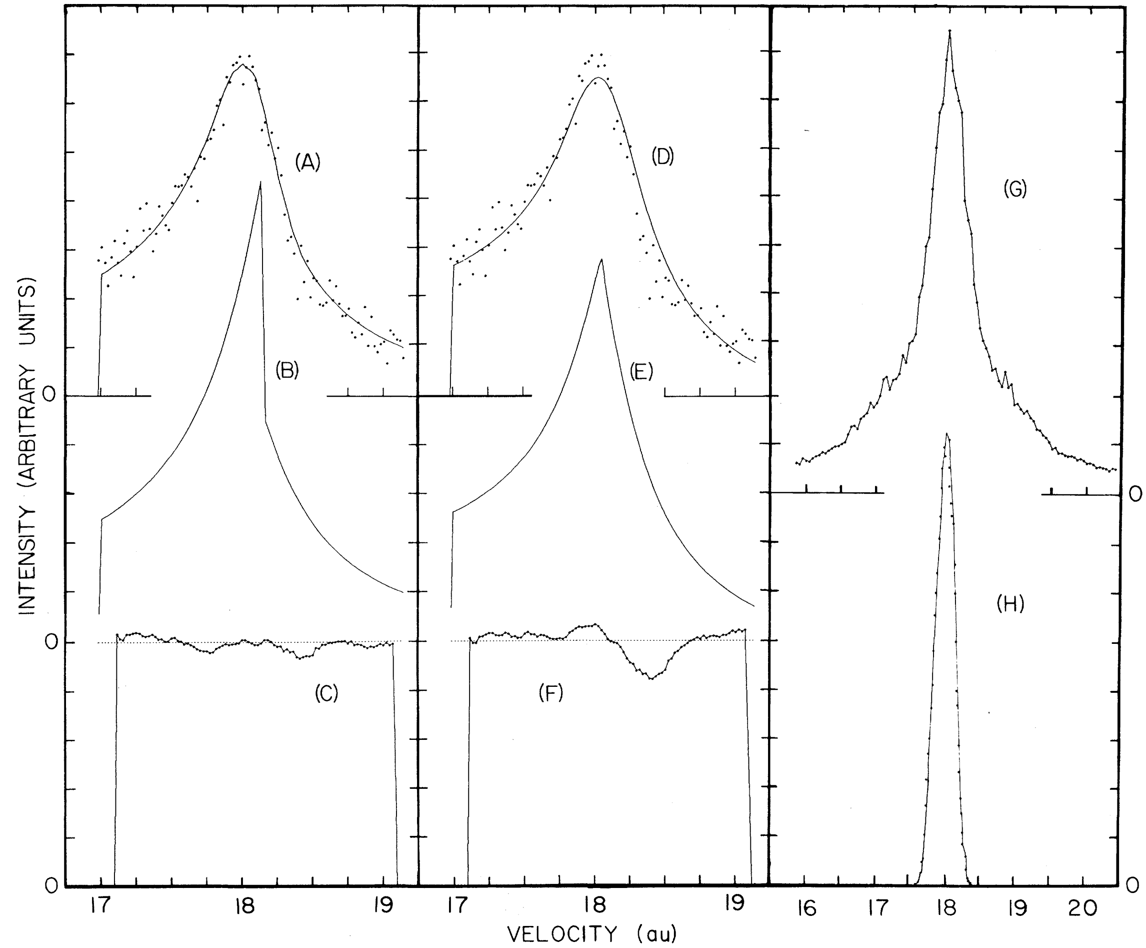

FIG. 1. Comparison of the central portion of ECC cusps obtained for 18.1 a.u. Ar^{18+} on He with the overlaid convoluted line shapes read from Ref. 4 (A) and Ref. 6 (D). The respective best fit theoretical shapes (B) and (E), when convoluted with the measured apparatus function (curve H), produce fits (A) and (D). A narrower more symmetric ECC spectrum for 8.5 MeV/u Ar^{13+} on He is shown in (G). Curves (C) and (F) display ten channel moving averages of the corresponding deviation spectra ($y_i - y_{\text{fit}}$ vs i) as discussed in the text.

observed.

The outcome of the first tests of the predicted second Born asymmetry conjecture—for Ar^{18+} on He—is the principal subject of this paper. We measured ECC spectra for higher velocities (15–18 a.u.) and for a heavier bare projectile (Ar^{18+}) than ever used, heretofore, in He, Ne, and Ar. The results provide better guidance to and stimulus for further quantitative calculations, especially for He. Strictly, the theoretical results apply to hydrogenic targets, and may need modification for He.[7] The obvious desirability of obtaining data for atomic H targets at slightly higher impact velocities presents unsolved experimental problems.

Briefly, 15 and 18 a.u. beams of bare Ar ions obtained from the Lawrence Berkeley Laboratory Super-HILAC accelerator pass through an ~2-cm-long gas cell containing He, Ne, or Ar at pressures well within single-collision conditions.[5] The cell is situated at the entrance focus of a double focusing, magnetic, 90°-sector analyzer set to record electron spectra for ejection within a cone of half-angle $\theta_0 = 1.7°$, centered on the forward direction. The momentum resolution is 1.7% full width at half maximum (FWHM). The techniques applied closely resemble those described in Ref. 5. Nuclear radiation backgrounds proved far less severe than originally feared (typically less than 20%). These backgrounds were removed by subtracting so-called "gas dump" spectra acquired when the same gas flux was fed directly into the vacuum system through a by-pass valve, leaving all other experimental conditions fixed.

Typical data for Ar^{18+} on He are displayed in Fig. 1, overlaid with the best fits with the data obtained with a convoluted Shakeshaft-Spruch (SS) line shape (curve A), and a convoluted Chan-Eichler (CE) line shape (curve D). Data were acquired over a wider velocity range, but since detailed line-shape predictions apply only very near $v = v_e$, only the corresponding region is displayed. Convolution of parametrized theoretical line shapes (curves B and E) with the 1.7% FWHM measured apparatus function shown in curve H (from electron-gun calibration data) yielded the best fits (curves A and D). That the asymmetries observed are valid is demonstrated in curve G, which depicts the narrower, much more symmetric line shape (with Auger structure superposed) obtained for forward electron loss[8] from 8.5 MeV/u Ar^{13+} on He. Here only the incident beam was switched, with all other conditions unaltered.

Because the theoretical curves B and E apply to $Z = 6$ at 9 a.u. in a hydrogenic target, our comparisons are only partially appropriate. However, these comparisons are sufficiently successful that a calculation for $v = 15-20$ a.u. in He would be very worthwhile. The characteristic feature of the SS shape is the sheer drop on the high-velocity side of the peak. When convoluted with the instrument function, a drop is expected whose slope and width are essentially determined by the analyzer resolution function—a feature displayed by every ECC cusp we have ever observed for C^{6+}, O^{8+}, Si^{14+}, and Ar^{18+} in He, Ne, and Ar at all velocities (5–18 a.u.)! This property is *not* shared by the CE shape. Second, the CE shape is predicted to become symmetric at high v as $\sim 1/v$. There is *no* evidence in our data for any decline in asymmetry. On the contrary, for He the asymmetry (as defined below) is found to increase slightly in the range 15–18 a.u. For C^{6+}, O^{8+}, and Si^{14+} on Ne, the asymmetry is an increasing function of v in the range 7–18 a.u., rising sharply as the beam velocity matches the neon K velocity.[8] Third, the ECC asymptotic velocity dependence of $d\sigma/dv_e$ predicted by Dettmann, Harrison, and Lucas,[6] when integrated over an appropriately scaled velocity region [e.g., $(1-\alpha)v$ to $(1+\alpha)v$ with $\alpha = 0.04$] is $\sim v^{-10}$. This dependence coincides with our experimental results for Ar^{18+} in He, which (over the range $v = 15-18$ a.u.) scale as $\sim v^{9.9}$, suggesting that the anticipated asymptotic dependence has been reached (not so for either Ne or Ar targets, which scale as $\sim v^{-7}$ over the same range).

Standard reduced χ^2 tests, in addition to a deviation test to be described, exhibit a marked preference for ths SS as opposed to the CE shapes. For the data of Fig. 1, the fitted SS line shape yields $\chi^2 = 1.2 \pm 0.2$, whereas the CE shape yields 1.8 ± 0.4. At the same velocity, the analogous values are $\chi^2 = 6.5$ and 10 for Ne, and 8.9 and 10.8 for Ar. These values demonstrate the inappropriateness of a single-cusp fit to data we expect to be characterized by overlapping cusps of somewhat different width for each target shell. Curves C and F are derived from the deviation spectrum ($y_i - y_{\text{fit}}$ vs i) corresponding to A and B. To extract trends from the large statistical scatter in the deviation spectrum, we have appropriated the moving-average technique routinely used by Wall Street chartists when confronted with similar scatter in financial market averages. Curves C and F represent ten-channel moving averages, smaller than but of the same order as the analyzer resolution (16 channels). The clear preference for the SS vs the CE fit is exhibited by the large dip in curve F, which shows that the CE shape simply lacks the dropoff characterizing both the SS line shape and—by this test—the data. A moving average over fewer channels *enhances* the valley in the deviation spectrum (at the expense of scatter). In dozens of spectra acquired for He, Ne, and Ar, pronounced valleys were invariably observed for CE fits, and were not observed for SS fits.

Spontaneous evidence that the dropoff is real arose in the fitting procedure. The CE shape was simulated by multiplying a symmetric Dettmann[6] cusp shape $A\{[(v_e - v)^2 + v^2\theta_0^2]^{1/2} - |v_e - v|\}$ by the asymmetric function $[1 - a(v_e - v)]$, with a starting value of the fitted parameter $a \approx 0.73$, read from Ref. 6. A very similar multiplicative factor $\{[1 - a(v_e - v)]$ for $v_e \leqslant v$ and $[b - a(v_e - v)]$ for $v_e \geqslant v\}$ simulated the SS shape, where the values $(a, b) = (0.73, 1)$ characterize the CE shape, and $(0.73, 0.63)$ characterize the SS shape read from Ref. 4. A key point is that the *starting* values of (a, b) in the SS case were chosen to be $(0.73, 1)$, deliberately biasing the iterative, gradient search, least-squares fitting routine in favor of the CE shape. The fitting routine spontaneously introduced a SS step! The best fit values for 18 a.u. Ar^{18+} on He gave $a = 0.12 \pm 0.02$, $b = 0.44 \pm 0.04$ for the SS fit ($\chi^2 = 1.2 \pm 0.2$), and $a = 0.69 \pm 0.10$ ($\chi^2 = 1.8 \pm 0.02$) for the CE fit.

A direct experimental measure of the asymmetry is the ratio $(\Gamma_l - \Gamma_r)/(\Gamma_r + \Gamma_l)$, where Γ_l and Γ_r are the half widths (half maximum) of the cusp to the left and right of the peak. At 15 a.u., the measured values in He, Ne, and Ar are 0.28 0.45, and 0.35, respectively. At 18 a.u., they are 0.35, 0.39, and 0.44, respectively. The range errors are ± 0.07 in each case.

Though the present shape and velocity-dependence data are much better in accord with Ref. 4 than with Ref. 6, other predictions of Ref. 4 are not observed. For example, the asymmetries observed in Ne and Ar are very similar for all bare projectiles for Z in the range 6–18, a finding not in accord with a predicted strongly Z-dependent asymmetry. Also, the yields scale at ~1:200:500 for 18 a.u. Ar^{18+} on He, Ne, and Ar, respectively, a dependence much weaker than a simple ${Z_{\mathrm{targ}}}^5$ dependence.[4] Here, the theoretical restriction to the case of asymptotic velocities in hydrogen may be limiting.

Confirmation of a dropoff at $v_e = v$ as steep as the analyzer resolution function permits is thus the strongest evidence in favor of the SS asymmetry conjecture provided by our data. An attractive experimental goal is to better quantify the size of the dropoff by improving the instrument resolution at the expense of intensity. We recommend a theoretical goal: a quantitative calculation of the predicted second-Born-term source of asymmetry for several bare nuclei traversing He in the present velocity range.

In a remarkable example of parallel developments in different subfields of physics, a large peak in the π^-/π^+ ratio for production of low-energy forward pions has recently been found[9] in heavy-ion pion production experiments carried out from 125 to 400 MeV/u. The peak is observed at a pion velocity very nearly equal to that of the projectile, and there can be little doubt that very similar underlying physical principles apply.

This work was partially supported by the National Science Foundation, by the Office of Naval Research, by the East Carolina Research Council, and by the Fundamental Interactions Branch, Division of Chemical Sciences, Office of Basic Energy Sciences, U. S. Department of Energy, under Contract No. W-7405-eng-26.

We thank Scott Berry for his excellent design[10] of the magnetic sector analyzer used for this work and the University of Tennessee machine shop for its fabrication.

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