Charge and velocity dependence of the ratio of double to single ionization of H^- by Ar^{q+} and Xe^{q+}

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Data and analysis for the ratio of double to single ionization of H^- in collisions with Ar^{q+} and Xe^{q+} are presented for $q=1-6$. Evidence is found for effects of electron screening in Ar^{+1} and Xe^{+1}. The data are analyzed in terms of both a Volkov-Keldysh approximation where the projectile field is strong compared to the target and a Born expansion in the electron projectile interaction where the projectile field is weak. At small q/v the H^- data are consistent with the Born expansion while at lower energies a Volkov-Keldysh calculation is in agreement with observation if in both analyses correction for electron screening is included. [S1050-2947(99)02006-5]

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I. INTRODUCTION

Two-electron transitions in fast atomic collisions provide a direct way to study dynamics of electron correlation when multielectron effects are relatively strong [1–9]. It is clear, for example, that electron correlation plays an important role in double ionization of neutral atoms by fast charged particles [10]. In very fast collisions with projectiles of low to moderate charge q more than one or two interactions with the charged projectile is unlikely. Then double ionization occurs predominately via either electron-electron interactions following a single interaction with the projectile or two interactions with the projectile possibly in the presence of correlation [2,6,10–12]. On the other hand, in collisions with projectiles of relatively large q at moderate velocities, the interaction with the field of the projectile is relatively strong and the target charge may be considered perturbatively with electron correlation possibly significant.

Most studies of double ionization have been done for neutral atomic targets [2,6–8,10,11]. These targets have most often been a rare gas, which is experimentally convenient to use. Most of these studies have been done on helium for which some theoretical analyses have been available. H^- is of interest because it differs significantly from helium. In helium the two electrons occupy similar regions of space and it does not make much sense to distinguish between the two electrons in their initial state. In H^- the electrons have different properties—i.e., the wave function for the two-electron complex may be more sensibly regarded as two electrons with different properties. A simple classical picture would correspond to an inner hydrogenlike electron and a loosely bound satellite electron. Since H^- differs from helium one may expect that electron correlation is different in H^- than in helium. This is expected to affect the cross sections for double ionization.

In this paper data for single and double ionization of H^- in collisions with Ar^{q+} and Xe^{q+} are presented for $q=1-6$. These data are analyzed in two ways. The first analysis is based on Volkov-Keldysh wave functions, which are applicable when the interaction of the electron(s) with the projectile is stronger than interaction with the target. The second analysis is based on second Born expansion where interaction with the projectile is assumed to be weaker than the interaction of the electron(s) with the target. While the Born analysis is expected to apply [10] when $(q/v)^2 \ll 1$ (i.e., the Massey criterion), the Volkov-Keldysh approach is applicable [1,13–16] when $v^2 \gg 1/q$. The Volkov-Keldysh picture corresponds to lowest order perturbation in the interaction of the electron(s) with the target charge q. Both of these pictures have been previously used [12,17] to analyze data for ratios of double to single ionization for helium.

The collision partners for H^- here are Ar^{q+} and Xe^{q+} ions which carry electrons. If the electron cloud is tightly formed around these ions, then one may expect that the effective charge of the ion is simply the net ion charge, i.e., q. However, in the case of small q, it may be that the size of the dressed ion is not small compared with the radius of the inner electron in H^-. In this case the double ionization rate may be enhanced by a larger effective charge for the Ar^{q+} and Xe^{q+} ions. For $q=1$ we find that such an electron screening effect appears to occur, which gives an enhancement of up to a factor of 4 to the cross section for double ionization of H^-.

II. EXPERIMENTAL METHODS

By means of the *crossed-beams* technique, we measured cross sections σ_{-+} for the total H^+ production in $H^- + X^{q+}$ collisions for $X^{q+} = Ar^{1+}, \ldots, Ar^{6+}, Xe^{1+}, \ldots, Xe^{5+}$, respectively. The principal experimental arrangement [18] and the signal recovery

TABLE I. Typical experimental parameters of σ_{-+} cross-section measurements for the reaction $H^- + X^{q^+} \rightarrow H^+ + \cdots$ for different ions, charge states, and CM-frame kinetic energies E_{CM}. E_{H^-} is the lab-frame energy of the H^- ions while the X^{q^+} ions delivered by a 5 GHz ECR ion source have the energy 10 keV q. I_{H^-}, I_{X^-} denote the respective ion beam currents. N, time averaged total H^+ count rate; S, time averaged true H^+ signal count rate; t, actual measurement time.

Ion	E_{CM} (keV)	E_{H^-} (keV)	I_{H^-} (nA)	$I_{X^{q+}}$ (nA)	N (s^{-1})	S (s^{-1})	t (s)
Ar^{1+}	100	110	93.1	150	6800	15.0	2251
Ar^{6+}	100	120	460	11.4	6000	7.5	5000
Xe^{1+}	50	55	86.5	39.7	2800	13.0	2089
Xe^{5+}	50	57	137	24.7	3500	8.0	5050

technique [19] have been described in detail previously. In short, two well collimated and charge-analyzed beams of adjustable energies are made to intersect at an angle $\theta = 45°$ in an ultrahigh vacuum of a few 10^{-11} mbar. Both ion beams are cleaned, shortly before intersection, from particles which originate from interactions of the ion beams with the residual gas. The H^+ ions formed in the hydrogen beam are separated immediately after the interaction from the parent H^- ion beam by electrostatic deflection and counted individually by a channeltron-based single-particle detector, while the parent ion beam is measured in a biased Faraday cup. The final charge state of the projectile ion $X^{(q-i)+}$ $(i=0,1,2)$ remains undetermined.

The signal of H^+ produced in ion-ion collisions is distinguished from the background of H^+ produced in ion-residual gas collisions by a beam modulation technique. Basically, the actual time spectrum of the H^+-detector counts is recorded while both the H^- ion beam and the X^{q+} ion beam are chopped by fast electrostatic deflectors. If both ion beams are switched on, ion-ion events masked by different background contributions are recorded. If only one or none of the ion beams are switched on, various background contributions are detected. Appropriate subtraction of count rates in different modulation periods isolates the true ion-ion signal. Since the background contributions are about three orders of magnitude more intense than the ion-ion signal, the main statistical errors in the determination of σ_{-+} arise from counting statistics. Experimental parameters which illustrate the performance of the apparatus are given in Table I for different CM energies and ion species. The geometrical form factor, which describes the overlap of the ion beams, is derived from a measurement in which both ion beams are scanned in a direction perpendicular to the interaction plane by a narrow slit. The accuracy of this measurement is within 2% and beam fluctuations are checked by measuring the form factor before, after, and for long measurements also in breaks within a measurement. The ratio σ_{-+}/σ_{-o} of double-to-single-detachment was calculated using single detachment cross sections σ_{-o} measured earlier [20,3]. In Tables II and III measured cross sections and calculated ratios are listed. The errors represent a 90% confidence limit of statistical uncertainty which is calculated from the independent statistical errors of σ_{-+} and σ_{-o}.

TABLE II. Measured cross sections σ_{-+} for double detachment in collisions $H^- + Ar^{q^+} \rightarrow H^+ + \cdots$ for charge states $q=1-6$. For completeness, cross sections σ_{-0} for single detachment $H^- + Ar^{q^+} \rightarrow H^0 + \cdots$ are also included in the table. The ratio σ_{-+}/σ_{-0} is calculated. Errors indicate the 90% confidence limit of statistical uncertainty.

q	E_{CM} (keV)	σ_{-0} (10^{-16} cm^2)	σ_{-+} (10^{-16} cm^2)	σ_{-+}/σ_{-0} (%)
1	50	44.6 ± 2.1	2.46 ± 0.16	5.51 ± 0.44
1	100	28.0 ± 1.2	1.15 ± 0.3	4.10 ± 1.08
1	200	18.4 ± 1.0	0.44 ± 0.23	2.39 ± 1.25
2	50	117 ± 4.8	3.72 ± 0.21	3.18 ± 0.22
2	100	71.4 ± 2.4	1.64 ± 0.33	2.29 ± 0.46
2	200	47.2 ± 1.9	0.85 ± 0.18	1.79 ± 0.38
3	50	207 ± 8.9	6.20 ± 0.6	2.99 ± 0.31
3	100	132 ± 8.6	3.59 ± 0.65	2.71 ± 0.52
3	200	81.7 ± 15	1.29 ± 0.33	1.57 ± 0.49
4	50	285 ± 13	12.8 ± 1.7	4.49 ± 0.63
4	100	223 ± 12	5.71 ± 1.3	2.56 ± 0.59
4	200	147 ± 25	2.75 ± 0.81	1.87 ± 0.63
5	50	387 ± 33	25.1 ± 4.7	6.48 ± 1.33
5	100	238 ± 35	10.4 ± 2.1	4.36 ± 1.09
5	200	156 ± 23	3.61 ± 1.2	2.31 ± 0.84
6	50	496 ± 30	31.8 ± 7.5	6.41 ± 1.56

III. RESULTS AND ANALYSIS

A. Volkov-Keldysh analysis

The Volkov-Keldysh analysis treats the target as a perturbation of the wave function of the electron in the field of the projectile. The continuum wave function for an electron in a strong electromagnetic field is the Volkov-Keldysh state [15,16]. The Volkov-Keldysh states for an electron in an electromagnetic field described by a vector potential $\vec{A}(t)$ may be expressed [16],

$$\psi_k(\vec{r},t) = (2\pi)^{-3/2} e^{i\vec{k}\cdot\vec{r} - i\vec{A}\cdot\vec{r} - (i/2)\int_0^t [\vec{k} - \vec{A}(\tau)]^2 d\tau}, \tag{1}$$

TABLE III. Measured cross sections σ_{-+} for double detachment in collisions $H^- + Xe^{q^+} \rightarrow H^+ + \cdots$ for charge states $q=1-5$. For completeness, cross sections σ_{-0} for single detachment $H^- + Xe^{q^+} \rightarrow H^0 + \cdots$ are also included in the table. The ratio σ_{-+}/σ_{-0} is calculated. Errors indicate the 90% confidence limit of statistical uncertainty.

q	E_{CM} (keV)	σ_{-0} (10^{-16} cm^2)	σ_{-+} (10^{-16} cm^2)	σ_{-+}/σ_{-0} (%)
1	50	44.6 ± 1.6	2.31 ± 0.45	4.95 ± 0.98
1	200	25.0 ± 1.2	0.54 ± 0.13	2.16 ± 0.53
2	50	123 ± 10	3.44 ± 0.86	2.88 ± 0.73
2	200	60.4 ± 5.3	0.85 ± 0.23	1.41 ± 0.41
3	50	193 ± 18	7.99 ± 1.8	4.13 ± 1.00
3	200	115 ± 11	1.50 ± 0.42	1.30 ± 0.38
4	50	287 ± 22	12.4 ± 3.4	4.32 ± 1.23
4	200	171 ± 14	2.62 ± 0.88	1.53 ± 0.52
5	50	374 ± 41	16.9 ± 3.8	4.51 ± 1.13
5	200	241 ± 25	7.04 ± 1.5	2.92 ± 0.60

where $\vec{A}(\tau)=-\int_0^t \nabla U(\vec{r},\tau)d\tau$. In dipole approximation we use $U(\vec{r},t)=q\vec{R}(t)\cdot\vec{r}/R^3(t)$, where $\vec{R}(t)$ is the internuclear distance and $\vec{k}$ is the momentum of the electron. This wavefunction has been used [3] for single ionization of H^-.

For single ionization of neutral targets, final state Coulomb interactions have been included by using a generalized Coulomb wave function [13],

$$\psi(\vec{r},t)=Q^{(-)}(i\nu,\vec{p}(t),\vec{r})e^{[-(i/2)\int_0^t p(\tau)^2 d\tau]}, \tag{2}$$

where $Q^{(-)}$ is a Coulomb wave with incoming boundary conditions and $\vec{p}=\vec{k}-\vec{A}(t)$, $\nu=q/p$, and q is the charge of the target atomic core. For H^-, $q=0$ and Eq. (2) coincides with Eq. (1). We note that a wave function similar to Eq. (2) has been used in multiphoton ionization by Kaminsky [21] and by Mittleman [22]. However, their wave functions contain additional phase terms which lead to nonorthogonality with discrete states of hydrogenic systems.

When there are two electrons in the final continuum a correlated two-electron wave function is used [17], namely,

$$\psi(\vec{r}_1,\vec{r}_2,t)=Q^{(-)}(i\nu_1,\vec{p}_1(t),\vec{r}_1)Q^{(-)}(i\nu_2,\vec{p}_2(t),\vec{r}_2)\times\Phi(\vec{r}_{12},\vec{d}_{12})e^{-(i/2)\int_0^t[p_1(\tau)^2+p_2(\tau)^2]d\tau}, \tag{3}$$

where $\Phi=e^{-\pi/2d}\Gamma(1+i/d)_1F_1(-i/d,1,i\vec{d}\cdot\vec{r}_{12}-idr_{12})$ carries the correlation and $\vec{d}=\vec{p}_1+\vec{p}_2+q(\vec{p}_1/p_1^2-\vec{p}_2/p_2^2)$. Cross sections calculated with the above functions are valid for medium and large velocities, $v\gg q^{-1/2}$.

In our calculation we consider double ionization as a product of single electron processes. Our probability is expressed,

$$W=\int\int d\vec{k}_2 d\vec{k}_1 \frac{1}{2}|A_1(\vec{k}_1)A_2(\vec{k}_2)\zeta(\vec{k}_1,\vec{k}_2)+A_1(\vec{k}_2)A_2(\vec{k}_1)\zeta(\vec{k}_2,\vec{k}_1)|^2. \tag{4}$$

Here A_1 and A_2 are probability amplitudes for independent single electron ionization processes, and the factor ζ determines the electron correlation effect associated with the correlated wave function above. In general, ζ may be separated as a cofactor only when the wave function of the initial state also factorizes. Our method is more fully described in an earlier paper [17] where the method was applied to double ionization of helium.

Comparison of our Volkov-Keldysh calculations with Ar^{q+} data is given in Fig. 1. Except for the $q=1$, our results are in decent agreement with the data. We have again considered the effect of screening for $q=1$. In this case we use the interaction of Brandt and Kitagave [23] to recalculate our probability amplitudes A_1 and A_2. As before, the effect of screening increases the cross section for double ionization by a factor of about 6 at $q=1$, leaving the single ionization cross section unchanged. The results of these calculations are shown in Fig. 1. If we ignore the $q=1$ data, then the remaining data for the ratio decrease to an asymptotic value at high v probably below 1%. This is consistent with the experimental results of Yu *et al.* [24], who observe a ratio about 0.3%, and also with calculations by Belinger *et al.* [25], who calculate a consistent value. This is similar to the asymptotic limit in helium of 0.26%.

B. Born analysis

A Born expansion may be made in powers of the interaction $V(t)$ between the projectile ion and the target electron(s) [10]. This picture is complementary to the picture used above where the target field is considered weak and the projectile field strong. The effect of such a weak projectile interaction is determined by the evolution operator, $U=Te^{i\int V_I(t)dt}$, where T is the time-ordering operator which gives a direction in time to the sequence of interactions $V_I(t)$. For Coulomb interactions, $V_I(t)=e^{iH_0t}q/|\vec{R}(t)-\vec{r}|e^{-iH_0t}$, where H_0 is the unperturbed many-electron target Hamiltonian and $\vec{R}(t)-\vec{r}$ is the distance between the moving projectile and the target electron. If one uses a straight line trajectory for $\vec{R}(t)$, then $dt=dZ/v$ (where Z is the direction of propagation) and one has

$$U=1+iq/v\tilde{V}+(iq/v)^2T\tilde{V}^2+\cdots. \tag{5}$$

In this expansion the $V_I(t)$ and scaled $\tilde{V}$ are many-electron operators [10,2] that depend on the collision velocity, v, through the e^{iH_0t} terms. For fast collisions we use the sudden approximation where the e^{iH_0t} terms are small. Then the $\tilde{V}$ operators are independent of q and v. This Born expansion in q/v has been used [7,12] to characterize data for single and double ionization in helium.

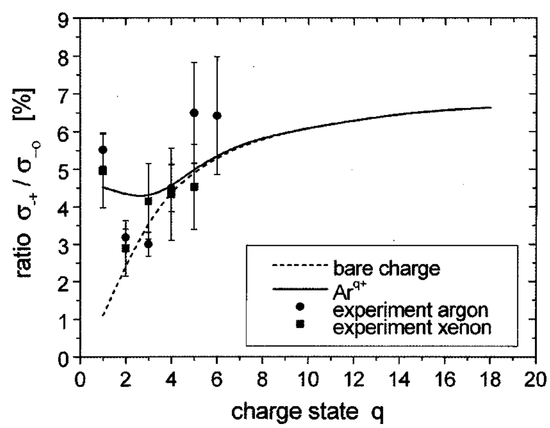

FIG. 1. Ratio of double to single ionization versus q at 50 keV/amu. Calculations are done in the lowest order Volkov-Keldysh approximation. The solid line is the Volkov-Keldysh result for a bare projectile charge of magnitude $+q$. The dashed line includes changes in electron screening of the projectile nucleus.

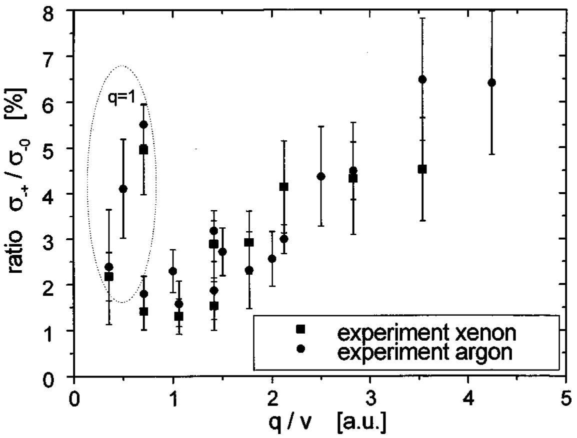

FIG. 2. Ratio of double to single ionization versus q/v, where q and v are the charge and velocity of the projectile. The $q=1$ data are anomalous, as is discussed in the text.

In this expansion in $\tilde{V}$ the first term goes to zero since nothing happens if $\tilde{V}=0$. Consequently, following perturbation theory, the quantum probability amplitude a for double ionization may be in general expressed as a power series in q/v beginning with the term linear in q/v, namely,

$$a=\langle f|U|i\rangle=(q/v)c_1+(q/v)^2c_2+\ \ldots,$$

$$\sigma=\int |a|^2 d\vec{b}. \tag{6}$$

Here the cross section σ is equal to the transition probability integrated over impact parameters $\vec{b}$ of the collision. The constants c_1 and c_2 are in general complex numbers which arise from calculation of the first and second Born matrix elements. Such an analysis does not quite apply to single ionization since a $(q/v)^2 \ln v$ term arises due to the long-range nature of the Coulomb interaction, which corresponds to quantum tunneling at large distances that are probed by the long range Coulomb potential. This term varies slowly in v.

The probability and cross section for double ionization vary as $(q/v)^2C_1'+(q/v)^3C_{12}'+(q/v)^4C_2'$. The q^3 term gives information about both time-ordering and the dynamics of electron correlation [12,26]. To a good approximation one may consider single ionization to vary as $(q/v)^2$. Then the ratio of double to single ionization varies with the collision strength parameter q/v as

$$R=\sigma^{++}/\sigma^{+}\simeq C_1+(q/v)C_{12}+(q/v)^2C_2. \tag{7}$$

Here C_1 is zero if there is no dynamic electron correlation. C_1 gives the dominant contribution in the small q/v limit. C_2 is from the second Born term where the projectile interacts twice with the target. C_2 includes the uncorrelated independent electron approximation in which the projectile interacts twice with the target. The C_{12} term arises from the cross term between first and second Born. This term carries both the charge asymmetry and effects of time ordering [26].

In Fig. 2 the ratio of double to single ionization is shown as a function of (q/v), where v is the collision velocity. This parameter is a measure of the strength of the interaction with the Ar^{q+} and Xe^{q+} ions. In Fig. 2 one sees that except for the $q=1$ data, which appear to be anomalous, the data are consistent with Eq. (7) for small q/v. If we ignore the $q=1$ data, then the remaining data appear to be consistent with Fig. 1. The ratio decreases, below 1% at high v, consistent with the experiment [24] and theory [25], and similar to the asymptotic limit in helium of 0.26%.

A simple estimate of the total shake probability is $P=\frac{3}{4}(s^2/Z^2)$, where s is the change in electron screening and Z is the nuclear charge of the target [10]. While this simple formula is too simple for accurate absolute values, it can give a guide to the relative differences between He and H^-. In both cases a plausible average value of s is 0.3. However, the Z values differ by about a factor of 2 so that the shake for H^- could be expected to be somewhat larger than for He. A higher value of this ratio in H^- would indicate that dynamic correlation is stronger in H^- than in helium. However, we note that the ratio for photoionization at high energy has been predicted [27] to be similar in both H^- and He. The error bars at intermediate q/v are too large to yield a useful value of C_{12} in Eq. (7). At the larger q/v the data in Fig. 2 seem to rise more slowly than $(q/v)^2$, indicating that the Born analysis may not be applicable in this regime, where the Born series is not likely to converge in the first two terms.

C. Electron screening

For single ionization of H^- it is likely that the outer electron is ionized. This electron sits at a distance of about four atomic units in a simple classical model. The electrons in Ar^{q+} and Xe^{q+} are confined to a region of about $1/q$. Thus, for impact parameters of about four atomic units, Ar^{q+} and Xe^{q+} may be regarded as point charges to a good approximation. For double ionization, however, the inner electron in H^- sits at about one atomic unit. Now Ar^{+1} and Xe^{+1} are no longer small compared to the inner electron in H^-. Thus it is possible that one may probe regions of Ar^{+1} and Xe^{+1} where the effective charge [29,28] is greater than 1. This effect of electron screening [23] can increase the cross section for double ionization.

We tested this effect of electron screening in a simple model. In our simple model, we took

$$\sigma=\int P_1(\vec{b})P_2(\vec{b})d\vec{b}, \tag{8}$$

where P_1 is the probability of ionizing the outer electron and P_2 is the probability of ionizing the inner electron in H^-. For single ionization we took $P_2=1$ and used a model for P_1 given by $P_1=Z_{\rm eff}^2(b)(1/16)e^{-b/4}/[(1/4)^2+v^2]$, corresponding to a function that is exponentially decreasing in b and falls off as $1/v^2$ at large v with a value of $P_1\sim 1$ when the collision velocity v matches the orbit velocity of the outer electron in H^-, taken to be 1/4. For double ionization we used $P_1=Z_{\rm eff}^2(b)e^{-b}/[(1)^2+v^2]$. This model gave sensible results for single ionization cross sections of H and H^- in the velocity range considered here for bare charges of $q=1$.

This model failed for double ionization of H^- by Ar^{q+} and Xe^{q+} for $q=1$ when we used an effective charge $Z_{\rm eff}(b)=q$. The ratio was about an order of magnitude smaller than observation. We then used a screening charge based on the first Born approximation [10,28], namely, $Z_{\rm eff}(b)=(Z_N-N\Phi)^2+N(1-\Phi)^2$, where N is the number of electrons and Z_N is the unscreened nuclear charge. Φ is the atomic form factor varying smoothly from 0 at $b=\infty$ to unity at $b=0$. The form of Φ was fit to the form found in first-order perturbation theory [29] for simple atoms. Then $Z_{\rm eff}$ varies smoothly from a fully screened value of $Z_{\rm eff}^2=q^2$ at $b=\infty$ to $Z_{\rm eff}^2=Z_N^2+N$ at $b=0$. This form of $Z_{\rm eff}$ begins to increase from q at $b_c\simeq 1/q$. Since our model probability, based on the first Born approximation, varies as $Z_{\rm eff}^2$, the effect of screening can be dramatic for Ar with $Z_N=18$ and Xe with $Z_N=54$. With this model, single ionization cross sections for H^- did not change when $Z_{\rm eff}$ was replaced by q. However, the double ionization cross sections for $q=1$ changed by a factor of 6 or more depending on the value of b_c chosen. Thus, using a screened charge based on first order perturbation theory, they gave at least qualitative agreement with the observed data. If the $q=1$ data points are corrected for this screening effect, then the data shown in Fig. 2 give a shape in q/v consistent with the shape of more extensive and more exact data for ratios of single to double ionization of helium [7].

IV. DISCUSSION

The ratio of double to single ionization has been presented in two complementary ways, namely in a perturbation formalism where q is assumed to be small and in a Volkov-Keldysh picture where q is assumed to be large. These approaches apparently both work in the case of helium [12,2]. It is noteworthy that these complementary approaches seem to have some overlap for helium. In both cases electron-electron interactions appear to play a significant role in double ionization. Also in the velocity range considered perturbation theory is plausible in both cases since the interactions are fast.

In the weak field limit it is clear [10,30] that the data for charged particle impact may be related to data for photon impact in helium. For H^- a prediction based on theoretical values of photoionization gives an estimate [1] of the high energy limit of double to single ionization in the range of 0.23–0.4 %, consistent with the trend of the data presented here. When data for single and double photoionization become available, it will be possible to test consistency of photon and charged particle data as has been done in helium [30].

It is also interesting to note that the Volkov-Keldysh states are used in interactions of atoms with strong laser fields. It is not clear that observations of collisions in strong laser fields can be simply related to observations for charged particles with strong fields, however. Recent data for the ratio of double to single ionization of helium by fast U^{+92} ions have been related to photoionization data using an independent electron approximation and the Williams-Weizsaecker relation, based on small q perturbation theory [31]. Volkov analysis of these results may give more insight into the nature of overlap of the validity of the weak and strong q limits. Aberg [32] has pointed out that capture is important for both photons and for charged particles. In the case of photons, the electron oscillates with the electric field independent of the nuclear target charge (the Volkov-Keldysh state), and the electron is thus effectively captured by the photon.

V. CONCLUSIONS

We have presented and analyzed data for single and double ionization of H^- in collisions with Ar^{q+} and Xe^{q+}. The ratio of double to single ionization has been presented in two complementary analyses. In the first analysis the ratio was plotted versus q and compared to Volkov-Keldysh calculations. Data for $q=1$ were anomalous, but could be explained in terms of variation of electron screening in Ar^{+1} and Xe^{+1}. The second analysis presented the ratio versus q/v motivated by usual perturbation theory where the charge q of the projectile is weak. In this case the high velocity limit of the ratio appears to be below 1% or so, which is consistent with other experiments and predictions and similar to the asymptotic ratio of 0.26% in helium. The data for $q=1$ were again anomalous. The $q=1$ anomaly was again explained by electron screening. In general, the Born analysis was satisfactory for small q/v while the Volkov-Keldysh analysis gave agreement for all q considered when electron screening correction was included. We recommend further experiments in H^-, including bare projectiles with $q=1$ and high collision velocities, to clarify the similarities and differences of this ratio with other targets. We also recommend that observation should be made with photons to test photon–charged-particle relations for weak fields.

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