Differential electron emission for isotachic H^+ and He^{2+} impact on helium

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Experimental data are presented for differential electron emission from helium induced by isotachic H^+ and He^{2+} impact. Electron emission at 15° was studied in order to investigate maxima in the $d^2\sigma/dv_e d\Omega$ spectra. These maxima were previously observed to shift to lower electron velocities as the projectile charge state increased and the shifts were interpreted as evidence of an independent saddle-point-ionization mechanism. The present data for H^+ and He^{2+} impact do not confirm any such shifts and indicate that previous He^{2+} measurements, where shifts were observed, are in error.

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BACKGROUND

In ionizing ion-atom collisions, two-center electron emission strongly effects the electron spectra for emitted electron velocities, v_e, between 0 and v_p, where v_p is the projectile velocity. Two-center electron emission means that the ionized electron is influenced by the combined electric fields of both the receding projectile ion and the ionized target. Examples of how both charge centers effect the differential electron spectra for fast, highly charged heavy ions have been presented by Stolterfoht *et al.* [1] and Schneider *et al.* [2,3]. At low impact velocities, where the two charge centers recede from each other more slowly, two-center emission plays a very important role. See, for example, Ref. [4].

Another example where both charge centers have been observed to influence the electron emission is in studies of electron capture to the continuum (ECC). See, for example, Ref. [5] and references therein. In this case, target electrons ejected in the forward direction with $v_e \approx v_p$ are strongly influenced by the projectile field while electrons emitted in the forward direction with lower velocities (between 0 and v_p) are influenced by both the target and the projectile potentials. All of these processes have been investigated previously and are qualitatively understood.

However, a theoretical study of intermediate energy H^+-H collisions by Olson [6] led to the suggestion of another ionization mechanism. This mechanism predicts that target electrons ejected with velocities near $v_p/2$ can find themselves stranded on the potential "saddle" between the receding projectile ion and the ionized target; hence significant numbers of electrons with velocities close to $v_p/2$ are expected. A later paper [7] detailed the predicted electron energy distributions and indicated that this phenomenon was not limited to electron emission in the forward direction; it also played a major role at larger angles.

The first experimental investigation into this phenomenon was in 1987 when Olson *et al.* [8] reported measurements for electrons emitted at laboratory angles of 17° and 25° in 60–200-keV proton-helium collisions. Through observations of the differential electron emission in velocity space, e.g., $d^2\sigma/dv_e d\Omega$, and comparisons with theoretical predictions made using the classical-trajectory Monte Carlo (CTMC) method, they contended that the *saddle-point-ionization* mechanism can dominate non-zero-degree electron emission to "unexpectantly high energies." The following year Irby *et al.* [9] provided additional evidence supporting the idea of a saddle-point-ionization mechanism by comparing the differential electron emission for isotachic (60–120 keV/u) H^+ and He^{2+} impact on helium. Maxima in $d^2\sigma/dv_e d\Omega$ were found to shift toward smaller electron velocities as the projectile charge increased and the shifts were in qualitative agreement with a simple saddle-point-ionization picture. Reasonable agreement between experimental cross sections and CTMC predictions was found but, perhaps significantly, the CTMC calculations predicted no shift.

For reasons discussed below, Gay, Gealy, and Rudd [10] performed additional measurements at another laboratory using a different, extremely well-documented apparatus [11]. Again shifts in the $d^2\sigma/dv_e d\Omega$ maxima for H^+ and He^{2+} impact were observed, particularly for 10° emission which was the smallest angle investigated. Additional support to the hypothesis of a saddle-point mechanism was obtained by studying collisions with helium, neon, and argon targets. The positions of the $d^2\sigma/dv_e d\Omega$ maxima were found to vary with the partially screened target nuclear charge—roughly in accordance with a saddle-point-ionization picture.

These series of experiments support the idea of an independent saddle-point-ionization mechanism. The strongest argument favoring such a mechanism was that two independent measurements clearly indicated a shift in the $d^2\sigma/dv_e d\Omega$ maxima as the projectile charge increased and that the observed shift was in qualitative agreement with predictions based on a saddle-point-ionization mechanism.

However, in 1989 Bernardi *et al.* [12] also reported measurements of the differential electron emission for H^+ and He^{2+} impact on helium. Their measurements were somewhat more extensive in that angular distributions between 0° and 90° were measured for impact energies of 50 and 100 keV/u. Neither these experimental data nor theoretical calculations based on the continuum-distorted-wave eikonal-initial-state (CDW EIS) model were in accordance with the hypothesis of an independent saddle-point-ionization mechanism. Bernardi *et al.*

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[13] then repeated the 17° measurements for 100-keV/u H^+ and He^{2+} impact on He. Unlike the results of Irby *et al.* [9], they did not observe, within their experimental uncertainties, any shift in the $d^2\sigma/dv_e d\Omega$ maxima. Similar results were found using a neon target.

Meckbach *et al.* [14] maintain that a truer picture of the ionization phenomenon can be obtained from $d\sigma/dv_e$ distributions, not from $d^2\sigma/dv_e d\Omega$ distributions. Their interpretation is that the $d\sigma/dv_e$ distributions provide no indication that a saddle-point mechanism is required for describing target ionization. Their experimental work demonstrated that the ECC cusp structure centered at v_p dominates the 0° $d\sigma/dv_e$ spectrum; but there is a smooth transformation to a broad maximum located approximately at $v_p/2$ for 10° emission (where Gay, Gealy, and Rudd performed some of their measurements). Hence, they contend that the maxima interpreted as evidence of a saddle-point mechanism simply are remnants of the ECC peak. However, this rather convincing evidence did not address the fact that shifts were observed in the "saddle-point" peak position in two independent measurements. As stated, no shift was observed by Bernardi *et al.* [13].

In order to resolve these discrepancies in the data and to help clarify whether an independent saddle-point-ionization mechanism is necessary for describing differential electron emission, a third, completely independent measurement of the differential electron emission for an isotachic proton and a He^{2+} impact on helium is reported here. As previous studies have shown that effects attributed to a saddle-point-ionization mechanism disappear for emission angles larger than 20°–25°, the experiment was performed at 15° which, due to mechanical restrictions, was the smallest achievable angle. Also, emphasis was placed on the He^{2+} measurements since the proton impact data reported by Irby *et al.* [9] and Gay, Gealy, and Rudd [10] generally are in agreement with those reported by Bernardi *et al.* [12,13], whereas the He^{2+} data are not. In order to more fully characterize this process, impact energies ranging from 50 to 250 keV/u were investigated.

EXPERIMENTAL PROCEDURE

As previous experimental studies have yielded conflicting results, a rather detailed discussion of the present experimental procedure will be given. The measurements were performed at the Pacific Northwest Laboratory using a 2-MV Van de Graaff accelerator to produce the ion beams. At the lowest impact energies, D^+, rather than H^+ ions, were used; however, for simplicity we shall refer to "proton" or H^+ beams henceforth. Beams of $^4He^{2+}$ ions were generated by accelerating $^4He^+$ ions to the desired energy, E, and then magnetically selecting and directing them toward the experimental apparatus. Directly after the analyzing magnet but prior to the scattering chamber, the He^+ ions passed through a gas cell, S, into which air was leaked in order to neutralize or strip portions of the original beam (see Fig. 1). Following this stripper cell, electrostatic deflectors separated the various beam components and directed the He^{2+} component into the scattering chamber. For ions with mass M and charge q, magnetic analysis identifies the quantity ME/q^2 while electrostatic analysis determines E/q. The present setup uses a combination of magnetic and electrostatic analysis which unequivocally eliminates any possibilities of contaminating the He^{2+} beam by hydrogen ions created either directly in the source or indirectly via subsequent molecular dissociation in the beam line.

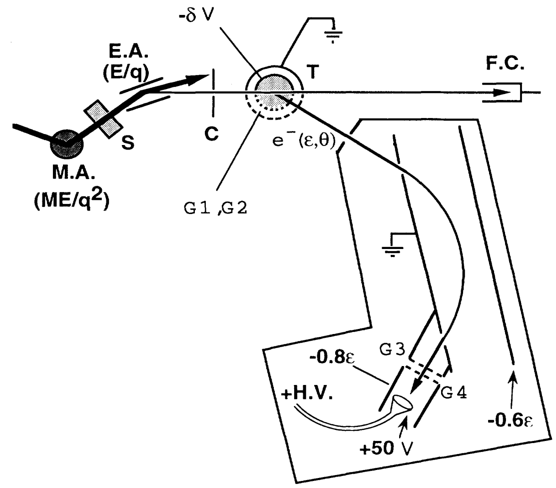

FIG. 1. Schematic diagram of the experimental apparatus used in the present study of doubly differential electron emission. M. A., magnetic beam analyzer for ME/q^2 selection; S, beam stripper cell for producing He^{2+} ions; E.A., electrostatic beam analyzer for E/q selection; C, beam collimator; T, differentially pumped target cell biased at δ volts; F.C., Faraday cup. $G1$ and $G2$; 78% transmission stainless-steel meshes covering the exit slits of the target cell; $G3$, 95% transmission mesh; $G4$, 85% transmission mesh. The parallel-plate electron spectrometer transmits electrons of energy ε with $V=-0.6\varepsilon$ applied to the rear plate. $G4$ is biased to repel electrons with energies less than 0.8 eV. The spectrometer resolution, solid angle, and observation angle was 12%, 1.6 msr, and $\Theta\pm1.5°$, respectively.

It is possible, however, that $^{16}O^{2+}$ ions could contaminate the $^4He^{2+}$ beam. This would happen if O^+ ions are formed in the source and accelerated to energy E and then are stripped to O^{2+} before reaching the analyzing magnet. After magnetic analysis, the fraction of these ions that do not undergo charge exchange in the stripper cell will enter the target chamber along with the desired $^4He^{2+}$ beam. However, a previous experimental study [15] used the same apparatus, techniques, and pressures for the production of $^4He^{2+}$ ions. This previous study also measured the projectile velocity and thus clearly identified any O^{2+} contamination. It was demonstrated that $^{16}O^{2+}$ contamination be monitored via the O^+ intensity, i.e., when the O^+ intensity was relatively large, significant contamination of the $^4He^{2+}$ beam was also present. Thus the O^+ intensity was used to test for O^{2+} contamination. We are confident that the data reported here are not influenced by such contamination.

Other possible contamination problems are He^0 and

He^+ particles produced via charge changing collisions with background gases after the electrostatic analysis region but before the target interaction region. To minimize this the beam collimation system was designed to ensure good pumping to within a few centimeters of the interaction regions. Using measured beamline pressures and known [15] charge-exchange cross sections, the amount of He^0 and He^+ contamination was determined to be less than a few percent of the He^{2+} intensity. Also, differential cross sections for electron emission induced by He^0 and He^+ impact were measured and these data were used to stimulate contaminated beam conditions. It was demonstrated that even extreme contamination levels, e.g., 50% He^+ and 20% He^0 ions, would not alter the conclusions to be derived from Fig. 2. To summarize, we are absolutely confident of the identity and purity of the proton and helium-ion beams and that the conclusions are in no way influenced by beam contamination problems.

An additional topic which could possibly influence the present experimental results is the precision with which the beam energies could be determined. Since the interest is in comparing spectra induced by isotachic H^+ and He^{2+} impact, uncertainties in the beam energy are important. Unlike the previous studies where the beam energies were provided via high-voltage power supplies and therefore were easily measurable or where the 0° cusp structure was used to precisely adjust the beam velocities, the present beam energies are based on the an accelerator energy calibration performed at approximately 2 MeV. Linearity of the analyzing magnetic field to the much lower energies used in the present study must then be assumed.

As a test for isotachic conditions, cross sections were compared for "equal velocity" H^+ and He^{2+} ion impact in the region above the binary encounter peak since, in this region, the cross sections for electron emission decrease extremely rapidly with increasing electron energy. By plotting the cross sections as a function of v_e/v_p, the two sets of data were found to agree somewhat better if the H^+ energy was increased by approximately 1.14 at 50 keV/u, 1.07 at 100 keV/u, and less than a couple percent at higher energies. Of course, this uses the assumption that the proton energy, being smaller, is known less accurately than the He^{2+} energy. However, since this procedure only provides an approximate indication of isotachic conditions, we chose not to adjust the data presented in Figs. 2–4 in this manner. Note, however, that should the data be adjusted in the manner just described, the maximum in the 100-keV/u H^+ data shown in Fig. 2 would shift *to lower velocities*, relative to the He^{2+} data, by roughly 3%. This is opposite to the shifts previously observed and would not alter any conclusions derived below.

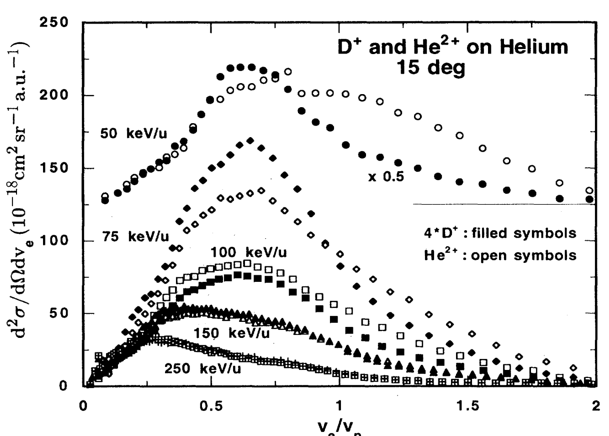

FIG. 2. Doubly differential cross sections, $d^2\sigma/dv_e d\Omega$, for 15° electron emission resulting from 50–250-keV/u D^+ and He^{2+} collisions with helium, shown by the filled and open symbols, respectively. The abscissa is the electron velocity, v_e, divided by the projectile velocity, v_p. For display purposes, the 75–250-keV/u D^+ data have been multiplied by 4, the 50-keV/u D^+ data have been multiplied by 2, and the 50-keV/u data have been shifted upwards by 1.25×10^{-16} cm^2/(sr a.u.).

The target, T, (see Fig. 1) was a differentially pumped gas cell inside which projectile ion–helium collisions occurred. Electrons exited the cell at 15.0°±1.5°, were energy analyzed by a shielded parallel-plate electron spectrometer and then counted using a channel electron multiplier. Magnetic shielding reduced residual magnetic fields in the chamber to less than 10 mG. The detection efficiency for low-energy (<5 eV) electrons was improved by surrounding the cell with a grounded cylinder, approximately 1 mm larger in radius, and biasing the inner cell with a negative voltage. Both the exit slit in the cell and a larger slit in the grounded cylinder were covered with high transmission grids, $G1$ and $G2$, in order to provide a uniform acceleration field between them. Tests demonstrated a considerable improvement in the detection of 1–2-eV electrons as the target cell bias voltage was increased from 0 to 1.5 V, but no major improvement for higher voltages; 2 V was used for the present study.

Background signals arising from scattering from slits, background gases, and surfaces within the spectrometer itself have been subtracted from all the data presented here. Typically these background signals were less than 5% of the foreground signal for electron energies greater than 10 eV. In the 1–10-eV region, the most serious background problem was from a combination of photons and partially deflected high-energy electrons that strike surfaces within the spectrometer itself and either scatter or produce secondary electrons. This background was dramatically reduced by blackening all surfaces within the spectrometer with carbon soot. In spite of these efforts, background signals increased below 10 eV and were sometimes as large as 40%–50% of the total electron intensity at 1 eV. However, data collected over a 3-month time span tended to agree within experimental uncertainties estimated to be ±20%.

Electron spectra were measured using known target densities and beam currents, were corrected for electron scattering losses between the interaction region and the detector, and also were corrected for background contributions. These data were placed on an absolute scale by measuring 15° electron emission for 0.3- and 1-MeV H^+-He collisions and normalizing to the absolute cross sections of Toburen [16]. His cross sections are presumably accurate to 1 eV because electron time-of-flight techniques were used. Since the absolute target density was known in the present work, this normalization procedure provided information about the efficiency and the solid angle for detecting electrons. Note, however, that the normalization plays no role when comparing relative differences between the magnitudes and shapes of the H^+ and the He^{2+} data.

RESULTS

In accordance with Irby *et al.* and Gay, Gealy, and Rudd who demonstrated maxima in $d^2\sigma/dv_e d\Omega$ curves which they claim shift towards lower velocities as the projectile charge increases, the present data are displayed in the same fashion. This is done in Fig. 2 for a series of impact energies ranging from 50 to 250 keV/u. Note that with the exception of 50 keV/u the proton (deuterium) data have been multiplied by 4 in order to account for the expected Z^2 scaling at higher impact energies. This multiplication also facilitates a closer inspection of differences between H^+ and He^{2+} impact. As originally demonstrated by Olson *et al.* [8], a maximum in $d^2\sigma/dv_e d\Omega$ is found and its position moves toward lower values of v_e/v_p as the impact energy increases. However, except for the 50-keV/u data, the maxima for isotachic H^+ and He^{2+} occur at *the same electron velocity*. A difference is observed for the very broad maxima at 50 keV/u but the shift is in the opposite direction to that predicted by a saddle-point-ionization mechanism and to that observed previously.

In Fig. 3 the present data for 100 keV/u and 15° electron emission are compared with the 17° data of Irby *et al.* [9] and Bernardi *et al.* [13] and with data of Gay,

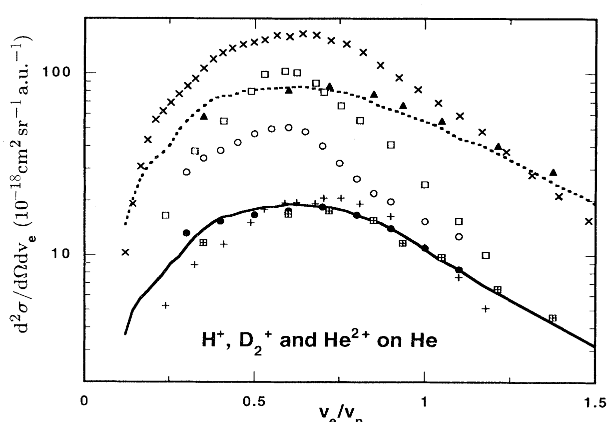

FIG. 3. Doubly differential cross sections, $d^2\sigma/dv_e d\Omega$, for electron emission resulting from H^+, D_2^+, and He^{2+} collisions with helium. 100-keV/u H^+ or D^+ impact: ——, present work, 15°; ●, Ref. [9], 17°, scaled by 0.44; ⊞, Ref. [13], 17°, scaled by 0.65; +, Ref. [10], interpolated to 15°, scaled by 0.69. 100-keV/u He^{2+} impact; — — —, present work, 15°, ○, Ref. [9], 17° scaled by 0.44; ▲, Ref. [13], 17°, □, Ref. [10], interpolated to 15°, scaled by 0.69. 56.25-keV/u D_2^+ impact data; ×, graphed as they would appear if the beam were mistakenly identified as a 100-keV/u He^{2+} beam. See text for details.

Gealy, and Rudd [10] which have been interpolated to 15°. In order to better compare absolute cross sections obtained using various normalization procedures, these data are presented on a semilogarithmic plot and the proton-impact data from Refs. [9,10,13] have been normalized to the present results at $v_e/v_p = 1$. Thus the published data of Irby *et al.* have been multiplied by 0.44, the interpolated data of Gay, Gealy, and Rudd by 0.69, and the proton data of Bernardi *et al.* by 0.65. The He^{2+} impact data of Bernardi *et al.* have not been scaled in order examine them more critically. The important point illustrated in Fig. 3 is that the present He^{2+} impact results agree with measurements reported by Bernardi *et al.* but are totally inconsistent with the He^{2+} data of Irby *et al.* and of Gay, Gealy, and Rudd.

As a possible explanation of this discrepancy, we investigated the following. One of the concerns expressed, but discounted, by Gay, Gealy, and Rudd was possible contamination of their He^{2+} beam by lower-energy H_2^+ ions originating from dissociation of H_3^+ ions after acceleration. This would produce a beam of 100-keV H_2^+ ions which would be deflected at a slightly lower magnetic field than would a 100-keV/u $^3He^{2+}$ beam whereas using only magnetic analysis, a 112.5-keV H_2^+ beam would be indistinguishable from a 100-keV/u $^3He^{2+}$ beam. Using this as an impetus, measurements for 225-keV D_2^+ impact were performed. The higher-energy D_2^+ beam was used to achieve better beam control and quality and introduces only minor differences in cross sections from those expected for 50-keV/u molecular hydrogen impact.

These data are included in Fig. 3 but have been plotted using the assumption that the D_2^+ beam was falsely identified as consisting of 100-keV/u He^{2+} ions. A misidentification of this type introduces two effects. First, due to charge state differences the beam normalization would be wrong; this increases the cross sections by a factor of 2. Second, the beam velocity, v_p, would be too large by a factor of 1.33 since it is thought to consist of 100-keV/u ions rather than 56.25-keV/u ions. This shifts the spectra toward *lower* velocities when plotted versus v_e/v_p.

Adjusting the D_2^+ measurements in this manner and including them in Fig. 3 demonstrates a similarity with the He^{2+} data of Irby *et al.* and of Gay, Gealy, and Rudd, but both the shape and magnitudes are different. Since these differences cannot be attributed to using 56.25- rather than 50-keV/u molecular hydrogen ions, attempts were made to fit their He^{2+} data by assuming that they unknowingly used a "mixed beam" of H_2^+ and He^{2+} ions. Various "mixed beam" configurations were simulated using the present D_2^+ and He^{2+} data but no reasonable fit to the data of Refs. [9,10] was achieved.

Another attempt to compare the various data sets obtained at different laboratories consisted of investigating He^{2+} to H^+ cross-section ratios. This method removes experimental uncertainties such as electron detection efficiencies and overall normalization factors since presumably these will influence the H^+ and He^{2+} data from a particular study in a similar fashion. Rather than simply determine ratios of cross sections, the square root of the ratio of the helium to proton-induced cross sections was used. This quantity is referred to as $Z_{\rm eff}(v_e,\Theta)$ as it is associated with the expected Z^2 scaling but also indicates that the scaling may vary with the momentum transferred in the collision. The momentum transfer is related to the ejected electron velocity and emission angle, which are measured experimentally.

Figure 4 displays $Z_{\rm eff}(v_e,\Theta)$ vs v_e as determined from data in Fig. 3. According to the Born approximation, $Z_{\rm eff}(v_e,\Theta)$ should be equal to 2 for a high-energy He^{2+} impact. At lower impact energies, the ionization probabilities become quite large for small v_e and Z^2 scaling is expected to break down. In this case, values smaller than 2 are expected. The data of Bernardi *et al.* clearly demonstrate these features.

The present data, although very similar in shape, are larger in magnitude. This could mean that the He^{2+} beam was contaminated with O^{2+} ions. If so, $Z_{\rm eff}$ would be larger than 2 for the close collisions, i.e., for large electron velocities, since in this region the oxygen nuclear charge is poorly screened by its bound electrons. But for distant collisions (small electron velocities) the oxygen will interact with a net charge of 2. Thus $Z_{\rm eff}$ will be approximately 2 for small v_e and be larger than 2 for large v_e. This scenario fits the present 100-keV/u data in Fig. 4 quite well but is probably not correct because for 150-, 250-, and 500-keV/u impact energies $Z_{\rm eff}$ is approximately 2, as expected (see Fig. 2). Thus, the possibility of O^{2+} contamination influencing the 100-keV/u He^{2+} is discounted since the contamination is related to the stripping cross section of O^+ and should therefore increase with increasing impact energy.

Other possibilities are that the present data yield values of $Z_{\rm eff}$ larger than expected because of a combination of relative uncertainties between the proton and helium beam normalizations and target gas densities or to uncertainties in producing isotachic conditions at impact energies less than 100 keV/u. This latter case is considered the most likely problem since it would influence $Z_{\rm eff}$ more as the impact energy decreased below 100 keV/u—exactly as was found.

Returning to the major point of Fig. 4, the present data and that of Bernardi *et al.* demonstrate similar characteristics and these characteristics are as expected for He^{2+} impact. On the other hand, the data of Irby *et al.* and of Gay, Gealy, and Rudd are quite different. Since Fig. 2 demonstrated reasonable agreement for all the proton measurements, this difference is attributed to their collisions not involving 100-keV/u He^{2+} ions. If is noted that in the region $v_e/v_p \approx 1$, their measurements yield a value for $Z_{\rm eff}$ in the 1.2–1.4 range which implies a beam of hydrogen ions possibly mixed with some He^{2+} ions. However, as stated above, present attempts to fit their data assuming a mixed beam of 56.25-KeV/u H_2^+ and 100-keV/u He^{2+} ions was unsuccessful. It is also difficult to imagine similar problems occurring on two different accelerators with entirely different types of ion sources. At this point one can only state that the present data and that of Bernardi *et al.* imply that He^{2+} measurements of Irby *et al.* and Gay, Gealy, and Rudd are incorrect and that they should not be used as supporting evidence of an independent saddle-point-ionization mechanism.

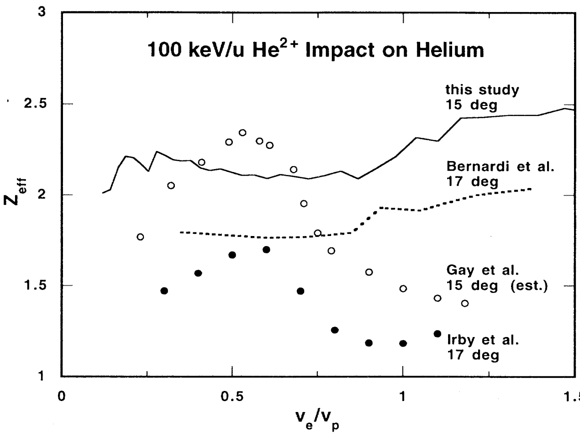

FIG. 4. $Z_{\rm eff}(v_e,\Theta)$ for 100-keV/u He^{2+} impact on helium. The data used for determining $Z_{\rm eff}(v_e,\Theta)$ have been taken from Fig. 3.

CONCLUSIONS

In conclusion, experimental data for 15° differential electron emission from helium resulting from isotachic H^+ and He^{2+} impact have been presented. The present data do not demonstrate any shift in the maxima in $d^2\sigma/dv_e d\Omega$ for different projectile charge states. Thus, the experimental studies of Irby *et al.* and of Gay, Gealy, and Rudd, where such shifts were observed and interpreted as evidence of an independent saddle-point-ionization mechanism are not confirmed. The present study implies that their He^{2+} measurements are in error.

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