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Z_1 oscillations of the mean charge for isotachic ions in carbon foils

A. M. Arrale, Jianyue Jin, Z. Y. Zhao, D. L. Weathers, F. D. McDaniel, and S. Matteson
Ion Beam Modification and Analysis Laboratory, Department of Physics and Center for Material Characterization,
University of North Texas, Denton, Texas 76203

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Oscillations in the mean-charge state of swift ions as a function of the atomic number Z_1 are reported for a wide range of ions of identical velocity (isotachic ions). A previously suggested mechanism for the enhancement of the mean charge for certain ion-charge combinations that involves closed shells is shown to be an inadequate explanation. Post-foil-Auger processes, however, are demonstrated to be a more plausible explanation for the observed behavior of the mean charge of the ions.

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An ion impinging on all but the thinnest of target foils experiences several inelastic charge-changing encounters with target atoms before it emerges from the foil. Inside the target, the charge state fluctuates as a result of the competition between electron loss and capture. An equilibrium charge-state distribution is established for thick enough targets for which the mean-charge state ($\bar{q}_f$) of the ion does not change with increasing thickness (until a thickness is reached for which appreciable energy loss occurs). Due to the lack of a comprehensive theory to treat the complex problem of the charge-state distribution, one is usually forced to rely on semiempirical expressions [1,2] for $\bar{q}_f$ that often obscure Z_1 oscillations that have been reported previously [3,4] for constant velocity (isotachic) ions emerging from thin carbon foils. The present work was performed to shed light on the origins of these oscillations.

For low-energy isotachic ions ($v=v_0$, v_0 being the Bohr velocity), Lennard and Phillips [3] have shown that the mean charge state ($\bar{q}_f$) exhibits a nonmonotonic dependence on the atomic number of the ion (Z_1) and has a broad peak at $Z_1 \approx 15$. Lennard and Phillips attributed the enhancement of $\bar{q}_f$ to the filling of inner-shell vacancies in the projectile ion in a post-foil-Auger decay that involves simultaneous ejection of an Auger electron. Their conclusion is partly supported by the absolute Auger yield measurement of Schneider *et al.* [5] that showed the *L*-vacancy fraction of $v=v_0$ phosphorus ions to be 0.63 ± 0.19, a markedly large fraction. Thus a phosphorus ion, for example, is expected to increase its mean charge state by one after exiting the foil, due to this Auger effect. Alternatively, Shima *et al.* [4] have reported oscillations of the mean-charge state ($\bar{q}_f$) as a function of Z_1 at ion energies 0.55, 1, and 2 MeV/u, which they argued are strongly correlated with shell structures of the ion. Furthermore, they contend that the maxima occur for ions whose mean number of residual electrons $n_e = Z_1 - \bar{q}_f$ is 2, 10, and 28, corresponding to full *K*, *L*, and *M* shells, respectively.

In this Brief Report, we present results obtained using a modified procedure for measuring the mean-charge states of ions exiting foils. The aim of the experiment is the resolution of the aforementioned dispute. The present work grew out of other work focused on the physical aspects of ion-induced electron emission (IIEE) processes and their applications [6]. The procedure developed to investigate IIEE phenomena also presented an efficient method of obtaining the mean-charge state of ions exiting thin foils. The present experiments were performed using the 3-MV tandem accelerator at the University of North Texas Ion Beam Modification and Analysis Laboratory. Vacuum conditions were maintained to provide a chamber pressure below 10^{-9} Torr. Positive ions of known velocity, charge, and mass were incident on a self-supporting carbon foil. By carefully integrating all the space currents—the current of the emitted electrons, the net current on the target, and the current into the Faraday cup after the foil—one obtained the mean-charge state of the exiting ions. This was computed from the ratio of the charge collected in the Faraday cup to the algebraic sum of all charge collected. More details of the experimental procedure are given in Ref. [6]. For each ion-energy combination used, five to ten measurements were made and the resulting mean-charge state averaged. The standard error of this measurement average was estimated to be ±0.13 charge state. For the ion energies employed in the present work, the carbon foil was sufficiently thick ($\geq 50\ \mu\text{g/cm}^2$) to ensure that the charge state reached its equilibrium value. No dependence of $\bar{q}_f$ on the projectile incident charge state was observed in the case of any of the following test ions: F^{+2} and F^{+3}; Cl^{+2} and Cl^{+3}; and Ag^{+7} and Ag^{+8} at $v=2v_0$. Similarly, the pressure in the chamber, over a range of one to two decades, was not found to influence the exiting mean-charge state of the ions that were used to check for the effect.

The measured equilibrium (mean-) charge state at constant velocity is plotted as a function of Z_1 in Fig. 1. For $v=2v_0$, the mean-charge state increases nonmonotonically with Z_1 with a small local maximum at $Z_1=5$. Then, with increasing Z_1, another maximum appears in the range $24 \leq Z_1 \leq 29$. It is worth mentioning that the reported peak [3] found at a lower velocity ($v = v_0$) around $Z_1 = 15$ seems to diminish at the present higher velocity. Nevertheless, its signature can still be identified in the range $6 \le Z_1 \le 17$. It has been a widely accepted notion that oscillations of $\bar{q}_f$ "damp out" at high velocity. On the contrary, while this may be true in certain instances, such as the disappearance of the peak found around $Z_1 = 15$ for low-velocity ions ($v = v_0$), an enhancement of $\bar{q}_f$ with increasing velocity was observed in the present work that needs further examination. The ion velocity was increased to $3v_0$ and then $4v_0$ to check the effect of the velocity on the enhancement of $\bar{q}_f$ observed in the region $24 \le Z_1 \le 29$. Figure 1 also shows the $\bar{q}_f$ data obtained at the higher velocities ($v = 3v_0, 4v_0$). Surprisingly, the peak around $Z_1 = 26$ persists at $v = 3v_0$ and becomes even more pronounced. At $v = 4v_0$ the peak broadens and becomes flattened at the top. In the present velocity regime, the results agree in magnitude with the limited available data obtained by others using a different method (see, for example, Wittkower and Betz [7], Betz [8], Bickel *et al.* [9], and Knystautas and Jomphe [10]). This observation both partially corroborates the present work and, at the same time, emphasizes the need for the kind of systematic study the present work reports.

Using the notation of Shima *et al.* [4], the ratio $\bar{q}_f / Z_1$ is plotted in Fig. 2 versus Z_1 for various ion velocities. Also shown in Fig. 2 are data from Lennard and Phillips [3] and Shima *et al.* [4]. According to Shima *et al.*, the maxima of $\bar{q}_f$ should correspond to ions having He-, Ne-, or Ni-like configurations, i.e., ions having full *K*, *L*, or *M* shells with no electrons in higher levels. Therefore, if the relations $Z_1 - \bar{q}_f = 2$, 10, and 28 are also plotted in Fig. 2, a maximum of $\bar{q}_f$ for each ion velocity should fall on the curve $\bar{q}_f / Z_1 = 1 - 10/Z_1$ and another maximum of $\bar{q}_f$ should fall on the curve $\bar{q}_f / Z_1 = 1 - 28/Z_1$. Shima *et al.* actually observed the second maximum only for ions with velocities $4.7v_0$ and $6.3v_0$ in their studies [4]. The curve $\bar{q}_f / Z_1 = 1 - 10/Z_1$ in Fig. 2 does indeed seem to pass near the maximum of $\bar{q}_f$ for two sets of data (v_0 and $4.7v_0$). However, for ions with the intermediate velocities ($2v_0, 3v_0$, and $4v_0$) of the present experiment, the contour does not pass through *any* maxima. In fact, in two instances, for ion velocities $3v_0$ and $4v_0$, the contour seems to pass through the *minima*. On the other hand, if one carefully investigates the evolution of the enhancement around $Z_1 = 26$ as the velocity increases from $v = 2v_0$, one can clearly observe its gradual approach to the peak reported at $v = 4.7v_0$ [4]. Therefore, it is our contention that the peak at $v = 4.7v_0$ cannot be accurately attributed to shell structure. This peak has been present all along and can be identified with the same peak that is observed at low velocity ($v = 2v_0$). The enhancement of $\bar{q}_f$ at $Z_1 = 26$ has even been reported for very high-velocity ions ($v = 6.3v_0$) [11], although no coherent systematic study was made.

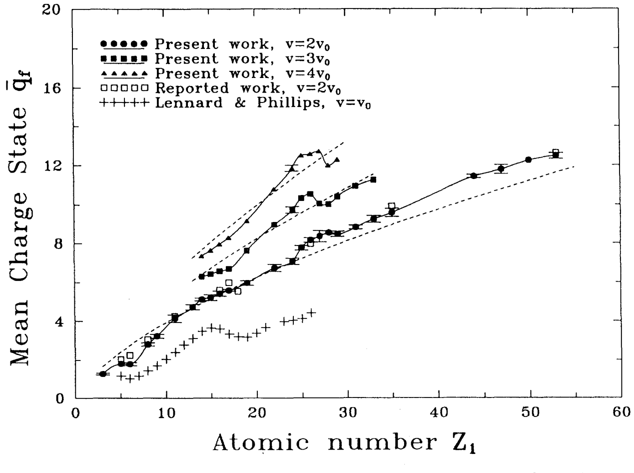

FIG. 1. The mean-ion charge state ($\bar{q}_f$) as a function of atomic number of ion (Z_1). The solid lines are drawn to guide the eye. The dashed lines were obtained from the empirical expression given in Shima, Ishihara, and Mikumo [2]. The open squares are extrapolated data from Wittkower and Betz [7] and Betz [8], except the boron and argon data, which were obtained from Bickel *et al.* [9] and Knystautas and Jomphe [10], respectively.

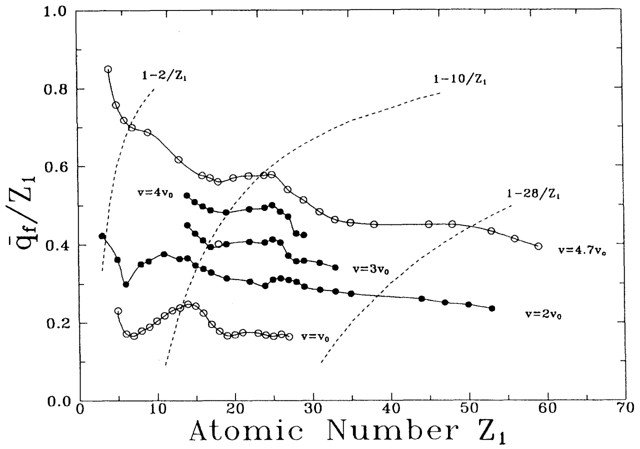

FIG. 2. The ratio of mean charge state $\bar{q}_f$ to Z_1 versus Z_1. The solid symbols are data from the present work at $v = 2v_0$, $3v_0$, and $4v_0$, while the open symbols are data for $v = 4.7v_0$ reported by Shima, Kuno, Kakita, and Yamanouchi [4], $v = v_0$ by Lennard and Phillips [3], and $v = 3v_0$ by Knystautas and Jomphe [10] (one open circle). The solid lines are drawn to guide the eye.

Shell effects, first observed by Moak *et al.* [12] in charge distributions, arise when electrons in a given shell (e.g., the *M* shell) are depleted. The remaining electrons have a relatively higher ionization potential and lower ionization cross section. Thus charge states corresponding to closed shells are favored at the expense of lower- or higher-charge states. The distortion that this effect causes to the Gaussian distribution of the charge-state fraction is termed the shell effect. The authors have observed shell effects in the *mean*-charge state of a given ion as a function of velocity. Figure 3 shows the decrease in the mean number of electrons attached to K, Cl, and P ions ($Z_1 - \bar{q}_f$) as the ratio of ion to Bohr velocity (v/v_0) increases. As the stripping proceeds towards the closed shell ($Z_1 - \bar{q}_f = 10$) (dashed line), one can easily see the "reluctance" of the ions to surrender their first *L*-shell

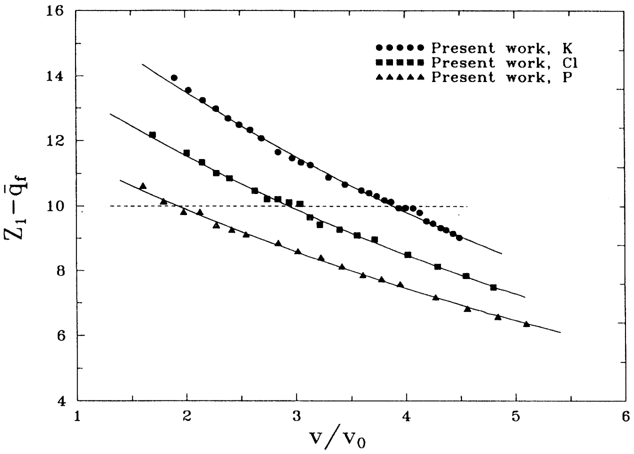

FIG. 3. The mean number of electrons $(Z_1 - \bar{q}_f)$ remaining in phosphorus, chlorine, and potassium ions as a function of v/v_0, where v is the ion velocity. The dashed line corresponds to $Z_1 - \bar{q}_f = 10$, a closed neonlike L shell. The solid lines were obtained from the most probable charge-state expression given by Heckman, Hubbard, and Simon [15] and Betz *et al.* [16].

electron. As a function of velocity, the shell effect causes a small but measurable change in the mean-charge state for a given ion, but this effect vanishes for neighboring $(Z_1 \pm 2)$ isotachic ions. Therefore, for a given velocity, the Z_1 dependence of the mean-charge state does not exhibit shell effects of significant magnitude to account for the reported peaks in $\bar{q}_f$ versus Z_1.

In understanding the nonmonotonic dependence of the mean charge state on Z_1, the model of Betz and Grodzins [13] seems to give some qualitative insights. Even though there are no projectile Auger electron yield data available at the present velocities to confirm the conjecture, certain features observed in the present experiment can still be understood within the framework of this model. The Auger effects for low-velocity ions $(v = v_0)$ that are reported [3] to have contributed to the peak at and around $Z_1 = 15$ become negligible at high velocity $(v = 2v_0)$ because these ions are deficient in the M-shell electrons required to fill the L-shell vacancy in the Auger process. Exiting ions with a mean number of electrons of at least 11 $(Z_1 - \bar{q}_f = 11)$ are expected to increase their mean-charge state through Auger processes. At $v = 2v_0$, this criterion is fulfilled by the ions in the range $19 \le Z_1 \le 29$. On the other hand, for constant velocity ions, the L-vacancy fraction is known to decrease with increasing Z_1 [14]. Therefore, the authors suggest that the competition between these two processes is the cause of the enhancement of the mean-charge state for a narrow range of atomic numbers. Whether this conjecture is validated or not by future work, it is clear that closed-shell effects are *not* the cause of observed enhancements in the mean-charge state of heavy ions as a function of atomic number for isotachic ions.

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[1] V. S. Nikoleav and I. S. Dimitriev, Phys. Lett. **28**, 277 (1968).

[2] K. Shima, T. Ishihara, and T. Mikumo, Nucl. Instrum. Methods **200**, 605 (1982).

[3] W. N. Lennard and D. Phillips, Phys. Rev. Lett. **45**, 176 (1980).

[4] K. Shima, N. Kuno, T. Kakita, and M. Yamanouchi, Phys. Rev. A **39**, 4316 (1982).

[5] D. Schneider, N. Stolterfoht, D. Ridder, H. C. Werner, R. J. Fortner, and D. L. Mathews, IEEE Trans. Nucl. Sci. **26**, 1136 (1979).

[6] A. M. Arrale, Z. Y. Zhao, J. F. Kirchhoff, D. K. Marble, D. L. Weathers, F. D. McDaniel, and S. Matteson, Nucl. Instrum. Methods B **89**, 437 (1994).

[7] A. B. Wittkower and H. D. Betz, At. Data **5**, 113 (1973).

[8] H. D. Betz, Mod. Phys. **44**(3), 465 (1972).

[9] W. S. Bickel, H. Oona, W. S. Smith, and I. Martinson, Phys. Scr. **6**, 7 (1972).

[10] E. J. Knystautas and M. Jomphe, Phys. Rev. A **23**, 679 (1981).

[11] K. Shima, M. Kakuta, S. Fujioka, and T. Ishihara, Nucl. Instrum. Methods B **14**, 275 (1986).

[12] C. D. Moak, H. O. Lutz, L. B. Bridwell, L. C. Northcliffe, and S. Datz, Phys. Rev. Lett. **18**, 41 (1967).

[13] H. D. Betz and L. Grodzins, Phys. Rev. Lett. **25**, 211 (1970).

[14] R. J. Fortner and J. D. Garcia, Phys. Rev. A **12**, 856 (1975).

[15] H. H. Heckman, E. L. Hubbard, and W. G. Simon, Phys. Rev. **129**, 1240 (1963).

[16] H. D. Betz, G. Hortig, E. Leischner, Ch. Schmelzer, B. Stadler, and J. Weihrauch, Phys. Lett. **22**, 643 (1966).