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Publication Date

1989-03-01

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Accelerator & Fusion Research Division

Presented at the 1989 IEEE Particle Accelerator Conference, Chicago, IL, March 20–23, 1989, and to be published in the Proceedings

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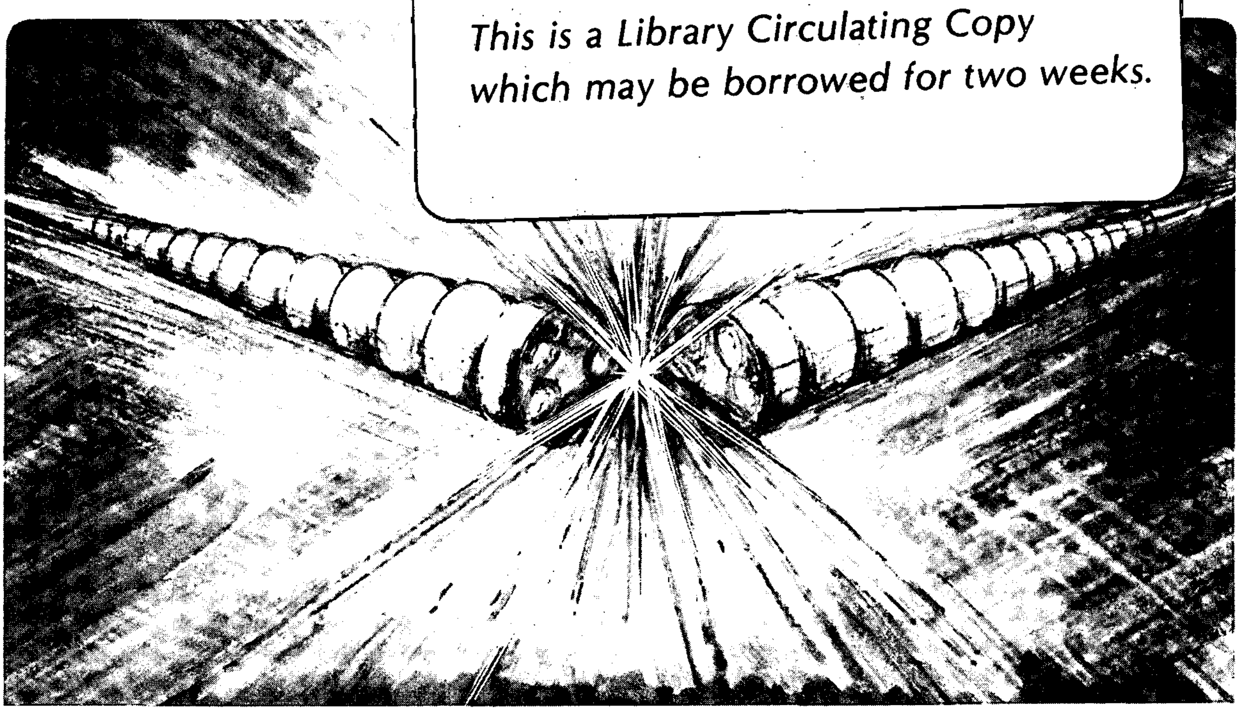

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

LBL-25930

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*This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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Abstract

We have extended the database of measured charge state distributions available in the literature through measurements at the SuperHILAC using carbon stripper foils in the energy range 1.2 - 8.5 MeV/u. Modifying a semi-empirical model to include the effect of electronic shells, we are able to correctly predict the mean charge state to within 1/2 a charge state for 6≤Z≤92 and energies from 30 keV/u to 16 MeV/u. We have determined parameters for the widths of the distributions for each electronic shell. For distributions lying across a shell boundary, we join two Gaussians of different widths to get an asymmetric distribution.

Introduction

The Bevalac facility at LBL consists of the Bevatron, a weakly focusing synchrotron, injected by either the SuperHILAC linac (SH) or a "local" injector (LI). The SH accelerates ions from protons to uranium at energies up to 8.5 MeV/nucleon. The LI injects ions up to argon at 5.1 MeV/nucleon. The SH beams are stripped to higher charge states with carbon foils after the second acceleration tank, at 1.2 MeV/nucleon. They also can be stripped before entering the transfer line to the Bevatron. The LI beams are stripped twice before injection.

It is important for efficient accelerator operations to have accurate predictions of the distribution of charge states after the various stages of stripping. A program has been used for several years which employed the formulation of Betz[1] to predict the centroid and width of the distributions, with constants fit to measurements of two ions at 8.5 MeV/u. It was found that the predictions of this code were often 1-2 charge states off the centroid and also did not predict the width very accurately. Thus we have undertaken a program of measuring charge state distributions at 1.2 MeV/nucleon as well as at some higher energies. Combining this new data with measurements available in literature, we have reexamined various empirical models for the mean charge and the width of the distributions and modified one of them to include corrections for shell effects.

Technique

The measurements were made at the SH at two locations The first location, between tanks 2 and 3 of the Linac, consisted of two analysis magnets plus a Faraday cup, with slits in front of each magnet to ensure the beam was centered. The beam was optimized for the strongest charge state with the slits in,then the slits removed and the magnets scaled to measure the current for the other charge states. The measurements in this area were limited to Z ≤ 67 because of saturation of the magnets. The absolute charge state was determined by calibrating the magnet current with very light ions (C, Ne) for which the charge states were known. The measurements at the higher energies were done in a similar manner using two magnets in one of the beamlines at the end of the accelerator. These measurements were limited for heavier ions because of the resolving power of the magnets. The energy was measured to <1% using the phase probe system of the SH.[2] 30-40 μg/cm² foils were used for the 1.2 MeV/u measurements, and 300-400 μg/cm² for the higher energies.

The measured charge states distributions F(q) for each ion were normalized so that the $\sum_q F(q) = 1.0$.

The mean of the distribution was calculated by

$$\langle q \rangle = \sum_q qF(q) \qquad (1)$$

*This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics, Office of High Energy & Nuclear Physics, U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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Table 1.
Centroids and Widths Measured in Present Work

Ion	E/u	<q>	d	Ion	E/u	<q>	d
C	1.2	5.03	.741	Ni	1.2	18.16	1.31
Mg	1.2	9.13	1.00	Kr	1.2	20.50	1.84
Si	1.2	10.07	1.08	Nb	1.2	22.45	2.06
	5.45	13.37	0.678		8.34	36.52	1.31
	8.75	13.78	0.436	Xe	8.43	45.63	1.41
Ar	1.2	12.03	1.19	La	1.2	30.01	1.44
Fe	1.2	17.09	1.32	Ho	1.2	32.48	2.08
	3.37	21.06	1.17				
	5.72	23.08	0.917				
	8.26	24.02	0.917				

and the width, d, by

$$d = \sqrt{\sum_q (q-\langle q \rangle)^2 F(q)} \qquad (2)$$

Results

The centroids and widths of the charge states measured in the present work are presented in Table 1. Sample distributions are given in Figure 1 for Fe at 1.2, 3.37, 5.72, and 8.26 MeV/u. The <q> increases with increasing energy and the width decreases. The shapes are approximately Gaussian, as one might expect from a simple model assuming cross sections for capture and loss which are approximately independent of q.[1]

Figure 2a) and 2b), show the measured <q>/Z and the width d, respectively, for the 1.2 MeV/u data. Included in the figure is data obtained by other authors[3,4] at 1.16 and 1.2 MeV/nucleon. Our results agree very well with the earlier data for overlapping systems (Z = 18 and 36). The location of the shell transitions at He-like, Ne-like, and Ar-like ions are included in Fig 3a, as well as that for Ni-like ions. Ni-like ions correspond to the filling of the 3d-shell, for which there is even a larger change in the ionization potential[5] than for Ar-like ions.

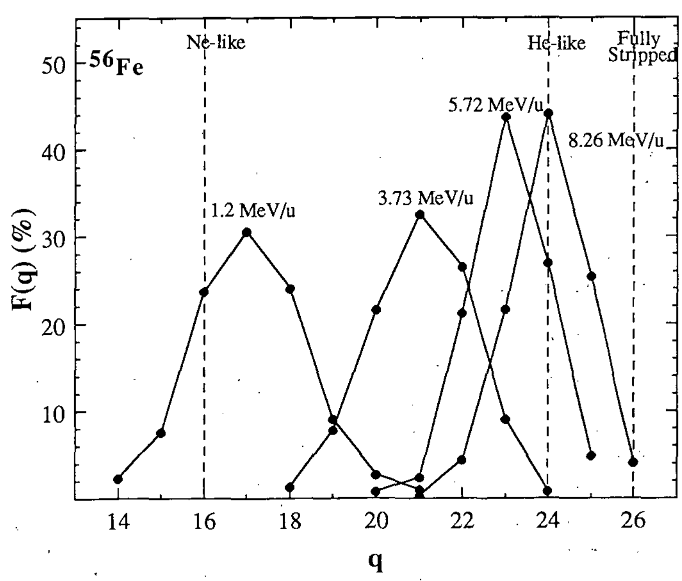


Figure 1.. Measured charge state distributions for ^{56}Fe at 1.2, 3.37, 5.72, and 8.26 MeV/u. The incident charge was +4 for the 1.2 MeV/u measurement and +17 for the higher energies. The vertical dashed lines correspond to the fully stripped , He-like, and Ne-like ions.

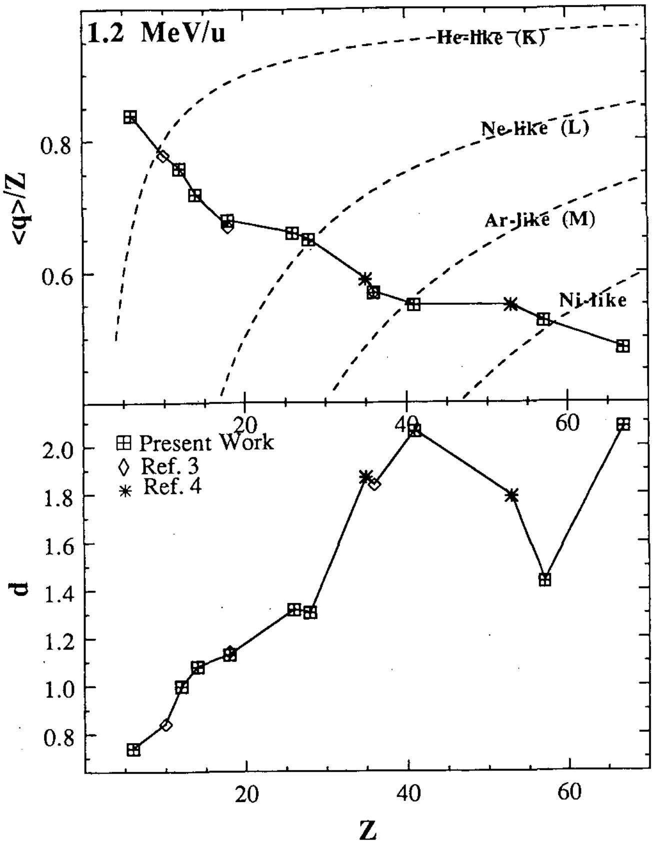


Figure 2. Normalized centroids, $\langle q\rangle/Z$ (a) and widths, d (b), at 1.2 MeV/nucleon as a function of Z of the ion. The data are from the present work (⊞), Ref. 3 (◊), and Ref. 4 (∗). The dashed lines in 2a) represent shell closures for each Z.

It can be seen qualitatively that the decrease in $\langle q\rangle/Z$ with Z is not smooth and the discontinuities seem qualitatively to be related to the presence of shells. The effect is more pronounced in the widths which show a decrease in the vicinity of a shell, especially for Ni-like ions.

Centroids of the Distributions

In Figure 3a), $\langle q\rangle/Z$ for all energies and ions, those of Table 1 as well as over a hundred other points from various references, are plotted on a universal curve in terms of the reduced velocity as defined by Nikolaev and Dmitriev (ND)[6]:

$$X = v/(v_o Z^{0.45}) \qquad (3)$$

where v_o = 3.6e8 cm/sec. Included on the plot is the semi-empirical formula of Shima et al.[7]:

$$\langle q\rangle_{SH}/Z = 1.-\exp(-1.25X + 0.32X^2 - 0.11X^3) \qquad (4)$$

While overall, the Shima formula gives a reasonable fit to the data over a wide range of reduced velocities, the variation in $\langle q\rangle/Z$ for different ions with similar reduced velocities is as large as 5%, which for something as heavy as gold or uranium, could be several charge states, a significant error. These variations are another manifestation of the shell effects seen in the earlier figures.

When one looks in more detail at the data, it appears that there are certain regions of Z and X where the variations are the largest, namely in the region of the shells. For example, the Shima formula works very well for Z ≤ 13. Just above that, we enter a region 14 ≤ Z ≤ 18 for which data exists for every Z. The deviation from the Shima prediction gets progressively larger as one moves from Si to Ar. (An exploded view of this region is shown in Figure 3b) for Si and Ar which details this progression.) With this consideration, we have adopted a prescription to calculate $\langle q\rangle/Z$ which includes a shell correction in certain regions of Z and X. The Shima formula for $\langle q\rangle$ is corrected by $\delta q = f(Z)\sqrt{E/1.2}$, where E is the energy in MeV/u and f(Z) is:

$$f(Z) = -0.0007Z^2+0.038Z-0.5056+(Z-6)^{1.10}\sin(60.Z^{0.1})/50. \qquad (5)$$

The function f(Z) represents a small parabolic correction term to the Shima model plus a sinusoidal function of increasing period and amplitude with increasing Z. The constants have been chosen to fit the data at 1.2 MeV/u. The E dependence is a crude correction based on the assumption that the magnitude of the shell corrections increase with increasing energy. The regions of Z and E for which this formula applies is given in Table 2a. The dashed lines in Fig. 3b) are the results of this correction for Si and Ar.

With this modification, the Shima formula works quite well to fit the data over the full range of ions and energies of Fig. 3. With the exception of uranium at very high energies (16 MeV/u), the maximum deviation between prediction and experiment is ~1%, compared to the 5% obtained using the original Shima formula.

Widths

The width of the charge state distribution is of practical importance because it is often the case that for one reason or another it is desired to tune the accelerator to a charge state that is not at the centroid of the distribution. Following an analysis of Cu data by Shima et al.[8], we have analyzed all the widths for which the measured charge states fall into one major shell and for each shell fit these to the expression $d = CZ^a$, giving the values of C and a for each shell tabulated in Table 2b.

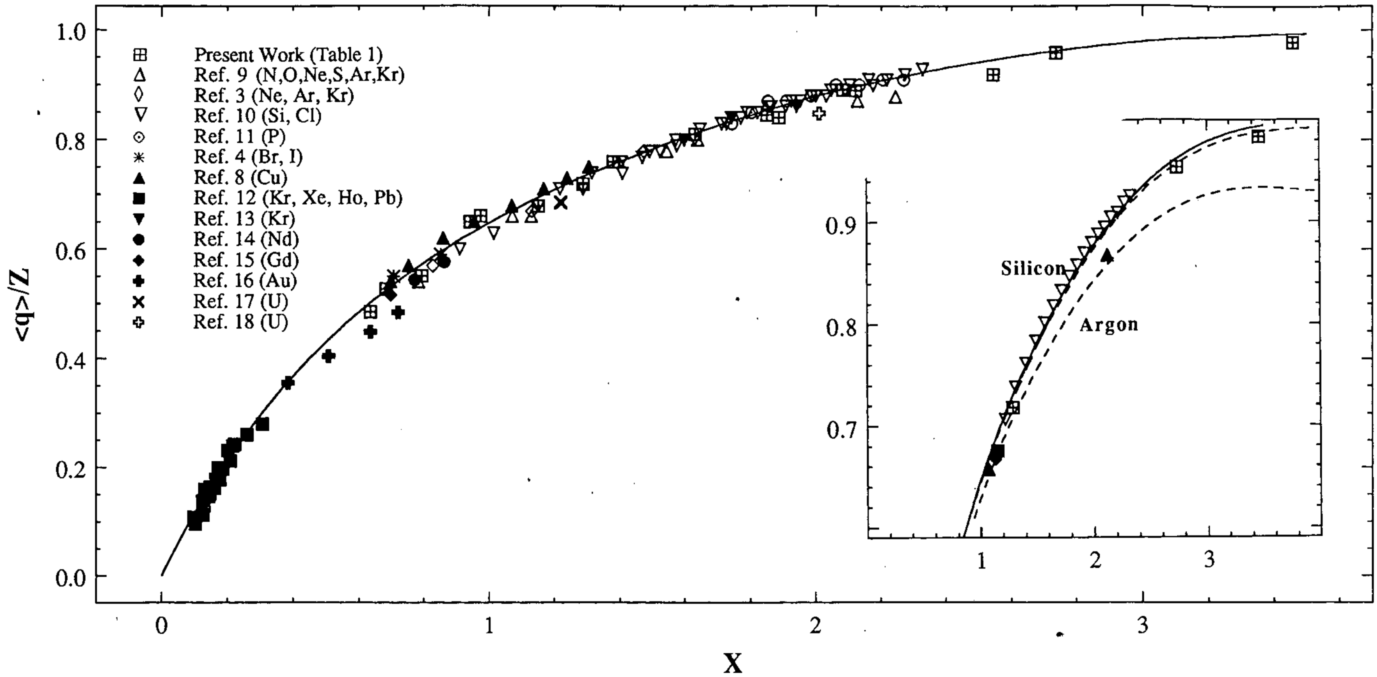
The prescription then for calculating a charge state distribution for a given ion and energy is as follows. 1) Calculate $\langle q\rangle$ using the Shima formula modified for shell corrections. 2) Calculate the location of the major shells for the ion. 3) Calculate F(q) assuming Gaussian distributions with the width determined by the shell. For example, for an ion that spans the L/M shell transition at $q=q_t$,

$$F(q) = 1/\sqrt{2\pi d_M}\,\exp\left(\frac{-(q-\langle q\rangle)^2}{2d_M^2}\right) \quad \text{for } q < q_t \qquad (6)$$

with a similar expression applying for $q>q_t$ with d_L for the width, and d_L and d_M given by the formula of Table 2b. Figure 4 shows the results of using this prescription for four sample distributions: Fe at 1.2 MeV/u and 3.37 MeV/u (4a) and Xe at 8.43 MeV/u and La at 1.2 MeV/u. The predicted distributions are quite accurate for all but the low energy La case, which is on the M/N shell boundary. It is likely that in these outer shells, one must take into account sub-shell boundaries as well as major shell boundaries. This is evidenced by the change in ionization potentials at the sub-shell boundaries[5]. We are now investigating whether enough data is available to determine width parameters for each subshell.

Table 2.
Prescription for predicting distributions

a. Centroids: $\langle q\rangle_{sh}$ given by Eqn. (4); f(Z) given by Eqn. (5)			b. Widths: $d = CZ^a$		
Z-range	E-range (MeV/u)	$\langle q\rangle$	Shell	C	a
6-13	all	$\langle q\rangle_{sh}$			
14-18	all	$\langle q\rangle_{sh} + f(Z)\sqrt{E/1.2}$	L	0.755	0.147
19-53	≤ 2	$\langle q\rangle_{sh} + f(Z)\sqrt{E/1.2}$			
	> 2	$\langle q\rangle_{sh}$	M	0.235	0.585
54-66	all	$\langle q\rangle_{sh}$			
67-78	all	$\langle q\rangle_{sh} + f(Z)\sqrt{E/1.2}$	N	0.876	0.209
79	≤ 0.60	$\langle q\rangle_{sh}$			
	0.60 - 2.	$\langle q\rangle_{sh} + f(Z)\sqrt{E/1.2}$	0	1.00	0.186
	> 2	$\langle q\rangle_{sh}$			
80-92	≤ 0.50	$\langle q\rangle_{sh} + f(Z)\sqrt{E/1.2}$			
	> 0.50	$\langle q\rangle_{sh}$			



The reduced velocity X versus <q>/Z for the present data plus data from the references cited in the legend. The solid line is calculated from Eqn. (4). b) An exploded view of 3a) for silicon (open points) and argon (solid) with data from present work (⊞, ■) plus Ref. 10 for Si (∇) and Refs. 3 (◆) and 9 (▲) for Ar. The solid line is Eqn. (4). The dashed lines include the Z-dependent shell corrections given by Eqn. (5).

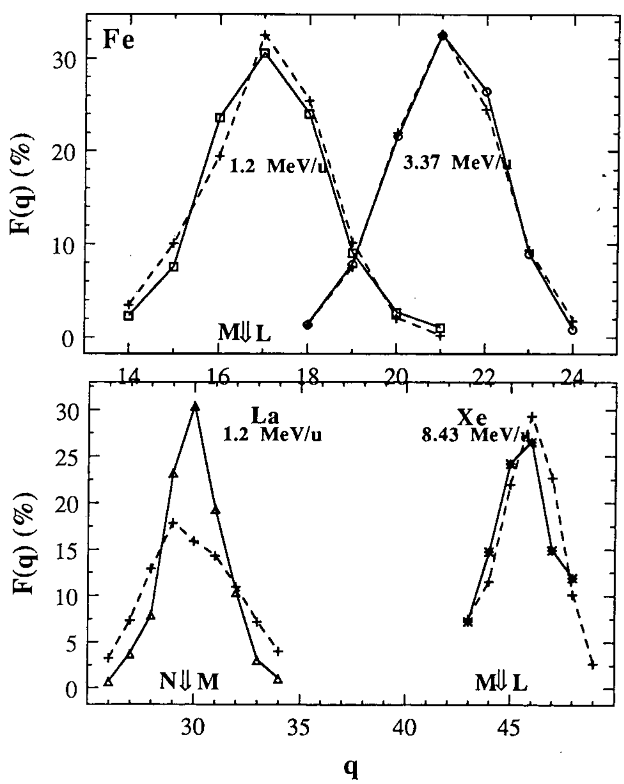


Figure 4. Measured (solid) and predicted (dashed) charge state distributions for a) Fe at 1.2 and 3.37 MeV/u, and b) La at 1.2 MeV/u and Xe at 8.43 MeV/u. The major shell transitions are shown by the arrows.

Conclusion

We have measured equilibrium charge state distributions in carbon targets for ions ranging from C to Ho and energies of 1.2-8.75 MeV/u. Compiling these together with measurements from literature, we have used the approximately 100 measured distributions to modify the formula of Shima et al.[7] to include the effect of shells on <q> and determined parameters for the width of the Gaussian distributions for all ions with distributions within a shell so that two Gaussian distributions could be joined for ions in transition regions. Using these modifications, we have improved the codes used at the Bevalac for predicting charge state distributions. More measurements are needed for heavy ions at the lower energies in order to better parametrize the behaviour for outer shell electrons and the very heaviest ions (Pb, U) Further details on this work will be presented in a forthcoming paper.

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