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Stripping of high-energy krypton ions by various solid materials

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The charge-state distributions of 373-, 444-, and 552-MeV krypton ions passing through carbon foils of different thicknesses were measured; they were found to agree within about one charge state with the existing semiempirical predictions. Measurements of equilibrium distributions produced by Cu, Ag, and Au foils showed differences of two to three charge states when compared to C-foil results. Evidence is also given that the distributions are not significantly modified when the angle of observation is different from 0°.

I. INTRODUCTION

Very sparse data are available concerning the stripping of heavy ions of mass number of the order of 100 at energies higher than 150 MeV. In addition, the now well-known semiempirical formulas of Betz[1] and Nikolaev and Dmitriev[2] predicting the average charge state $\bar{Z}_\infty$ and the width d of the equilibrium charge-state distributions are not yet checked in this range of mass and energy.

Most of the actual heavy-ion accelerator designs, which are of a two-stage type with a stripper in between, require the knowledge of the equilibrium charge-state distributions. Moreover, many experimentalists in atomic or nuclear physics need these data for different target materials, energies, and projectiles.

The goal of this paper is to report on the average charge states and charge distributions of krypton ions passing through carbon, copper, silver, and gold foils as a function of the projectile energy and the stripper thickness. The energies were 373, 444, and 552 MeV; the carbon thicknesses ranged from 3 to 190 $\mu g\,cm^{-2}$, while the other materials were 150–190 $\mu g\,cm^{-2}$ thick. Evidence is also established that equilibrium distributions do not strongly depend on the scattering angle around 0°.

II. EXPERIMENTAL PROCEDURE

The high-energy krypton ions were produced by the ALICE linac-cyclotron accelerator.[3] After extraction, the beam was analyzed by a 19° bending magnet and focused onto the detector by two pairs of quadrupoles (Fig. 1). Part of the collimation was made by two 0.5×0.5-mm diaphragms 575 cm apart, located between the quadrupoles. After passing through the stripper, the beam was furthermore collimated by a 0.17-mm-diam hole at the entrance of an analyzing magnet which deviated the particles by an average angle of 5° on a position-sensitive detector. The system was not devised to measure the charge-state distributions of Coulomb-scattered beams; the measurements were thus made only at 0°, within an aperture of ±1.44 mrad (0.08°). The maximum available magnetic field was 2.2 T, and in order to ensure a clean separation between the charge states, radial focusing was provided by the addition of shims; the resultant field gradient was 0.17 T/cm.

The target holder could carry as many as 20 1-cm-diam targets. Up to 100 $\mu g\,cm^{-2}$, the carbon target thicknesses were measured by a light-absorption method calibrated by a method using the change in frequency of a quartz crystal. The heavier C foils and the Cu, Ag, and Au ones were weighted. None of these methods could account for the local thickness variations and, for values smaller than 50 $\mu g\,cm^{-2}$, these variations were sometimes found to be as large as 50%.

The position-sensitive silicon-surface-barrier detector was 5 cm long and registered all the beam components at the same time. Except for the very thick targets, the peak-to-valley ratio was larger than 15 : 1 (Fig. 2). The total number of counts ranged from 9×10^3 to 9×10^4, while the counting rate was kept below 300 per sec to protect the detector.

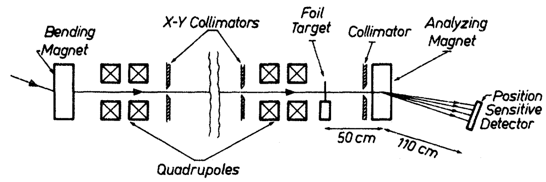

FIG. 1. Experimental setup.

The energy and position-times-energy signals were stored in 32 and 512 channels, respectively, on a magnetic tape through a multichannel analyzer. No division of the second signal by the first one was made, due to the constant response of the detector to the monoenergetic beams.

The pressure in the pipes was everywhere better than 2.10^{-6} Torr and the purity of the incident charge state, measured without foil, was found to be better than 1%.

The equilibrium and nonequilibrium charge-state distributions were obtained for three different incident energies: 373, 444, and 552 MeV; these values are known to within a 2% accuracy.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Nonequilibrium distributions

If $N(Z)$ is the number of ions having charge state Z, the charge-state fraction is defined by

$$P(Z) = N(Z) \Big/ \sum_{Z} N(Z) \,. \tag{1}$$

Figures 3(a)–3(c) show the evolution of the charge-state fractions as a function of the carbon target thickness x for the three above-mentioned energies.

Each $P(Z)$ reaches an equilibrium value which no longer changes when the target thickness is further increased. Figure 4 represents the evolution of the average charge state

$$\bar{Z} = \sum_{Z} Z P(Z) \tag{2}$$

versus x. Although the incident charge state is

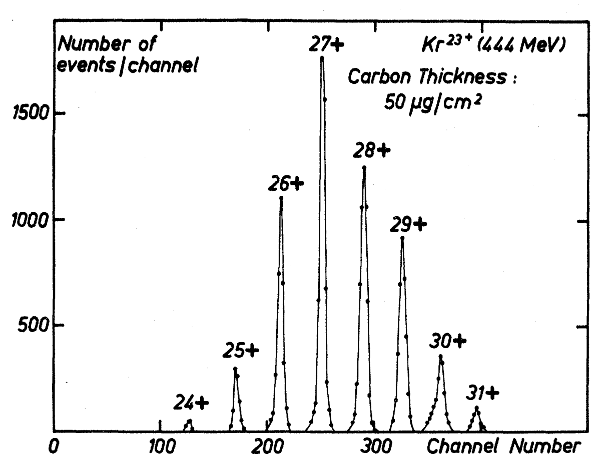

FIG. 2. Typical spectrum of 444-MeV krypton ions stripped by a carbon foil, recorded by the 5-cm-long position sensitive detector.

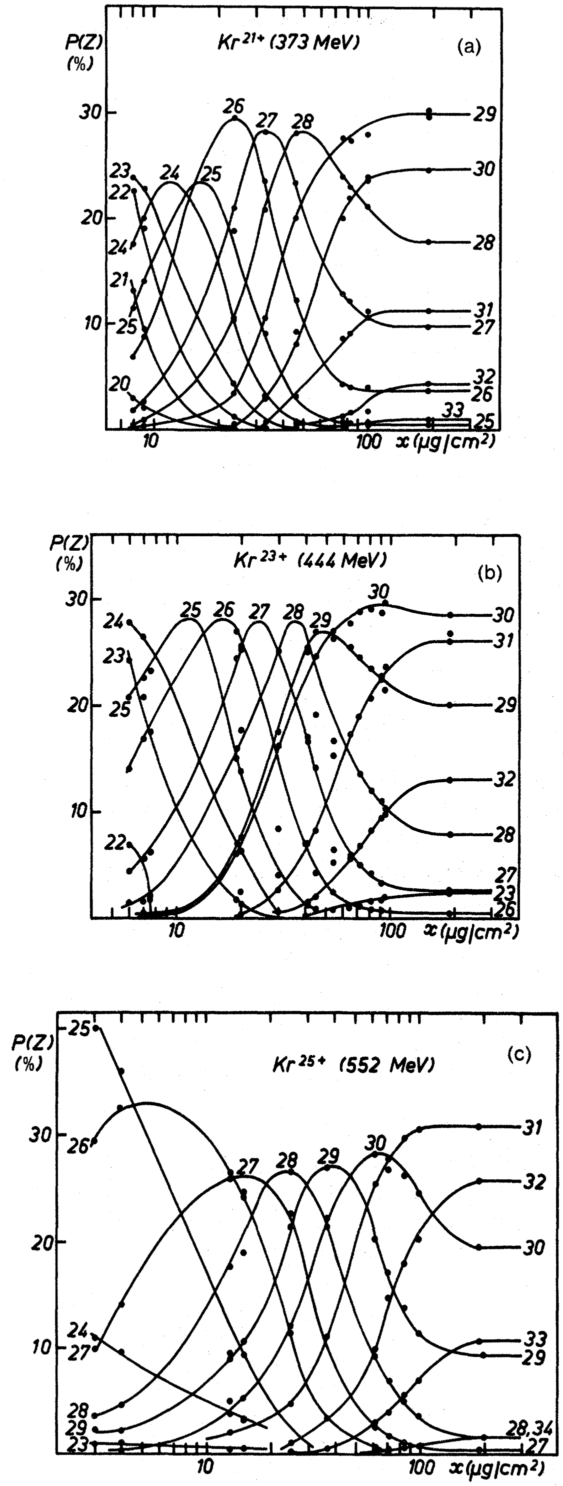

FIG. 3. (a)–(c): Nonequilibrium charge-state distributions for (a) 373-, (b) 444-, and (c) 552-MeV krypton ions passing through carbon. The full curves are only drawn to guide the eye.

different for each energy W, it is seen that the equilibrium thickness increases noticeably with W.

The three curves were fitted by an analytical formula suggested by Bohr and Lindhard[4] for gas strippers,

$$\overline{Z}(x)=\overline{Z}_\infty+(Z_i-\overline{Z}_\infty)e^{-kx} \quad (3)$$

where Z_i and $\overline{Z}_\infty$ are the incident and equilibrium charge states, respectively.

The values of k, along with the thickness required to reach 99% of $\overline{Z}_\infty$, are shown in Table I.

B. Equilibrium charge-state distributions with carbon strippers

Equilibrium distributions may in many cases be approximately represented by a normal distribution,

$$P(Z)=\frac{1}{d\sqrt{2\pi}}\exp\left(-\frac{(Z-\overline{Z}_\infty)^2}{2d^2}\right), \quad (4)$$

with[5]

$$d^2=\sum_Z (Z-\overline{Z}_\infty)^2P(Z)-\tfrac{1}{12}h , \quad (5)$$

where h is given here by $h=\Delta Z=1$.

The experimental distributions are shown in Fig. 5; the solid curves are calculated with expressions (2) and (4).

Two different semiempirical formulas were proposed for $\overline{Z}_\infty$ and d. For a projectile of atomic number Z_0 and velocity v passing through a solid foil, Betz proposed

$$\overline{Z}_\infty=Z_0[1-C(0.71Z_0^{0.053})^{v/v_0}] \quad (6)$$

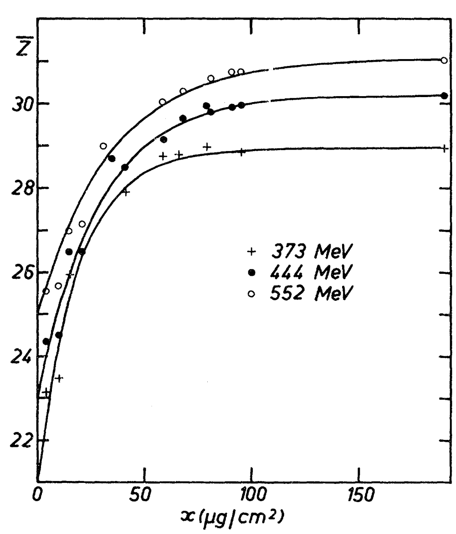

FIG. 4. Carbon thickness dependence of the average charge state of krypton ions.

TABLE I. Factor k as defined by Eq. (3), and equilibrium thickness for each of the three incident-ion energies.

Z_i	W (MeV)	k ($cm^2\,\mu g^{-1}$)	$x_{99\%}$ ($\mu g\,cm^{-2}$)
21	373	0.052	63
23	444	0.035	90
25	552	0.029	102

and

$$d=0.27Z_0^{1/2} , \quad (7)$$

where $v_0=2.188\,10^8$ cm/sec and C is an experimentally determined constant ($C\simeq 1.094$ for krypton). Nikolaev and Dmitriev derived another set of formulas,

$$\overline{Z}_\infty=Z_0\{1+[v/(v'Z_0^\alpha)]^{1/k}\}^{-k} \quad (8)$$

and

$$d=\tfrac{1}{2}\{\overline{Z}_\infty[1-(\overline{Z}_\infty/Z_0)^{1/k}]\}^{1/2} , \quad (9)$$

where $v'=3.6\,10^8$ cm/sec, $\alpha=0.45$, and $k=0.6$.

One of us[6] recently attempted to fit all existing experimental data using (8) with adjustable parameters.

There are three sources of error on the experimental results.

(i) The statistical error on $\overline{Z}_\infty$ can be derived from (4) and is given by[7]

$$\delta\overline{Z}_\infty=\pm d\Big/\left[\sum_Z N(Z)\right]^{1/2} . \quad (10)$$

The present figures are typically of the order of

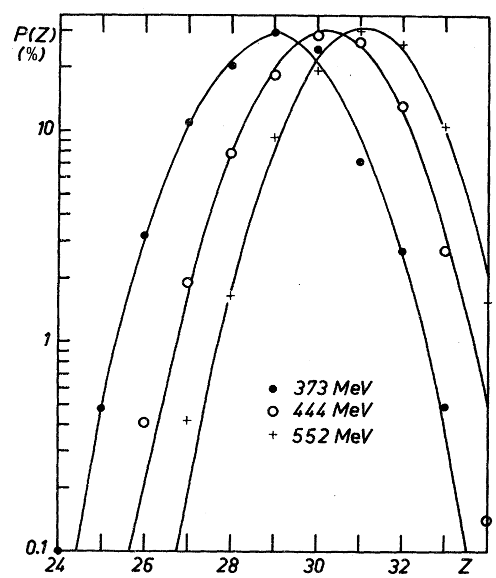

FIG. 5. Equilibrium charge-state distributions of krypton ions passing through carbon.

$\pm 10^{-2}$, depending on the statistics.

(ii) The uncertainty δW on the incident energy introduces an error which can be estimated by differentiating (6) or (8) with respect to v; one then obtains $\pm 4 10^{-2}$ with $\delta W/W = \pm 1\%$.

(iii) The largest source of error lies in the local thickness variations of the foils. The only estimate that could be made was to average the dispersion of the $\bar{Z}_\infty$ values for nine different target positions in the beam; the net result, which also includes (i), amounts to

$$\delta \bar{Z}_\infty = \pm 0.2 \ .$$

Table II gives the comparison between the experimental results and the semiempirical predictions.

It thus appears that, in this range of projectile mass and energy, the Nikolaev-Dmitriev prediction with properly adjusted parameters ($\alpha = 0.43$, $k = 0.61$) is the best, while Betz's formula gives too high a value of $\bar{Z}_\infty$ and, of course, no dependence of d on energy. [It must be mentioned, however, that Betz assumes that (7) is valid only for $W < 80$ MeV.] Trying to adjust to parameter C to fit the experimental results (Fig. 6) leads to a value of 1.57 which is way outside the range Betz indicates ($1.030 \lesssim C \lesssim 1.098$).

C. Equilibrium distributions with Cu, Ag, and Au strippers

The equilibrium distributions were measured for the three krypton energies with the following targets: C (190 μg cm^{-2}); Cu (145 μg cm^{-2}); Ag (150 μg cm^{-2}); and Au (150 μg cm^{-2}). It is easy to show that, although the emerging energies were not identical due to the different stopping powers and thicknesses, the shift on $\bar{Z}_\infty$ is much less than the error caused by the uncertainty on the initial energy value and on the target thickness.

Figure 7 shows the $\bar{Z}_\infty$ variation as a function of the target atomic number Z_t. The $\bar{Z}_\infty$ value for any Z_t with krypton as a projectile may be approximated by the formula

$$\bar{Z}_\infty(Z_t) = \bar{Z}_\infty(6)[1 - 5.21\times 10^{-3}(Z_t - 6) + 9.56\times 10^{-5}(Z_t - 6)^2 - 5.96\times 10^{-7}(Z_t - 6)^3] \ , \qquad (11)$$

where $\bar{Z}_\infty(6)$ stands for the average charge state obtained with a carbon stripper for the same krypton energy.

Figure 7 suggests that, if one knew how to make thin self-supporting lithium or hydrogen targets, the average charge state would be higher than that for carbon.

TABLE II. Comparison between the average charge states $\bar{Z}_\infty$ and widths d: expt, experimental; B, Betz; ND, Nikolaev and Dmitriev; D, Delaunay.

	W (MeV)	373	444	552
$\bar{Z}_\infty$	expt	28.94 ± 0.2	30.20 ± 0.2	31.07 ± 0.2
	B	30.96	31.82	32.77
	ND	28.84	29.59	30.44
	D	29.29	29.99	30.80
d	expt	1.34	1.30	1.24
	B	1.63	1.63	1.63
	ND	1.49	1.44	1.36

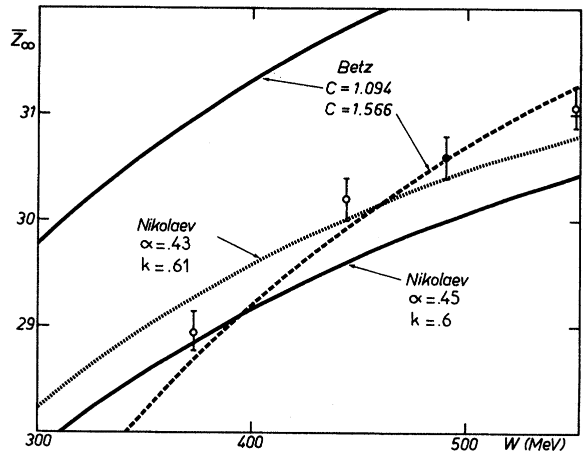

FIG. 6. Energy dependence of the average charge state of krypton ions at equilibrium when passing through carbon. Open circles, present experiment; solid circle, previous experiment where the scattering angle was 3°.

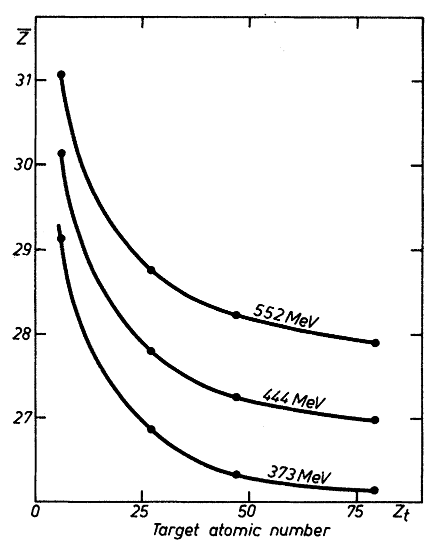

FIG. 7. Average charge states of krypton ions at equilibrium for different energies and target species.

This can be explained by the fact that, as the target atomic number decreases, the average velocity of the target electrons becomes much lower than the ion velocity: The capture rate then goes down, and with a loss rate remaining approximately constant, the net result is an increase of $\bar{Z}_\infty$. This phenomenon appears clearly in the present experiment, due to the very high velocity.

D. Influence of scattering angle

The question has been raised of the influence of the scattering angle at which the charge-state distributions are measured. For instance, Kessel[8] observed a very strong dependence when measuring the charge states of 1.5–12-MeV iodine ions scattered by single collisions on xenon through angles between 2.5° and 8°; he showed that, for a distance of closest approach corresponding to the ion and atom L shells beginning to interpenetrate, the $\bar{Z}_\infty$ value increases rapidly.

In Fig. 6 are shown the present $\bar{Z}_\infty$ values, measured in the forward direction, along with the result of an experiment described elsewhere[9] which was obtained at 3° and 495 MeV. It is difficult to assert that this point lies outside of the $\bar{Z}_\infty(W)$ curve within the experimental errors. Following Kessel's argument, the closest distance of approach r_0 between a carbon atom and a 500-MeV krypton ion scattered at 3° is about 1000 times smaller than the average radius r_k of the k shell; even for angles much smaller than 3°, r_0 is negligible in comparison to r_k. Therefore, a possible effect of highly interpenetrating collisions exciting energy levels related to internal shells and resulting in highly ionized states is already included in the net charge-state distribution observed in a solid angle ω centered around 0°, even if ω is very small.

In addition, violent collisions leading to the loss of several electrons by ions traversing a solid will result in a subsequent larger capture rate for these ions as compared to nondeflected ions. The final average charge state will then tend toward the same value as for the beam observed in the forward direction, and may be below this value since the velocity has been reduced in the Coulomb collision.

As a conclusion, the measurements of charge-state distributions at an angle not too far from but different from zero are not erroneous, provided the projectile energy is sufficient for the K shells to interpenetrate even at 0°.

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