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ON IONIC CHARGE DISTRIBUTIONS OF HEAVY EVAPORATION RESIDUES PASSING THROUGH A CARBON FOIL

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The knowledge of the ionic charge distributions (ICD) for heavy ion reaction products, especially for the heavy evaporation residues (ER), is important from the point of view of effective work of the kinematic recoil separators, i.e., achievement of optimum transmission (for instance see the recent review [1] and refs. therein). The ICD of the ER formed in nuclear reaction and knocked out from a target is not an equilibrated one. A possible transfer of nuclear excitation to the inner atomic shells and subsequent deexcitation of moving atoms via a cascade of Auger electrons make ICD of ER unpredictable. A carbon foil placed at a position of several centimeters downstream from a target restores the equilibrium of the ICD of ER [2].

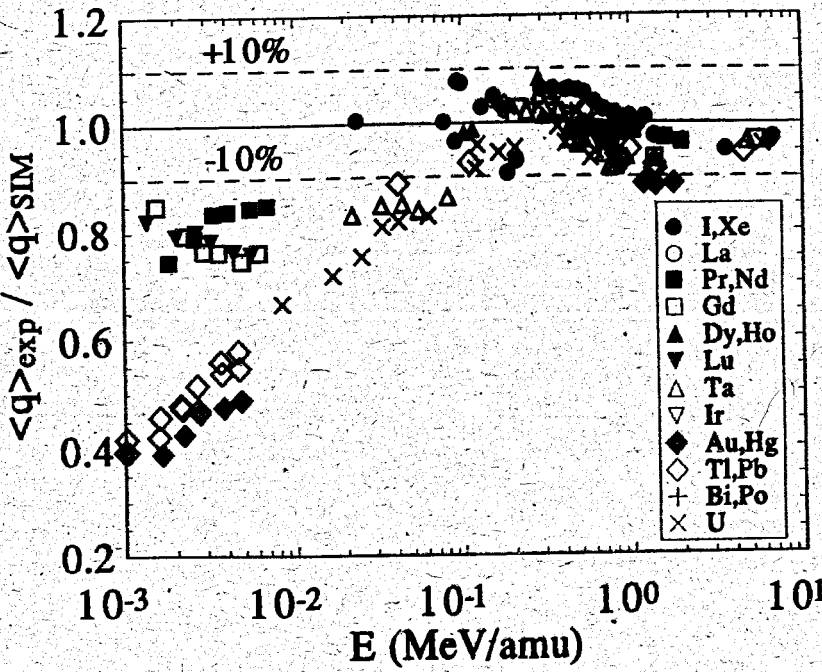

Fig.1. *Comparison of experimental mean ionic charges* — $< q >_{exp}$ *with the empirical predictions by Shima et al. [4]* — $< q >_{SIM}$ *(eq.(1))*

Applications of the empirical systematics for the equilibrated ICD [3, 4] in ion-optical calculations for the case of specific separation systems [5, 6] showed significant deviations of the calculated transportation efficiencies for the ER from the experimental ones [7–9]. Evidently, this is caused by differencies of the adopted ICD from the real ones. Indeed, the data on

the ICD for the heavy ER are poor [2]. Therefore the empirical systematics of mean charges $< q >$ and charge distribution width d [3, 4] based on the data obtained for lighter ($Z \leq 36$, mostly at $E \geq 1$ MeV/amu) heavy ions passing through a carbon foil are used for ion-optical calculations. We considered the available experimental data on ICD for $Z \geq 53$ heavy ion beams at non-relativistic energies ($E \leq 10$ MeV/amu) compiled in [10–12] (see also refs. therein) and the recently obtained data [13] along with the data for ER [2]. The comparison of these data for mean charges with the predictions given by the empirical formula of Shima et al. [4] is shown in fig.1. The mean charge is expressed in this formula as

$$< q >_{SIM} = Z[1 - \exp(-1.25X + 0.32X^2 - 0.11X^3)],$$
$$X = 3.86\sqrt{E}/Z^{0.45}, \qquad (1)$$

where Z is the ion atomic number and E is the ion energy in MeV/amu.

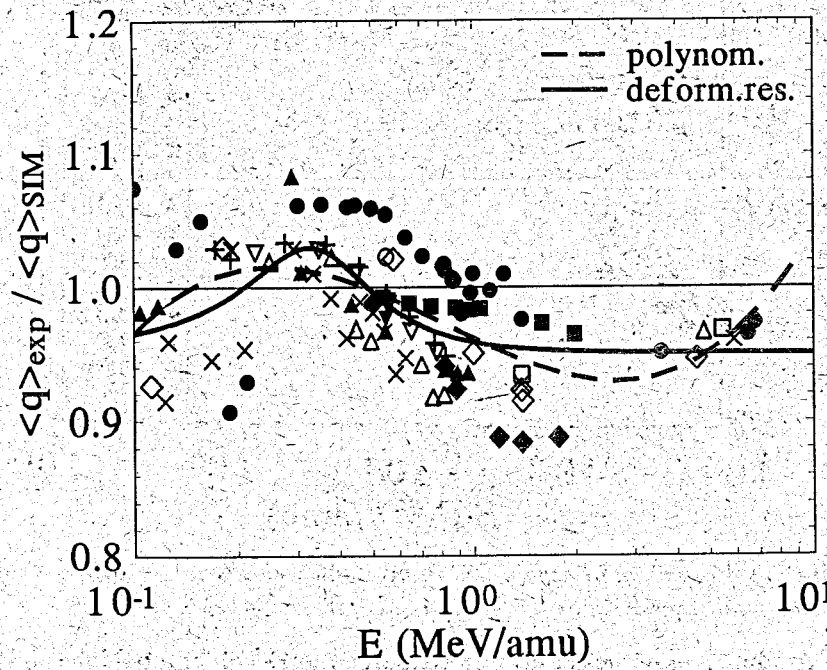

Fig.2. *The same as in fig.1 except the energy region ($0.1 < E < 10$ MeV/amu). The results of least-square fit are shown: solid line — eq.(2), dashed line — polynomial (for comparison)*

The strong deviations of the experimental data from the predictions (up to 40%) and bad scaling with Z in the energy range of our interests ($0.01 < E < 0.1$ MeV/amu) are evident from fig.1. This is observed for both systematics [3, 4]. The similar discrepancies were obtained with others [14].

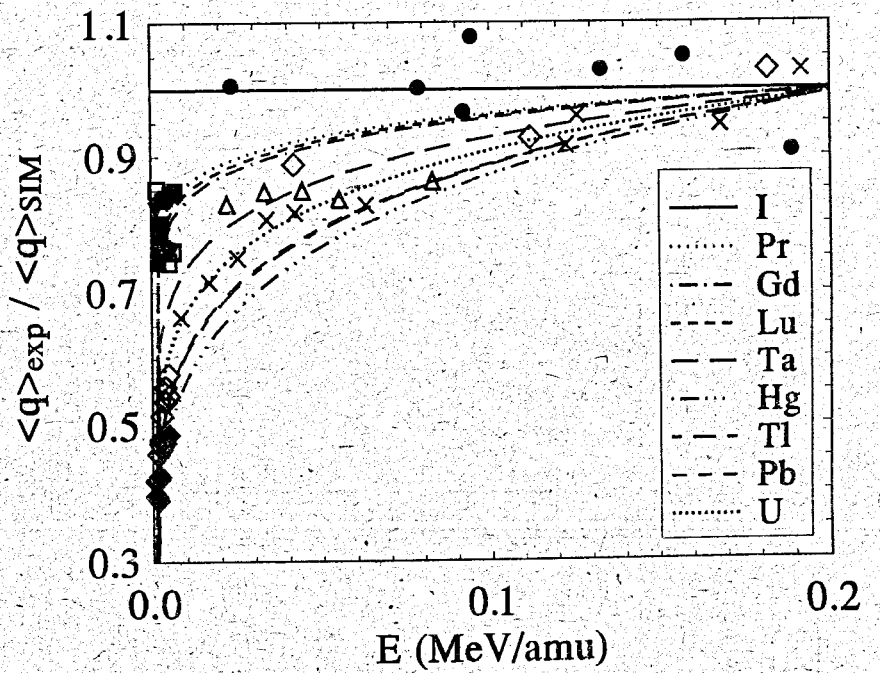

Fig.3. *The same as in fig.1 except the energy region ($0 < E < 0.2$ MeV/amu) and the energy scale (linear). The results of least-square fit using eq.(3) are shown with the different lines for ions of the different Z (symbols are the same as in fig.1)*

The purpose of this work is an improvement of the empirical systematics of ICD [3, 4] in their application to the very heavy ions. To improve the $< q >_{SIM}$-systematics we considered the ratio $R(Z, E) = < q >_{exp} / < q >_{SIM}$. For $E \geq 0.1$ MeV/amu $R(Z, E) \simeq f_1(E)$, which was approximated by a deformed resonant function:

$$f_1(E) = p_1 + \{p_2\Gamma/[(E - p_3)^2 + \Gamma^2]\}, \qquad \Gamma = p_4[1 - \exp(-p_5 E)], \quad (2)$$

as it is shown in fig.2. The values of the constants p_1–p_5 were obtained from least-square fitting to the data at the energies $0.1 \leq E \leq 10$ MeV/amu (see table 1).

Table 1. *Fitted constants in eqs.(2),(3)-(6) of the correction function of eq.(7) to the mean charge evaluation given by Shima et al. [4] (eq.(1))*

$f_1(E)$		$f_2(E,Z)$	
p_1	0.95001	a_1	1.088
p_2	0.01488	a_2	5.990×10^{10}
p_3	0.35744	b_1	5.158×10^{-2}
p_3	0.30325	b_2	3.254×10^{10}
p_3	2.78276	α	16.993
		β	29.353

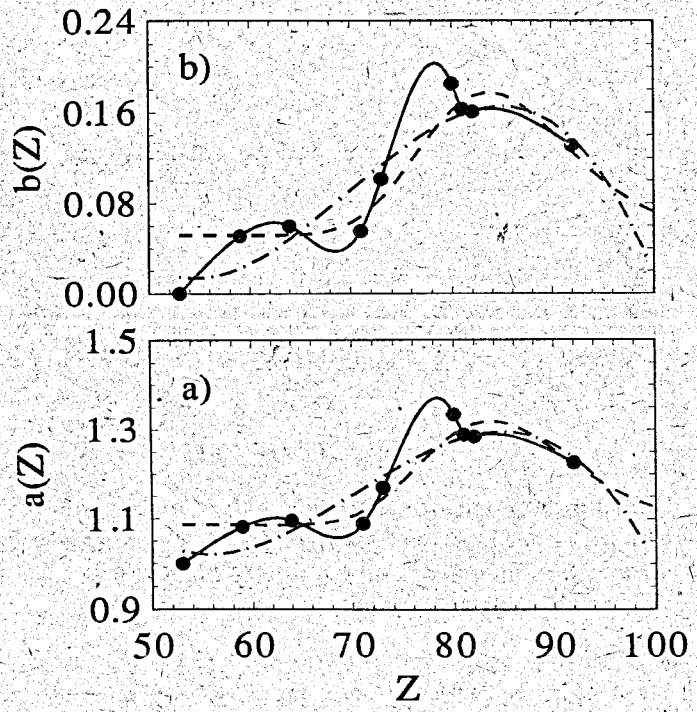

Fig.4. *Changes of the parameters $a(Z)$ — (a) and $b(Z)$ — (b) vs. Z. Filled circles are the a_Z and b_Z values obtained from fit using eq.(3), solid lines are the results of a spline interpolation (see table 2), dashed lines are the results of least-square fit using eqs.(4)-(6) with constants listed in table 1. Polynomial fit is also shown for comparison (dash-dotted lines)*

For $E \leq 0.1$ MeV/amu we chose for $R(Z,E) \equiv f_2(Z,E)$ the form:

$$f_2(Z,E) = a(Z)E^{b(Z)}. \tag{3}$$

To find the parameters $a(Z)$ and $b(Z)$ we derived the values a_Z and b_Z by fitting the energy dependence (3) to the available data at low energies for different Z. The results are shown in fig.3. The obtained a_Z, b_Z values have been fitted to the function of the form:

$$a(Z) = a_1 + a_2 f(z), \tag{4}$$
$$b(Z) = b_1 + b_2 f(z), \tag{5}$$
$$f(z) = z^{\alpha}\exp(-\beta z), \qquad z = (Z-53)/53. \tag{6}$$

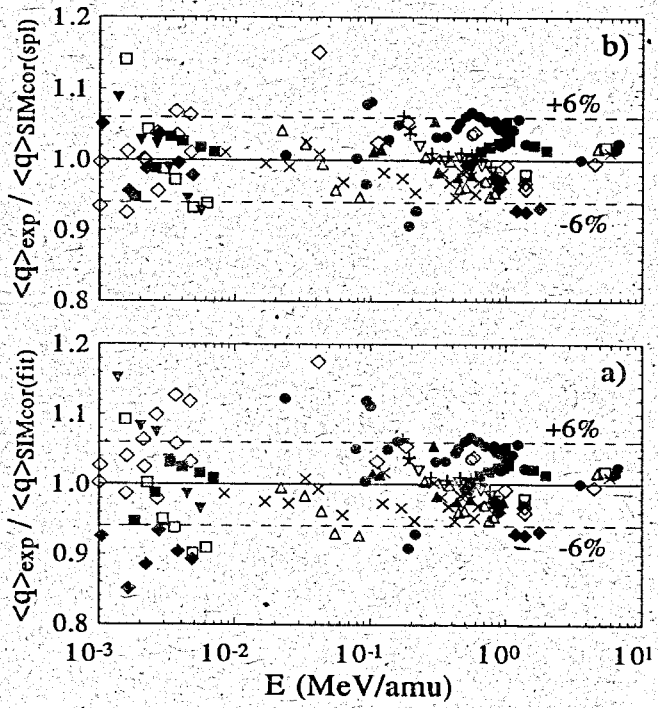

Fig.5. *The same as in Fig.1 except the application of the correction function of eqs.(2)-(7). Low energy corrections are given with the parameters $a(Z)$ and $b(z)$ of eq.(3) obtained from:* **a)** *— least-square fit using eqs.(4)-(6) with constants in table 1, and* **b)** *— splinc-interpolation with parameters in table 2*

Results of the least-square fit are shown in fig.4. The determined from the fit constants a_1, a_2, b_1, b_2, α and β are listed in table 1. To consider the detailed behaviour of $a(Z)$ and $b(Z)$ a spline interpolation combined with a linear extrapolation for $Z > 92$ was made. The obtained coefficients $a(Z)$ and $b(Z)$ are listed in table 2. The fit of the parameters of the function (3) was satisfying the condition of matching with the function (2) at $E = 0.21$ MeV/amu, where approximate equality $f_1(E) \simeq f_2(E,Z) \simeq 1$ was fulfilled (see figs.2,3 also).

Combining (2) and (3) the correction function to the formula of Shima et al. [4] could be expressed as

$$R(E,Z) = k f_1(E) + (1-k) f_2(E,Z), \quad \text{where} \quad k = \begin{cases} 1, & E \geq 0.21 \\ 0, & E < 0.21 \end{cases} \quad (7)$$

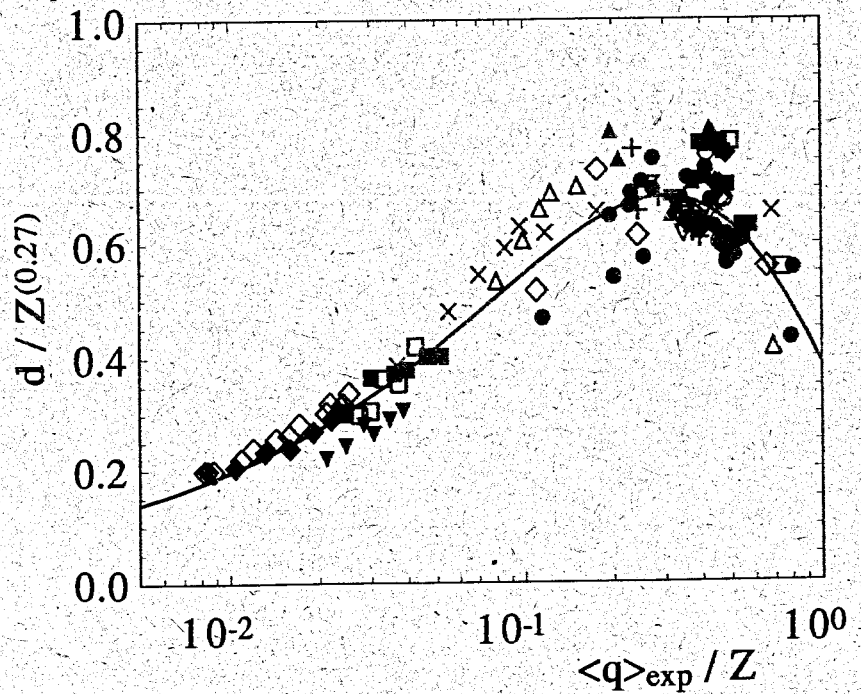

Fig.6. *Systematics of the charge distribution width (symbols are the same as in fig.1). The solid line is the result of least-square fit using eq.(8) with constants in the text*

Table 2. *Spline interpolated parameters $a(Z)$ and $b(Z)$ in eq. (3). Linear extrapolation is used for $Z > 92$*

Z	$a(Z)$	$b(Z)$	Z	$a(Z)$	$b(Z)$
53	1.0000	0.0000	82	1.2847	0.1605
54	1.0156	9.640×10^{-3}	83	1.2889	0.1625
55	1.0308	1.909×10^{-2}	84	1.2899	0.1629
56	1.0455	2.814×10^{-2}	85	1.2881	0.1619
57	1.0592	3.661×10^{-2}	86	1.2839	0.1598
58	1.0718	4.430×10^{-2}	87	1.2775	0.1566
59	1.0829	5.101×10^{-2}	88	1.2693	0.1525
60	1.0921	5.653×10^{-2}	89	1.2597	0.1477
61	1.0989	6.052×10^{-2}	90	1.2491	0.1424
62	1.1025	6.264×10^{-2}	91	1.2377	0.1368
63	1.1024	6.253×10^{-2}	92	1.2260	0.1310
64	1.0979	5.984×10^{-2}	93	1.2142	0.1251
65	1.0888	5.456×10^{-2}	94	1.2025	0.1193
66	1.0776	4.803×10^{-2}	95	1.1907	0.1134
67	1.0671	4.193×10^{-2}	96	1.1789	0.1076
68	1.0603	3.795×10^{-2}	97	1.1672	0.1017
69	1.0599	3.777×10^{-2}	98	1.1554	9.591×10^{-2}
70	1.0691	4.308×10^{-2}	99	1.1436	9.006×10^{-2}
71	1.0906	5.554×10^{-2}	100	1.1318	8.422×10^{-2}
72	1.1260	7.596×10^{-2}	101	1.1201	7.838×10^{-2}
73	1.1716	0.1015	102	1.1083	7.254×10^{-2}
74	1.2223	0.1286	103	1.0965	6.670×10^{-2}
75	1.2729	0.1547	104	1.0848	6.085×10^{-2}
76	1.3178	0.1773	105	1.0730	5.501×10^{-2}
77	1.3518	0.1940	106	1.0612	4.917×10^{-2}
78	1.3695	0.2025	107	1.0495	4.333×10^{-2}
79	1.3656	0.2003	108	1.0377	3.749×10^{-2}
80	1.3346	0.1850	109	1.0259	3.165×10^{-2}
81	1.2892	0.1628	110	1.0141	2.580×10^{-2}

Fig.5 illustrates the data of fig.1 (application of formula (1)) corrected with the function (7). A general agreement is achieved for the whole energy range. This agreement is within $\pm$ 6 % for the spline interpolated $a(Z)$ and $b(Z)$ (fig.5b) and slightly worse for these parameters determined by the least-square approximation (fig.5a) at low energies.

We obtained also a new systematics of the charge distribution width. Fig.6 displays the $y = d/Z^{0.27}$ values [15] plotted against $x = < q >_{exp} /Z$ for the available data for $Z \geq 53$. We fitted a function of the form

$$y = Ax^B \exp(-Cx) \qquad (8)$$

to the data, by the least-square method. The best values of the fitting constants were obtained:

$A = 2.10176$, $B = 0.510987$, and $C = 1.68505$.

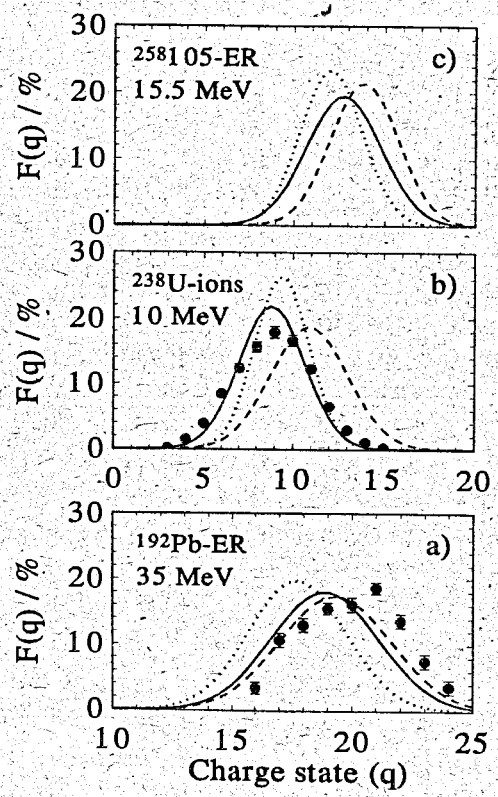

Fig.7. *Some examples of the ionic charge distribution. Experimental data [2, 16] are shown as filled circles, our predictions using eqs.(1)–(8) are shown with solid lines, calculations by Nikolaev and Dmitriev [3] are shown with dotted lines and calculations by Shima et al. [4, 15] are shown with dashed lines*

The presented systematics of the mean charges and the charge distribution widths were used to predict ICD for some heavy ions and ER. The predicted distributions are shown in Fig.7 along with similar ones obtained from the other predictions [3, 4, 15] and some experimental distributions for ER [2] and U-ions [16] passing through a carbon foil. The correction for $< q >_{SIM}$ is small for the Pb ER. Because of this, the ICD is nearly the same as the predicted one given by the formula (1) [4] and width systematics [15]. Being necessary to obtain a good agreement with the experimental data [16], our correction is significant for heavier ions. Without this correction the predicted ICD [3, 4, 15] deviate considerably from the experimental ones [16].

Present estimations of the ICD are used for the computer simulation of the ER's transportation through the electrostatic recoil separator VASSILISSA [6]. A good agreement was achieved between the calculated and experimental transportation efficiencies for the Po – Ac ER in the investigated energy region of 10 – 40 MeV [17]. Carring out the experiments on synthesis of $^{258}105$ in the reaction $^{27}Al(^{236}U,5n)$ [18], the showed ICD for the $^{258}105$ (fig.7c) was used for the optimization of the separator parameters.

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