Charge state distributions of heavy ions passed through a solid medium have been under study for a long time (see review [1]). The charge state of an energetic ion moving in matter is mainly determined by the balance between capture of electron(s) from media atoms and loss of electron(s) by the ion. Complications in the description of charge-exchange processes are connected with the effect of multi-electron losses, appearance of meta-stable excited states, Auger and radiative transitions in the excited multi-electron system of the moving ion. Such complexity is the reason why a large body of collected experimental data exist along with a lack of theoretical models, and one has to use empirical formulas in practice (see Refs in [1]). Complexity of charge-exchange processes is doubled when we consider the charge state distribution of heavy evaporation residues (ER) produced in nuclear reactions. Excited nuclear states strongly affect the ionization of inner atomic shells due to the conversion of nuclear transitions in ER (see [1] and Refs therein). The vacancies formed by the conversion of inner shells of ER ionized atoms lead to Auger cascades, which significantly increase the ion charge states over the expected equilibrium values. It leads to asymmetric charge state distributions shifted to higher values of the charge relatively to the equilibrium distributions. For the first time such distributions were observed for near-earth atoms of ER as early as in 1963 [2].

In our study of complete fusion reactions $^{12}$C + Pb [3] and $^{16}$O + Au [4], the electrostatic deflector [5] was used for the measurements of production cross sections for Ra and Fr ER, respectively. A maximal yield for Ra ER was observed at a strength electric field in the range corresponding to the mean equilibrium charges estimated from various systematics (see Refs in [1]). The maximal yield for Fr ER was observed at the strength of 2–3 times less than one could expect from the same charge systematics. Such a difference can be uniquely explained by the different sets of charge states for ER atoms emerging the Pb and Au target. A more detailed study of these observations revealed a two-humped character of the yield curves as a function of the strength of electric field for specific Ra and Fr isotopes, which implies a dominance of the only component (equilibrated or nonequilibrated one) [6]. In continuation of this work we started to analyze similar curves for heavy-mass ER produced in different fusion-evaporation reactions according to statistical model calculations) transmission through the deflector reproduces the observed yields with the adjusted parameters of the charge state distribution. Common $\sigma$-widths $\Delta Q = 1.1 Q_{eq}$ [8] are used in these simulations. The most probable values $Q_{1}$ expressed in units of the corresponding parameters $Q_{eq}$ for the equilibrium distribution [8] are shown in the figure. $Q_{1}$ values deduced from the simulations are comparable with the corresponding charges derived with our 3-component LogNormal function fit to the $^{197}$Pb charge state distribution obtained in the $^{158}$Gd ($^{40}$Ar,6n) reaction with a magnetic spectrograph [9] (right panel). Note that both these data sets correspond to $Q_{1} = 0.9 Q_{eq}$ and $\Delta Q = 0.9 Q_{eq}$, i.e., the values predicted by various systematics for an equilibrium charge distribution (see Refs in [1] and [8,10]). The additional ionization of atoms can been also included in the analysis whose aim is to obtain and to systemize main parameters of charge state distributions for ER atoms produced in fusion-evaporation reactions. This can help in the development of models describing variations of charge states of excited heavy atoms produced in experiments, otherwise it could be useful in further fusion experiments with electro-magnetic separators.
be expressed via the most probable charges as \( q_1 = Q_{m2} - Q_{m1} \) and \( q_2 = Q_{m3} - Q_{m2} \). The most probable \( q_i \) values obtained in our analysis are close to the average charges resulting from a sudden vacancy in the \( K, L \) and \( M \) shells as was estimated in [11] for Pb.

![Graph](image)

**FIG. 2.** The most probable charge values for equilibrated and non-equilibrated components of the Tb–Ho ER charge state distributions obtained in various fusion-evaporation reactions [1,2,9] as a function of their relative velocity (symbols) are shown in upper panel. Relative contributions of these components are shown in bottom panel. The most probable equilibrium charge values corresponding to systematics (see Refs in [1] and [8,10]) are also shown for comparison (lines).

We used a 2-component LogNormal function fit to the charge state distribution data for Tb to Ho ER produced in various fusion-evaporation reactions [1,2,9] in order to extract main parameter values relating to the equilibrated and non-equilibrated components of distributions. Earlier, this approach was successfully applied to the analysis of the transmission (yield) curves as a function of the strength of electric field for Ra and Fr atoms [4,6]. The results of our analysis are shown in figure 2, where the most probable equilibrium/non-equilibrium charges and their relative contributions to the observed distributions are plotted as a function of the relative ER velocity \( V/V_0 \) (where \( V_0 \) is the Bohr velocity). The most probable equilibrium charge values derived in our analysis are close to those predicted by various systematics (see Refs in [1] and [8,10]) as shown in the upper panel. As one can see in the bottom panel, the equilibrated component amounts to less than 30% of the total observed charge state yield, as it follows from the results of our analysis. Non-equilibrium charge states corresponding to the additional ionization (expressed, as in the previous case, via the most probable charges as \( q = Q_{m\text{neq}} - Q_{m\text{eq}} \)) reveal the most probable \( q = 5–9 \). These values are similar (within error bars) to the average charges resulting from a sudden vacancy in the \( K, L \) and \( M \) shells as was estimated in [11] for \( Z = 65–67 \). Our analysis unambiguously shows that the contribution of the non-equilibrated component to the observed charge distributions amounts to \((70–96)\%\) and this value does not depend on the velocity of ER, as is clearly seen in figure 2 (bottom panel). The last statement is in contrast to the conclusion on the growth of the additional ionization with the velocity of ER atoms [9], which is based on the systematics of the average ionic charge of nuclear reaction products. Bearing in mind very high charge states of actinide atoms at low velocities [12,13], one might suggest that the additional ionization of ER atoms is determined by the presence of delayed \( \gamma \)-transitions (short-lived isomeric states) in ER and by their conversion that forms vacancies in the \( K, L \) and \( M \) shells of atoms.

The remaining LNL data on the yields of ER (\( Z_{CN} = 70–86 \)) in dependence on the strength of electric field are now under analysis.

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