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# Reaction between $^{238}$U and $^{238}$U at 7.42 MeV/Nucleon

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Inclusive measurements have been performed for the charge, kinetic-energy, and angular distributions of reaction products from $^{238}$U + $^{238}$U at 7.42 MeV/nucleon. Fission of one or both colliding nuclei is found to dominate. For the surviving U-like fragments, more particle diffusion at a given energy dissipation is observed than in other systems. A search for the production of superheavy elements has yielded an upper cross-section limit of $2\times10^{-32}$ cm$^2$.

The mechanism of nuclear reactions between very heavy ions is of great current interest.[1-4] We have used the U beam available at the Unilac in Darmstadt to extend such studies to the U+U system. Our motivation has been twofold: (1) to investigate the gross features of the reaction products associated with their charge, total-kinetic-energy, and angular distributions; and (2) to learn about the prospects of synthesizing superheavy elements in this reaction. In this Letter we report on first results of single-particle-inclusive measurements. For U-like fragments surviving fission, we also present an observed correlation between the total-kinetic-energy loss and the amount of nucleon transfer ("diffusion") with a slope much smaller than that observed previously for other systems.[4]

The experiments were performed with a U beam of 7.42 MeV/nucleon and $10^{10}$ particles/s on a sputtered target of 450 $\mu$g/cm$^2$. Charge and energy distributions of the reaction products were analyzed in a three-section ionization chamber[5] with a $Z$ resolution of effectively $\Delta Z/Z\approx 1/50$. Details of the $Z$-calibration procedure are given elsewhere.[6] During the run, the chamber was moved in steps of 3° (equal to the acceptance angle) within lab angles of 28°–52°, a finer angular division being possible by the measured time difference between the anode and cathode signals. On the other side of the beam at the relative angle of 86° to the ionization chamber a large surface-barrier detector with an acceptance angle of 16° allowed the detection of kinematic coincidences for binary events. This detector was additionally gated in between macropulses of the Unilac (2–20 ms) to search for $\alpha$ and spontaneous-fission activities of implanted recoil nuclei. A Ge detector was located immediatedly behind the latter detector to measure possible $\alpha$–x-ray coincidences.

The charge distribution of the single reaction products, integrated over all energies and lab angles 32.5°–44.5°, is shown in Fig. 1. Several striking features are immediately obvious. The

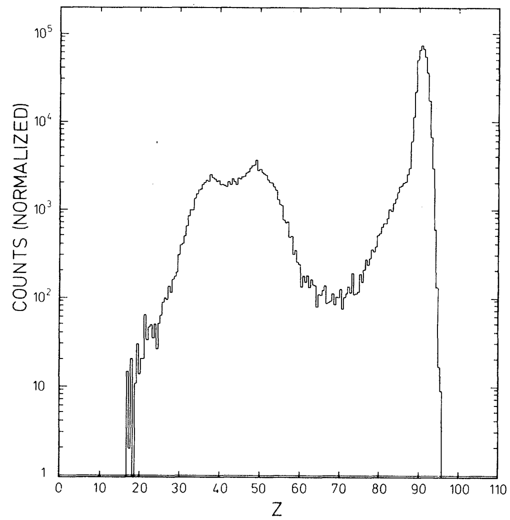


FIG. 1. Charge distribution of single reaction products formed in U+ U at 7.42 MeV/nucleon integrated over all final kinetic energies and laboratory angles 32.5°–44.5° relative to the beam. The intensity ratio between the fission-fragment component and the rest does not resemble the ratio of the total cross sections because of the very different angular distributions.

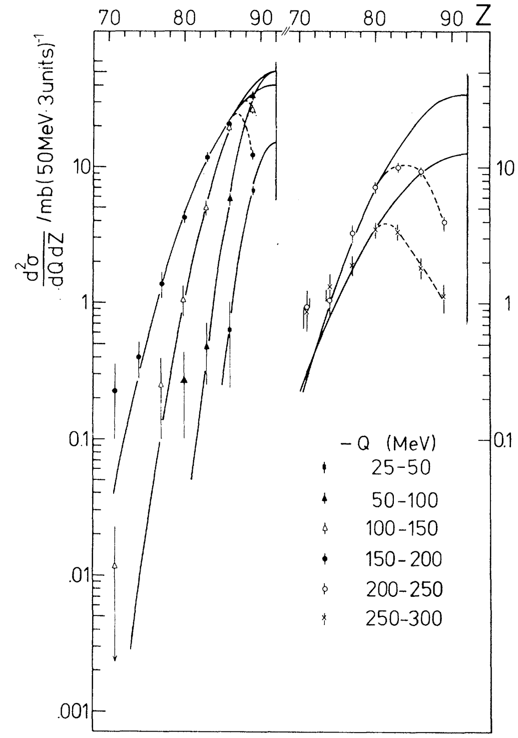


FIG. 2. Double-differential cross section of U-like fragments as a function of $Z$ and $Q$ value, integrated over c.m. angles 56°–90°. The full lines are Gaussian functions centered at U. Deviating data points are connected by dashed lines (see text). The error bars reflect the purely statistical uncertainties.

fragmentation around U is extremely asymmetrical. Within the $Z$ resolution, no events at all are found beyond the near-U environment. Below U, the element yield decreases monotonically, more reminiscent of Xe + U[7] than of Kr + U[8] where a very pronounced maximum at Au was observed (at forward angles our data actually show a slight maximum around $Z \approx 88$). The region $30 \lesssim Z \lesssim 60$ of conventional fission fragments contains the major fraction of the total cross section; the double-humped nature of this part indicates a large contribution from fission at rather low excitation energies (see below).

We interpret the observed shape of the charge spectrum as being due to the superposition of essentially three components: (1) the quasielastic events around U, (2) the elements with $70 \lesssim Z \lesssim 90$ arising from an originally symmetric distribution in the binary fragmentation of the U + U complex and then surviving the competition between fission and neutron evaporation during the deexcitation process, and (3) fission fragments with $Z \lesssim 70$ arising from sequential fission of the primary fragmentation, which then accounts both for the absence of nuclei above U and the slight shoulder around $Z \approx 88$. The second component thus represents primarily ternary events, and the third the sum of ternary and quarternary events.

This interpretation is qualitatively supported by the angular distributions.[6] The energy-integrated differential cross section for the region $70 \leqslant Z \leqslant 90$ exhibits a maximum at lab angles of ~ 45° and a width $\lesssim 20°$ full width at half-maximum (FWHM) with some tendency to broaden for smaller $Z$, pointing to angular focusing not quite as strong as observed[1-4] for other heavy systems at bombarding energies $< 1.5V_B$. The third component, on the other hand, hardly depends on angle, compatible (also in energy) with the much wider distribution in angular space expected for a sequential process with an additional $Q$ value of about + 200 MeV due to fission.

The double-differential cross section as a function of $Z$ and $Q$ value (total-kinetic-energy loss) integrated over c.m. angles 56°–90° is displayed in Fig. 2. The conversion into the c.m. system has been performed by an iterative procedure,[6] assuming a binary fragmentation and correcting for neutron emission dependent on $Q$. As found before in other heavy systems,[1-4] the transfer of more than a few nucleons away from U is accompanied by large energy damping, well separated already for $Z=90$ from any quasielastic events. Taking account of the ratio $\Gamma_n/\Gamma_f$ decreasing with increasing $Z$ and (for fixed $Z$) increasing excitation energy, the qualitative appearance of these distributions with maxima shifting away from U for more negative $Q$ values is readily understood: The fission competition cuts in close to U, and only the tail on the left-hand side of the distributions resembles the primary yield.

Although a much more quantitative analysis will have to be made in the future including the detailed influence of the angular-momentum transfer,[6] we have nevertheless made a preliminary attempt to reconstruct the primary charge distributions assuming (1) the distributions to be unshifted, i.e., no charged particles have been emitted, (2) the yields for $Z \leq 89$, 83, 80 with energy losses $-Q \leq 100$, 200, 300 MeV, respectively, to be essentially undistorted by fission, and (3) Gaussian functions centered at U to represent the original distributions[1-4,9] which were then fitted to these yields. Assumption (2) can be justified with data from fission induced by light projectiles[10]: In the $\alpha$ + Pb reaction a fission probability of 0.1 has been determined for $Z=84$ at an excitation energy of 100 MeV—corresponding, in our case, to a $Q$ value of $-200$ MeV (equipartition of the energy). From the reconstruction, a total cross section for the damped component of $850 \pm 50$ mb (surviving part $230 \pm 20$ mb) is obtained, equivalent to a fraction 0.5 of the total reaction cross section of $1.63 \pm 0.11$ b deduced from the quarter-point angle $\theta_{1/4}{}^{\text{c.m.}} = 87.5° \pm 2°$ of the elastic scattering.[6] A slightly smaller ratio of 0.4 has been arrived at independently by the analysis of the total fission cross section[11] at the lower average beam energy of 6.82 MeV/nucleon.

If we accept this reconstruction, we can correlate the average $Q$ value for each charge distribution with its variance $\sigma_Z^2$ as shown in Fig. 3. A monotonic relationship between energy dissipation and particle diffusion is obtained, but surprisingly with an initial slope much smaller than that observed previously for a variety of other systems.[4] The difference (about a factor of 3) appears to be far too large to be solely caused by strong violations of our assumptions (1) and (2). One can, at present, only speculate about the origin of this effect. In the framework of the recent diffusion model,[9] it may point to larger particle-diffusion coefficients and/or longer interaction times, since the width of the energy-integrated charge distribution of ~11 charge units FWHM (compatible with 30 mass units[11]) is also larger

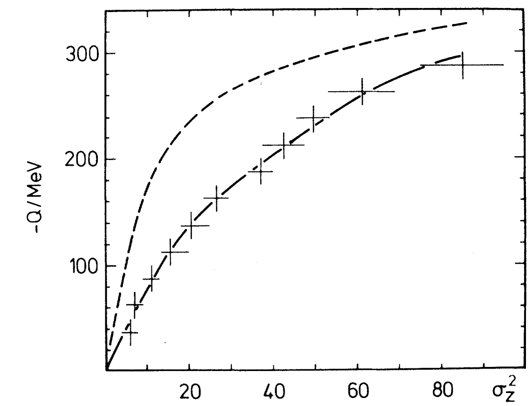


FIG. 3. $Q$ value (in 25-MeV bins) as a function of the variance $\sigma_Z^2$ of the reconstructed charge distributions of the U-like fragments shown in Fig. 2. The dashed line shows the relation of $Q$ vs $\sigma_Z^2$ obtained for the reactions $^{84}$Kr + $^{165}$Ho, $^{84}$Kr + $^{209}$Bi, $^{136}$Xe + $^{165}$Ho, and $^{136}$Xe + $^{209}$Bi (Ref. 4).

than in other systems.[1,4,7,8] In any case, nucleon-transfer processes seem to proceed "colder" in this reaction than in the others, i.e., given elements in the U environment are produced at smaller average excitation energies. This may explain the more pronounced fission competition in Kr + U[8] and may also contribute (apart from the difference in $N/Z$) to the enhancement of transuranium yields by up to several orders of magnitude in U + U[11] compared to Kr + U and Xe + U.

Our direct search for superheavy elements produced in U + U has thus far been negative, although off-line counting of any activities deposited in the large surface-barrier detector has continued for many weeks. All $\alpha$ transitions observed[6] could be identified as due to known isotopes between Pb and Th, although the data are by far not as detailed as those obtained by chemical separation techniques.[11] No single spontaneous-fission event has been found, corresponding to an upper cross-section limit of $2 \times 10^{-32}$ cm$^2$ for a half-life window of milliseconds to months. This negative result can be illustrated with a rough estimate of the cross section to be expected[6] for the island $112 \leq Z \leq 114$. Based on the measured yields (Figs. 1, 2) of the partner elements $70 \leq Z \leq 72$, corrected for tails from the fission-fragment background, we assumed (1) a Gaussian extrapolation of the $Q$-value distribution down to small $Q$ values, (2) a partition of the available excitation energies according to the masses, and (3) (3) multiple-chance-fission competition with calculated $\Gamma_f/\Gamma_n$ ratios.[10] Folding the excitation energy distribution into the survival probability, a value of $10^{-32}$ cm$^2$ is obtained, consistent with the experimental limit mentioned above. Although a similar estimate for Cf isotopes reproduces the experimental order of magnitude of $\sim 10^{-29}$ cm$^2$,[11] the number deduced may only represent an upper limit because of the influence of angular momentum and deformation on the survival probability. It nevertheless appears not to be totally discouraging.

In summary, nuclear reactions of U+U are dominated by fission of U-like fragments. The analysis of the surviving part of the binary fragmentation seems to indicate smaller energy dissipation for the same amount of particle diffusion compared to other systems—a feature highly desirable for the synthesis of heavy elements.

The authors want to express their gratitude to the staff of the Unilac for providing the extremely stable U beam. The assistance of the on-line group during the data analysis is gratefully acknowledged.

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# Formation of Negative Ions in Magnetic Fields

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It is argued that the negative helium ion exists in magnetic fields. Similarly, nontrapping isoelectronic impurities in semiconductors trap with magnetic fields. Crude estimates of binding energies are given.

It is well known that a shallow square well will bind in one dimension but not in three. Here we wish to point out an elementary but striking consequence of this fact which affects the physics of atoms in magnetic fields. The new states which we discuss for He$^-$ and other ions might make chemistry in strong magnetic fields quite different from conventional chemistry and should be considered in study of stars with large magnetic fields and large concentrations of helium. These states will also have analogs in isoelectronic impurities in solids.

Because of a combination of polarization effects and imperfect shielding, the interaction between a neutral atom and an extra electron is attractive, but as this is the analog of the three-dimensional well, a negative ion will form only if the attraction is sufficiently strong. For example, the common belief is[1] that noble gases do not have stable negative ions.[2,3]

As distinct from this, constant magnetic fields confine electrons in two dimensions in cyclotron orbits so that the net attractive force will produce a situation analogous to the one-dimensional well, i.e., binding of the electron in the third dimension as well as "tying down" the center of the cyclotron orbit.

In fact, it is not very hard to show[4] that if $V$ is, for every $\epsilon > 0$, the sum of an $L^2$ function and a function bounded in absolute value by $\epsilon$, a sufficient condition for the Hamiltonian[5]

$$H = (2m)^{-1}(\vec{p} - \vec{A})^2 + V(\vec{r}), \text{ with } \vec{A} = \tfrac{1}{2}\vec{B} \times \vec{r}, \qquad (1)$$

to have bound states is that $\int V(\vec{r})\, d^3r < 0$ or that outside some ball $V(\vec{r}) < 0$. [To see this, use a trial wave function of the form $\varphi_\lambda(x, y) f(z)$, for