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Authors

Sikkeland, Torbjorn
Clarkson, Jack E.
Lebeck, Donald F.
et al.

Publication Date

1966-04-01

UCRL-16773

University of California

Ernest O. Lawrence Radiation Laboratory

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Berkeley, California

Journal of Inorg. and Nucl. Chem. Letters

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AEC Contract No. W-7405-eng-48

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In the region of the hypothetical shells at $Z = 126$ and $N = 184$, the fission barriers, after becoming vanishingly small, rise once again to values of several MeV,(1) making these nuclei more stable against decay by spontaneous fission. Such nuclei might be produced in interactions between complex nuclei in which the cross sections are proportional to the ratio $\Gamma_n/(\Gamma_n + \Gamma_f)$, where Γ_n and Γ_f are the level widths for neutron emission and fission, respectively. This ratio increases with increasing fission barrier.(2,3) Hence, the possibility arises of producing these super heavy nuclides in sufficient quantitities for identification.

Although the existence of these magic numbers is rather questionable,(1) a quantitative evaluation of the cross sections for various production schemes is justified on the gound that it might be a guide in future experiments in the field.

These superheavy nuclei are possible products in the following three types of reactions:

1. Fission following a fusion of two heavy nuclei such as $^{238}U + ^{238}U \rightarrow {}^{476}184$ (fission).

This scheme has the attractive feature that the products represent a wide variety in Z and N numbers. At low excitation, nuclides might be produced preferentially in the region of the next double magic numbers irrespective of what these numbers might be. Here the cross sections could be of the order of 10^{-29} cm^2 (assuming the fusion cross section to be of the order 10^{-27} cm^2 and the fission yield of a particular nucleus to be of the order of one per cent).

2. Grazing reactions, in which nucleons are interchanged between target and ion nuclei.

No model exists for this mechanism from which spallation yields can be predicted. By extrapolating experimental results, involving relatively light ions and targets(4) we deduce the cross sections for the production of nuclei in the neighborhood of Z = 126 and N = 184 to be less favorable for this type of reactions than for the spallation reactions discussed as type 3 below. However, for production of more neutron rich nuclei, grazing reactions might be feasible and their cross sections comparable to those of fusion-fission described as type 1.

3. Complete fusion of target and ion nuclei followed by neutron evaporation.

This type of reactions shall be considered in some detail for the following three systems:

$$^{252}\mathrm{Cf}\,(^{60}\mathrm{Ni},\ xn)^{312-x}126$$

$$^{232}\mathrm{Th}(^{80}\mathrm{Kr},xn)^{312-x}126 \qquad (1)$$

$$^{180}\mathrm{Hf}(^{132}\mathrm{Xe},xn)^{312-x}126$$

where x represents the number of neutrons emitted. In all three cases, isotopes of element 126 with mass numbers around 310 are formed. These combinations have been chosen to show the effects of Z of the ion on the yield of the products. Furthermore, they should be representative for production schemes leading to nuclides in the neighborhood of the double shells.

As a basis for the calculation of the cross sections, the Jackson formula,(5) modified for fission competition(6) and angular momentum effects,(7) will be used:

$$\sigma_x = \prod_{i=1}^{x} \Gamma_n/(\Gamma_n + \Gamma_f)\ i \sum_{\ell=0}^{\ell_c} \sigma_\ell P_{x,\ell} \qquad (2)$$

where decay modes other than neutron evaporation and fission have been ignored. A brief outline of the definitions and calculations of the terms in equation (2) follows in part a through d.

a. Values for $\Gamma_n/(\Gamma_n + \Gamma_f)$ were computed from the formula for Γ_n/Γ_f as given in reference 2. It is assumed that this ratio is independent of the excitation energy, E, and angular momentum, ℓ, of the nucleus.

b. The quantity σ_ℓ, is the cross section for the ℓth partial wave of the incident ion, and is given by:(8)

$$\sigma_\ell = \pi \lambda\!\!\!^{-2}(2\ell + 1)T_\ell \qquad (3)$$

where $\lambda\!\!\!^{-}$ is the de Broglie wavelength of the projectile, and T_ℓ is the transmission coefficient of the wave. In the estimation of T_ℓ we used a parabolic approximation(9) to the real part of the effective optical model potential with the following parameters: $V_o = -70$ MeV, $r_o = 1.25$ fermis and $d = 0.44$ fermis.(10)

c. The last term in equation (2) is the probability of boiling out exactly x neutrons and is estimated from the formula:(5)

$$P_x = I(\Delta_x, 2x-3) - I(\Delta_{x+1}, 2x-1), \text{ where}$$

I(Z,n) is the incomplete gamma function and

$$\Delta_x = (E_{cm} + Q - \sum_0^x Bi - E_R)/T \qquad (4)$$

$$\Delta_{x+1} = (E_{cm} + Q - \sum_0^{x+1} B_i - E_R)/T$$

Here E_{cm} is the center-of-mass kinetic energy of the ion, Q is the mass difference in MeV between the interacting nuclei and the nucleus formed in a CF (complete fusion) process, B_i is the binding energy of the ith neutron in the cascade, E_R is the rotational energy of the system and T is the nuclear temperature. Values for nuclear masses and for B_i were taken from references 1 and 11. For the parameter T, we used the value 1.3 MeV independent of E.(2,6)

The rotational energy is calculated from the equation:

$$E_R = \hbar^2 \ell(\ell + 1)/2\Im \qquad (5)$$

where $\Im$, the moment of inertia, was rather arbitrarily taken to be equal to that of a spherical rigid body. In equation (5), we have ignored the angular momentum carried off by an evaporated neutron. The summation in equation (2) is cut off at a value ℓ_c of ℓ that is the lowest of either of the two values estimated from the following two equations:

$$\hbar^2 \ell_c(\ell_c + 1)/2\Im = E_{cm} + Q \qquad (6)$$

$$\sum_{\ell_c}^{\infty} \sigma_\ell \Big/ \sum_{0}^{\ell_c} \sigma_\ell \;=\; \sigma_{ICF}/\sigma_{CF} \cong 0.03\ A_I \qquad (7)$$

where $\Im$, E_{cm}, and Q are defined above and A_I is the mass number of the ion.

The physical interpretation of the cut-off value in equation (6) can be given as follows:

The term on the left side of equation (6) represents the lowest value of the rotational energy, E_R, for the nucleus at an angular momentum ℓ_c. That on the right side represents the excitation energy E. Hence, for $\ell > \ell_c$, E_R would exceed E which is physically impossible. Here, even though the whole ion is transmitted through the barrier, a complete fusion is prohibited since there are no states available in the compound nucleus.

The cut-off value in equation (7) is a consequence of ICF (incomplete fusion) reactions that take place from the highest ℓ - waves (from ℓ_c and up) of the incoming projectile.(12) This equation is purely empirical and is based on results from bombardments of ^{238}U with ions of 10.4 MeV/ nucleon in which the ratio σ_{ICF}/σ_{CF} was found to be 0.33,(13) 0.43,(13) 0.72(13) and 1.0(14) for ^{12}C, ^{16}O, ^{20}Ne, and ^{40}Ar, respectively. It is then further assumed this ratio is independent of ion energy.

The calculations were performed on an IBM 7094 computer. The results are summarized in Table 1 where we have listed the maximum values for σ_x, the corresponding bombarding energies E_m, and the FWHM of the peaks in MeV. The calculations have not been extended past four neutrons. For comparison, we have also included in Table 1 values for the same quantities for the systems:

$$^{152}\mathrm{Sm}(^{48}\mathrm{Ti},xn)^{200-x}\mathrm{Po}$$

$$^{116}\mathrm{Cd}(^{84}\mathrm{Kr},xn)^{200-x}\mathrm{Po}$$

For these reactions, the final products are α emitters whose decay properties are fairly well known. Hence, the predicted values of Table 1 should be tested for these products.

One interesting feature of the system (Hf + Xe) is the relatively low excitation energies at bombarding energies that correspond to the barrier. A consequence of this is the possibility of observing nuclei formed in a CF reaction followed by γ de-excitation only. Such a reaction takes place when E is less than $(B_n + E_R)$ and its cross section, σ_γ, is given by:

$$\sigma_\gamma = \sum_0^{\ell_c} \sigma_\ell - \Sigma\sigma_x \qquad (8)$$

where the first and last terms are the total cross sections for CF reactions and neutron out reactions, respectively. Values for σ_γ and E_m for this system are shown in Table 1. The values for σ_γ for the other systems are several orders of magnitude lower and have thus not been listed.

As is seen from Table 1, most of the cross sections are of the order of 10^{-27} cm^2 (mb). This is to be compared to a cross section of the order of 10^{-30} cm^2 for production of 102 isotopes by the use of heavy ions.(15,16) In the latter cases, ion intensities of 10^{-7} particle amperes were found to be sufficiently high for identification of α emitters when target thicknesses of about 500 μg/cm^2 were used. For the systems listed in Table 1, due to larger ranges of the recoils, even thicker targets can be employed. Consequently, ion currents as low as 10^{-10} particle amperes can be useful in initial experiments in this very interesting region.

Krypton ions have been accelerated at the Berkeley HILAC and it is hoped that the very small beam observed can be increased to a value sufficiently high to be able to start exploratory experiments soon. In addition to this possibility a new direction is under study at Berkeley in the form of a unique accelerator concept called the Omnitron. This unusual accelerator will make possible the acceleration of all atoms in the Periodic System to energies as high as 400 MeV per nucleon and will thus make possible a wide range of experiments in many fields.

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TABLE 1. ANALYSIS OF CALCULATED EXCITATION FUNCTIONS FOR THE ISOTOPES $^{312-x}126$ AND $^{200-x}\mathrm{Po}$.

System	Spallation Product	Peak Cross Section (mb)	Ion Energy (MeV)	MeV Nucleon	FWHM (MeV)
$^{180}\mathrm{Hf} + {}^{132}\mathrm{Xe}$	$^{312}126$	95	708	5.4	42
	$^{311}126$	77	734	5.6	36
	$^{310}126$	64	754	5.7	43
	$^{309}126$	59	773	5.9	53
	$^{308}126$	60	794	6.0	63
$^{232}\mathrm{Th} + {}^{80}\mathrm{Kr}$	$^{311}126$	0.4	436	5.4	
	$^{310}126$	19	441	5.5	12
	$^{309}126$	53	452	5.6	17
	$^{308}126$	69	471	5.9	26
$^{252}\mathrm{Cf} + {}^{60}\mathrm{Ni}$	$^{311}126$	2×10^{-3}	344	5.7	8
	$^{310}126$	1	346	5.8	9
	$^{309}126$	22	350	5.8	13
	$^{308}126$	65	366	6.1	26
$^{116}\mathrm{Cd} + {}^{84}\mathrm{Kr}$	$^{199}\mathrm{Po}$	3×10^{-4}	330	3.9	8
	$^{198}\mathrm{Po}$	2.3	331	3.9	13
	$^{197}\mathrm{Po}$	50	341	4.1	25
	$^{196}\mathrm{Po}$	120	366	4.4	36
$^{152}\mathrm{Sm} + {}^{48}\mathrm{Ti}$	$^{199}\mathrm{Po}$	$< 10^{-4}$	--	--	--
	$^{198}\mathrm{Po}$	3×10^{-3}	203	4.2	9
	$^{197}\mathrm{Po}$	2.1	205	4.3	12
	$^{196}\mathrm{Po}$	81	214	4.5	20