Synthesis of Fermium and Transfermium Elements Using Calcium-48 Beam *

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The fragmentation theory is used to suggest possible targets to be used with the ^{48}Ca ion beam produced recently at the JINR U-300 heavy-ion cyclotron. Calculations are made for $100 \leq Z \leq 116$ and are supported by a successful test experiment for the isotope ^{252}102.

1. Introduction

Use of $^{48}_{20}$Ca as a projectile for the production of superheavy elements (SHE) through compound nucleus formation has been cherished in the minds of both experimentalists and theoreticians for nearly $7-8$ years now [1,2].

Following Myers and Swiatecki [3], Flerov [1] estimated the halflife of $Z = 114$ isotopes for various kinds of decays which showed a strongly increasing trend with the increase of neutron number. Based on this result, he suggested to bombard neutron rich targets, such as $^{244}_{94}$Pu, $^{248}_{96}$Cm and $^{252}_{98}$Cf, with a $^{48}_{20}$Ca projectile whose A/Z ratio is rather high. Later on, Nix [2] also suggested to use very asymmetric target-projectile combinations, such as $^{48}_{20}$Ca on $^{250}_{96}$Cm and $^{257}_{100}$Fm, for the production of SHE by means of compound nucleus reactions. His suggestion was based on calculations of the kinetic energy for different nuclear shape configurations using an idealised liquid drop model. Such an experiment was, however, considered to be very expensive, because of the very small (0.19%) content of ^{48}Ca in its naturally occuring element, till very recently [4].

A ^{48}Ca ion beam has recently been produced at the JINR U-300 heavy-ion cyclotron and used succesfully [4] in the synthesis of the isotope ^{252}102 in

reactions with different $^{208, 207, 206, 204}$Pb isotopes. It is shown that the fusion reactions with this projectile lead to the formation of compound nuclei with very low excitation energies $(17-18$ MeV$)$ such that the cross sections are large for the case of emission of a small number of neutrons. The reaction ^{206}Pb$(^{48}$Ca, 2n$)^{252}$102 has the largest cross section of about 5×10^{-31} cm^2 and this value exceeds by a factor of about 40 the cross sections obtained earlier [5] for the reactions ^{239}Pu$(^{18}$O, 5n$)^{252}$102 and ^{235}U$(^{22}$Ne, 5n$)^{252}$102. This value is however still smaller by a factor of about 5, compared to the Berkeley results for the reactions [6] ^{244}Cm$(^{12}$C, 4n$)^{252}$102 and ^{244}Cm$(^{13}$C, 5n$)^{252}$102. An experiment using ^{48}Ca on ^{208}Pb and ^{244}Pb was also proposed to be carried out at Berkeley [7] but we are unaware of its progress.

In this paper, we consider an application of our fragmentation theory [8-10] for suggesting the best possible targets to be used with ^{48}Ca ion beam, for the production of new elements via compound nucleus reactions. Calculations are made for the various isotopes of $100 \leq Z \leq 116$ elements and are supported by the above mentioned experiment for the isotope ^{252}102. The theory is very briefly outlined in Sect. 2 and the results of our calculation are given in Section 3. Our conclusions are summarized in Section 4.

2. The Theory

The details of our theory are given in References [8-10]. It is based on the experimental result [4,11] that for a compound nucleus formed with a minimum of excitation energy, the number of neutrons emitted would be small and consequently the cross section for the formation of the nucleus in the

ground state would be large. Since a compound system can be reached by various projectile-target combinations, the excitation energy of a given compound system is calculated in our theory for all the possible combinations. Using the asymmetric two-center shell model [12, 13], the nuclear shape is defined in terms of five coordinates: the relative distance R, the collective surface coordinates or the deformations β_1 and β_2 of the individual nuclei, the neck parameter ε, and the mass or charge fragmentations

$$\eta = \frac{A_1 - A_2}{A_1 + A_2} \quad \text{and} \quad \eta_z = \frac{Z_1 - Z_2}{Z_1 + Z_2} . \tag{1}$$

A specimen shape is shown in Figure 1. The parameters ε, β_1, β_2 and η_Z are determined by minimizing the potential energy (calculated with the Strutinsky shell correction method [14]) for a given pair of R and η values. The potential energy surfaces $V(R, \eta)$ calculated in this way for both the asymptotic $(R \geqq R_c)$ and interaction $(R < R_c)$ regions, give the following results. Here R_c is some critical distance at which the two nuclei come in close contact with each other and can be calculated from the empirical relation of Gutbrod et al [15].

Firstly, it is shown that for each compound nucleus deep minima in the potential energy occur at only a few η-values and that these minima are not only stable in η but also no new minima appear after the two nuclei overlap to form a compound system. The important result is that the potential $V(\eta)$ for $R = R_c$ gives already the positions of the minima with respect to η, thereby introducing a very great simplification in the calculations. The potential $V(\eta, R \geqq R_c)$ can be easily computed as

the sum of the Coulomb interaction and the ground state binding energies of the two nuclei

$$V(R, \eta, \eta_z) = (Z_1 Z_2 e^2/R) \tag{2}$$
$$- B(A_1, Z_1) - B(A_2, Z_2)$$

where Z_1 and Z_2 correspond to the minimized $V(\eta_z)$ for each η-value. The minimization in β-coordinates is thus automatically done in this process.

The second important result of our theory is that the Hamiltonian is shown to couple the surface vibrations and the mass and charge fragmentations strongly. This means that any change in η or η_z is associated with a change of nuclear shape and hence a transfer of energy into the surface degrees of freedom. Then apparently if the incoming nuclei lie outside the potential energy minimum, the driving forces $-\partial V/\partial \eta$ and $-\partial V/\partial \eta_z$ according to classical mechanics are non-zero which would make the system run in the direction of the potential minima with a transfer of large amounts of energy into the excitation of the surface vibrations. On the other hand, if the incoming nuclei lie on the potential energy minimum, the driving forces would be zero. The η-dependence of the wave functions is then given by the zero-point motion around the potential minima. Hence, in a central collision, for the compound system reached along the minimum in the potential $V(R, \eta, \eta_z)$, the excitation would be minimum. This method has been used successfully [8, 10] for the optimal choice of projectile-target combinations in cases of $^{254, 256}104$ and $^{258, 260}106$ isotopes and is further applied in this paper to the special case of ^{48}Ca as the projectile.

Finally, since the potential energy minima are related to the shell effects, our theory suggests that
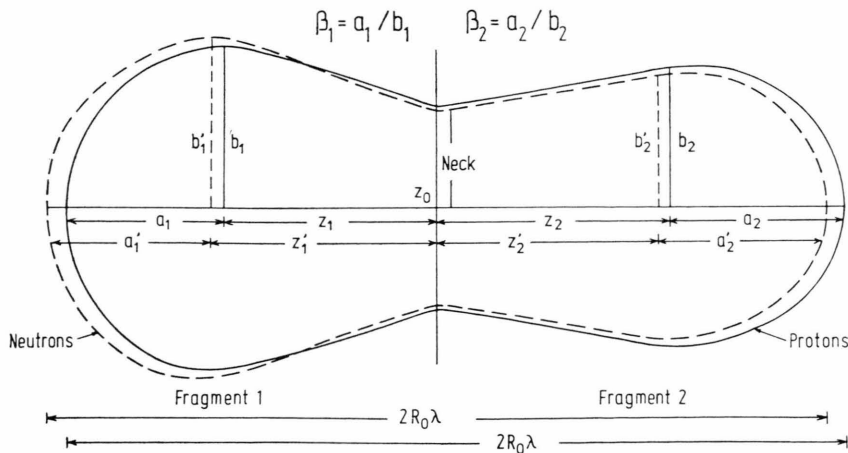

Fig. 1. A sample nuclear shape parametrized in the asymmetric two-center shell model.

the nucleus reacting should be a spherical nucleus. This already supports the choice of Pb-targets used in the experiment [4] on ^{252}102 isotope with ^{48}Ca ion beam.
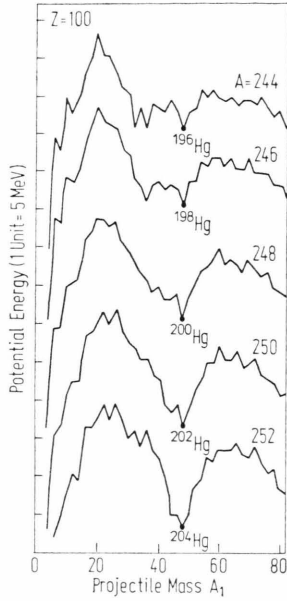
3. Calculations and Results

We have made calculations for various compound systems of $100 \leqq Z \leqq 116$ elements, by using Equation (2). The binding energies $B(A_i, Z_i)$ are taken from Reference [16]. The results of our calculation are shown in Figs. 2 – 5 which give the potential energy as a function of the projectile mass $A_1 = (A/2)(1 + \eta)$, where A is the mass of the compound nucleus (pro-

Fig. 2. Potential energy as a function of the projectile mass A_1 at the relative distance $R \approx R_c$ for various compound nuclear masses (A) with $Z = 100$. The target nuclei relevant to ^{48}Ca projectile are also shown.
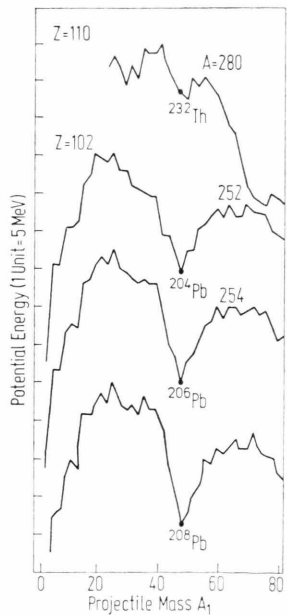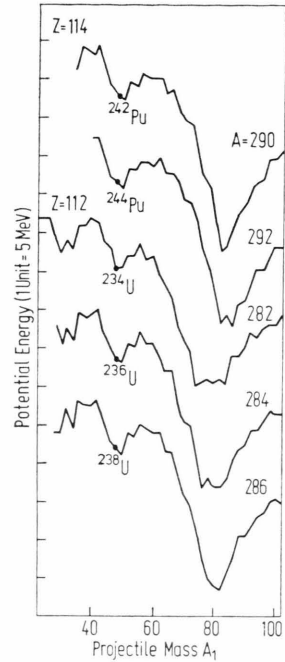

Fig. 4. Same as for Fig. 2, for $Z = 112$ and 114.

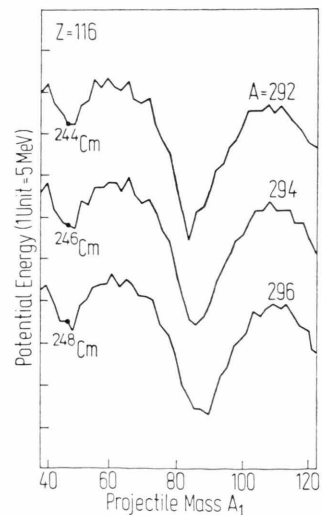
Fig. 3. Same as for Fig. 2, for $Z = 102$ and 110.

Fig. 5. Same as for Fig. 2, for $Z = 116$.

jectile mass + target mass). The associated charges Z_1 and Z_2 for each projectile and target combination are obtained by minimizing V in η_z, as mentioned before. In this paper, since we are interested to look for ^{48}Ca as a projectile, the potential energy surfaces in Figs. 2 – 5 are given only for the region of η in its neighborhood.

It is interesting to find that close to $A_1 = 48$, a single deep minimum occurs in all the potential energy surfaces plotted here. In most of the cases the deepest minima correspond to ^{48}Ca whereas in a few cases ^{48}Ca lies next to the minimum, as shown by a thick dot and the target nucleus isotope in all the figures. For each element, we have made calculations for eight compound systems and find that for the masses heavier than plotted here either the projectile nucleus at the minimum (or next to it) is not ^{48}Ca or the corresponding target nucleus is not stable in nature. On the other hand, for more neutron-deficient isotopes the potential energy surfaces tend to become flat in this region and other new minima start to develop. Secondly, we have given here no plot for the elements 104, 106 and 108 since in these cases the target nuclei to be used with ^{48}Ca projectile are Po, Rn and Ra respectively, which are again unstable in nature and it is very difficult to make these targets.

4. Conclusions

Considering only the nuclei whose targets can be prepared in the laboratory, we find that our theory recommends the target nuclei $^{204, 202, 200, 198, 196}$Hg, $^{208, 206, 204}$Pb, ^{232}Th, $^{238, 236, 234}$U, $^{244, 242, 240}$Pu and $^{248, 246, 244}$Cm to be used with the ^{48}Ca beam for the synthesis of the various isotopes of the elements 100, 102, 110, 112, 114 and 116 respectively. Experimentally, the stable isotopes in the ground state will be obtained after the emission of, say, 2 neutrons. Our predictions apparently include the isotope ^{252}102 which has already been synthesized at the JINR, Dubna laboratory [4]. We might mention here that the ^{48}Ca ion source produced at JINR, U-300 heavy-ion cyclotron can reach energies and intensities required to induce reactions on U, Pu and Cm targets, which are suggested in our calculations. The minimum excitation energies of the compound nuclei in these cases are estimated to be of the order of 20 – 25 MeV where the probability for the compound nuclei to proceed to the ground state with an emission of a small number of neutrons is expected [4] to be finite provided the production cross sections exceed 10^{-35} cm^2 or so.

Finally, we would like to mention that our calculations for the element 102 (Fig. 3) also show that the projectiles ^{18}O and ^{22}Ne used in the earlier reactions at Dubna [5] are unfavorable as compared to the recent use of ^{48}Ca projectiles at Dubna [4] and ^{12}C projectiles used at Berkeley [6].

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