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Heavy ion fusion and the production of 103,105,107 elements

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ABSTRACT: *The synthesis of 103, 105 and 107 elements through heavy ion reactions is discussed in the context of the fragmentation theory by estimating the production cross sections with the help of the statistical model, including fission competition. It is shown that the most favourable target - projectile combinations predicted by theory coincide with the ones already used in the experiments for the production of transfermium elements provided that the critical angular momentum value is determined by the condition of vanishing of the fission barrier.*

1. INTRODUCTION

The production of elements belonging to the transfermium region is one of the most interesting problems in heavy ion fusion reactions. In spite of the difficulties due to the low production cross sections new transfermium elements up to the atomic number $Z = 107$ have been identified and the corresponding cross sections measured. Cross section knowledge is interesting not only for the understanding of the mechanism of reactions leading to these new elements but also for the possibility to extend this method towards higher elements. Therefore, reliable theoretical estimates of the cross sections would be of great help in the synthesis of new elements.

Recent theoretical work based on fragmentation theory brought a new insight into this problem showing that cool compound nuclei can be reached only by few target-projectile combinations which correspond to the bottom of the few fragmentation valleys appearing in the potential energy computed as a function of the relative distance and mass asymmetry (Săndulescu et al. 1976, Zohni 1976, Săndulescu and Greiner 1977, Săndulescu et al 1978). The choice of the reaction partners was further optimized by studying the potential barriers and nuclear shapes at various mass asymmetries. It was shown that the best target-projectile combinations correspond to the largest mass- and charge asymmetries, largest interaction radii and smallest interaction barriers (Gupta et al. 1977). Estimates of complete fusion - and production cross sections of even -

even transfermium elements as for example $^{252}102$ on the basis of the statistical model including fission competition around such a fragmentation valley (Magda et al. 1978) confirmed the conclusions of the fragmentation theory.

In the present paper we study mainly the production of odd-Z transfermium elements $^{253}103$, $^{257}105$ and $^{263}107$ by heavy ion fusion. We show that the potential energies of these nuclei at the touching radii, as a function of mass asymmetry, have three main minima corresponding to three main fusion valleys and that the statistical model including fission competition can satisfactorily describe the experimental data if a critical angular momentum for which the fission barriers are vanishing is introduced. The best target - projectile combinations, for achieving a cool compound nucleus and consequently largest production cross sections, correspond to the largest mass - and charge asymmetries, in complete agreement with the experimental information.

Various isotopes of these elements have been identified in different laboratories ; without intending to exhaust the matter we mention some of the works reporting the synthesis of 103, 105 and 107 elements through heavy ion reactions (Ghiorso et al. 1961, Ghiorso et al., 1970, Flerov et al. 1971, Flerov and Zvara 1971, Oganessian et al., 1976, Oganessian et al., 1976. a) . For identification chemical methods must be used, but due to the low production cross sections and especially very short half-lives, physical methods have been used. One of the methods of identification, which is related to our calculations is the one based on the measurement of the fission half-lives of residual products obtained by fusion of different target - projectile combinations which after neutron evaporation lead to the same nucleus with the same fission half-life. We should like to mention that our estimates of the production cross - sections support this method.

2. CHOICE OF THE BEST TARGET - PROJECTILE COMBINATIONS

Following a procedure established earlier in the frame of the fragmentation theory (Gupta et al. 1977, Săndulescu 1978) a simplified method was employed in order to select the best target - projectile combinations namely those combinations leading to the largest production cross sections.

The method consists of calculating the potential energy surfaces of a given compound system for all possible target - projectile combinations as functions of the mass $\eta=(A_1-A_2)/(A_1+A_2)$ and charge $\eta_Z = (Z_1-Z_2)/(Z_1+Z_2)$ asymmetries, at a given distance (R) close to the one (R_c) corresponding to the touching configuration. For the asymptotic region defined by $R > R_c$, the potential energy is given by the following simple expression :

$$V(R,\eta,\eta_Z) = \frac{Z_P Z_T e^2}{R} - B(A_P,Z_P) - B(A_T, Z_T) \qquad (1)$$

The first term in eq. (1) represents the Coulomb energy and B(A,Z) are the ground state binding energies of the interacting nuclei.

It was demonstrated in earlier works (Gupta et al. 1977 , Săndulescu 1978) that the general behaviour of the potential energy is changing smoothly with the distance, the valleys appearing in the potential energy being stable in η . Therefore the results are independent on the choice of R, which was taken approximately equal to the fusion radius, for the calculation of which an empirical relation was used (Gutbrod et al. 1973).

The potential energies (1) for all possible combinations of the target and projectile nuclei leading to the same compound nucleus were calculated and the results are given in the upper parts of the figures 1 - 3 for compound nuclei $^{253}103$, $^{257}105$ and $^{263}107$. Only the most favourable combinations consisting of nuclei which can be produced in the laboratory are mentioned. For a given Z - target and Z - projectile there is one combination having a minimum value of the potential energy as one sees on figs. 1 - 3, where by 20, 30, 40 etc. are labelled the atomic numbers of the projectile. We also notice that for each compound nucleus deep minima appear in the potential energy at only a few η - values, as observed earlier for the case of other transfermium nuclei (Săndulescu et al. 1976, Săndulescu et al.1976,a, Gupta et al. 1977 , Săndulescu 1978). We shall call these valleys "fusion valleys". Most of the target - projectile combinations corresponding to the fusion valleys coincide with the ones already used in experiments for the synthesis of 103, 105 and 107 elements (Oganessian et al. 1976). Nevertheless, the deepest minima in the potential energy correspond to nearly symmetric or less asymmetric target - projectile combinations, which have been shown as not being suitable for producing fusion reactions (Nix and Sierk 1976). Then the question arises why only the asymmetric reactions are favourable for the synthesis of new elements. We shall show in the next chapter that the answer is given by the estimation of the fusion cross sections, with a proper de -

termination of the critical angular momentum. This is in complete agreement with the previous results based on static arguments : the interaction length (defined as the length of the composite nucleus at the top of the interaction barrier) and the associated nuclear shapes (Gupta et al. 1977).

3. *CROSS SECTION ESTIMATIONS*

The complete fusion cross sections were calculated for a given compound nucleus at a fixed excitation energy, formed by the target - projectile combinations selected above. We have shown, for the case of a transfermium compound nucleus too (Magda et al. 1978), that the behaviour of the fusion cross sections is conveyed to the production cross sections what justifies our procedure.

The complete fusion cross sections were calculated by the usual formula :

$$\sigma_{CP} = \pi\lambda\!\!\!^{-2} \sum_{\ell=0}^{\ell_{cr}} (2\ell + 1)T_\ell \tag{2}$$

where $\lambda\!\!\!^{-}$ is the reduced wave length and T_ℓ the transmission coefficients corresponding to the ℓ^{th} partial wave. The transmission coefficients are approximated by the penetration factors of a parabolic barrier with frequency $h\omega_\ell$ as suggested by Thomas (Thomas 1959) :

$$T_\ell(E) = \frac{1}{1+\exp\left|2\pi(V_\ell-E)/\hbar\omega_\ell\right|}$$

$$h\omega_\ell = \left| \frac{h^2}{\mu} \; \frac{d^2 V_\ell}{dr^2} \right|^{1/2}_{r=R_{fus}}$$

where μ is the reduced mass, V_ℓ the total (Coulomb, centrifugal and nuclear) potential and E is the incident c.m. energy. As in an earlier work (Magda et al. 1978) the parameters defining the nuclear potential have been selected by fitting the available data concerning nuclei in the mass region of interest. The following parameters defining the Igo - nuclear potential V_o=70.0MeV, r_o = 1.25 fm and the diffuseness parameter d = 0.44 fm were used. They agree with the ones given by other authors (Oganessian et al. 1975).

The sum over ℓ in eq. (2) ends up at the critical angular momentum (ℓ_{cr}) which in general is lower than the maximum one. The existence of a critical angular momentum limiting the fusion cross section is explained either by the inability of the compound nucleus to take over large angular momenta or by the fact that when large angular momenta are involved the colliding nuclei cannot fuse because being kept apart by the centrifugal force which is preponderant. Therefore critical angular momenta can be defined as related to the entrance channel dynamics (ℓ^d_{cr}) and to the stability conditions of the transient composite system (ℓ^s_{cr}). The ℓ^d_{cr} can be determined with the method proposed by Bass (Bass 1974) or with an empirical method (Sikkeland and Viola 1963). The ℓ^s_{cr} can be determined starting from the stability considerations of the rotating nucleus as the angular momentum for which the fission barrier vanishes (Cohen et al. 1974, Blann and Plasil 1975, Toneev and Schmidt 1978). Then the angular momentum limiting the complete fusion cross section would be determined as the minimum value of the critical angular momenta resulting from the above mentioned considerations namely (Magda 1979) :

$$\ell_{cr} = \min(\ell^{d}_{cr}, \ell^{s}_{cr}) \tag{3}$$

The ℓ^{d}_{cr} is the one usually determining the cross sections, as nuclei with masses under 200 are involved. On the contrary, when the compound nuclei are highly fissionable as is the case of transfermium nuclei, the critical angular momentum would be given by the condition that the fission barrier is equal to zero. As in a previous paper (Magda and Săndulesçu 1978) for the nuclei involved in the present analysis the ℓ^{s}_{cr} was estimated semiempirically by comparing calculated evaporation cross sections with the experimental ones. Calculations of the evaporation cross sections are based on the statistical model and were performed with the code OVERLAID ALICE (Blann 1976). The fission competition is included as given by the Bohr-Wheeler expression. Because OVERLAID ALICE Code is known and used in many laboratories we shall not dwell upon its description but we shall discuss the choice of the parameters involved in the present calculations. Aiming to a realistic choice of these parameters we used the values resulting from the analysis of the measured cross sections for close nuclei (Magda et al. 1978). So the ratio of the level density parameters for the saddle point configuration and the residual nucleus after the emission of a particle $\nu(a_f/a_\nu)$ was assumed equal to unity. The level density parameter a_ν was taken equal to A/8. The option of the code was employed which treats approximately the angular momentum in the exit channel assuming that each evaporated particle carries a constant amount of angular momentum namely 2ħ, 3ħ and 10ħ for the case of neutrons, protons and α-particles respectively. Attempts to modify the fission barrier (calculated with the liquid drop model as given in the code) by multiplying it with a factor different from unity did not lead to agreement with existing experimental data :throughout the calculations the multiplication factor was set equal to unity.

The code has the facility that calculations are performed for each partial wave in the entrance channel and can be stopped at a given value of the angular momentum thus determining the magnitude of the cross sections. Then the critical angular momentum is easily obtained as the number of partial waves required to achieve agreement with the measured evaporation cross sections.

The results of calculations for the compound nuclei $^{253}103$, $^{257}105$ and $^{263}107$ are shown in the lower part of the figs. 1 - 3. Excitation energies of 20, 30 and 50 MeV were considered in the calculations but the values given in the figures refer to an excitation energy of 50 MeV. Black circles represent the complete fusion cross sections estimated with the Bass method. One sees that the cross section values follow the evolution of the potential energy : more deeper is the minimum of the potential energy, more larger is the cross section. We should like to mention that for smaller excitation energies, 20 or 30 MeV, the maximum of partial waves in the entrance channel is so low that no cut-off criteria are needed to be applied.

For comparison with experiment we have chosen the following (HI,xn) reactions (Oganessian et al. 1976) : $^{203}\mathrm{Tl}(^{50}\mathrm{Ti},xn)^{253-xn}103$, $^{206}\mathrm{Pb}(^{51}\mathrm{V},xn)^{257-xn}105$, $^{208}\mathrm{Pb}(^{55}\mathrm{Mn},xn)^{263-xn}107$ and $^{209}\mathrm{Bi}(^{54}\mathrm{Cr},xn)^{263-xn}107$. The results are given in table 1 , where the analyzed reactions and the compound nuclei are listed along with the experimental cross sections. Due to the fact that most of the above experimental data are obtained at low bombarding energies which correspond to quite low excitation energies of the compound nucleus, in the following, are discussed only $(\ell^{s}_{cr})_{th}$ determined theoretically with the rotating liquid drop model and $(\ell^{s}_{cr})_{exp}$ determined empirically in such a way to reproduce the measured values. We can see that in order to reproduce the experimental evaporation cross-sections we need ℓ_{cr}-values smaller than the values predicted by the rotational liquid drop model. It is interesting that for the $^{263}107$ compound nucleus, the $(\ell^{s}_{cr})_{exp}$ determined from two different reactions in which this compound nucleus is formed agree within the limit of 2h. We should like to mention that the same result has been obtained for other transfermium nuclei formed in different reactions (Magda and Săndulescu,1978). Such a spread in the value of the critical angular momentum would modify the values of the corresponding complete fusion cross sections only in the limit of few percents.

If these empirical, unique for a given compound nucleus ℓ^{*}_{cr} - values are introduced in the eq. (2) different values of the cross sections result as one can see on figs. 1-3 (open circles). The above described picture changes: it appears that the more asymmetric combinations are most favourable in agreement with previous experimental and theoretical results. Particularly, the fusion cross section of the ^{209}Bi + ^{54}Cr system has the largest value in good agreement with the experimental observation (Oganessian et al. 1976 a).

The result that different values of the complete fusion cross sections are obtained for various target-projectile combinations forming a given compound nucleus (in spite of the fact that the sum over ℓ ends up at the same term) is understood as due to their different interaction barriers leading to different transmission coefficients.

We remark that the absolute values of the complete fusion cross sections given in figs. 1 - 3 are calculated in the hypothesis that the whole reaction cross section goes into complete fusion processes, what is true as long as other reaction channels are not open, what is likely to happen in the case of reactions occurring at low energies above the interaction barrier . If new reaction channels open, for instance deep inelastic processes are involved in the reaction mechanism the absolute values of the estimated complete fusion cross sections would be overestimated but their relative values are still reliable. However, the complete fusion cross sections obtained here for the compound nuclei $^{253}103$, $^{257}105$ and $^{263}107$

are of tens up to around hundred mbarns in agreement with existing data for transfermium nuclei (Ter-Akopian et al. 1979).

4. PREDICTIONS FOR SYNTHESIS OF SUPERHEAVY ELEMENTS

Attempts to synthesize superheavy elements by (HI,xn) reactions did not lead to a positive result : only upper limits of the cross sections have been obtained so far (Oganessian 1979). It is still not decided if this situation is due to the excessively low production cross sections or to the special properties of the superheavy nuclei. Therefore, it is of great interest to use the same procedure as in the case of trans - fermium nuclei to estimate the cross sections for the synthesis of superheavy nuclei.

In the following we assume that the reaction mechanism does not change for heavier systems what enables us to extend the procedure described before to the estimation of (HI,xn) cross sections in the region of superheavy elements. The case of three isotopes of 114 element has been considered namely $^{288}114$, $^{220}114$ and $^{292}114$ produced in the following reactions: $^{240}Pu(^{48}Ca,xn)^{288-xn}114$, $^{238}U(^{50}Ti,xn)^{288-xn}114$, $^{242}Pu(^{48}Ca,xn)^{290-xn}114$ and $^{244}Pu(^{48}Ca,xn)^{292-xn}114$. Present calculations with the same parameters as before cover the internal of excitation energies in the compound nuclei between 25 and 40 MeV. The maximum values of the cross sections for the evaporation of two, three and four neutrons are listed in table 2. We used for the critical angular momentum two values the first one given by the liquid drop model equal to 54 h and

The second one given by the average value of the empirical critical angular momentum of transfermium elements $\ell^{e}_{cr} = 45\hbar$ (see table 1). It is obvious that the predicted evaporation cross sections based on the empirical value $\ell_{cr} = 45\hbar$ deduced from the analysis of production of transfermium elements are reasonable in agreement with the present experimental information. The use of critical angular momentum given by the rotating liquid drop model would over estimate the cross sections, leading to values larger than the sensitivity limits of some performed experiments (Oganessian 1979).

A decrease of the empirical critical angular momentum by few $\hbar$-units will decrease the cross sections by another order of magnitude. An increase with 10% of the level density parameter ratio (a_f/a_ν) would also decrease the cross sections with approximately an order of magnitude. These two modifications are not independent, both leading to the same effects in the evaporation cross sections.

We concluded that the production cross sections of superheavy nuclei are smaller than predicted up to now. The final answer to this problem will be given by new experiments with increased detection sensitivity. Also new data in transfermium region will allow a much better choice of parameters used for cross section estimates.

5. CONCLUSIONS

The evaluation of the production cross sections for 103, 105 and 107 elements shows that the choice of the target-projectile combinations corresponding to a fusion valley (with largest mass asymmetry) in the potential energy is a necessary condition for fusion to occur.

The importance of the stability conditions of the compound nucleus in limiting the fusion cross sections is demonstrated for the case of transfermium nuclei. Recently the effect of the critical angular momentum determined by the stability conditions of the compound nucleus was also stressed in the special case of the quadruply system $^{208}Pb + {}^{48}Ca$ (Nitschke et al. 1979). In fact, earlier attempts to explain the observed anomalies of the cross sections by shell effects failed while the use of an angular momentum corresponding to the vanishing of the fission barrier succeded to explain the experimental data.

The present predictions of the cross sections for production of superheavy elements in (HI,xn) reactions show that an increased sensitivity of the actual experiments would allow the discovery of these elements.

Finally, we conclude that the present estimates of the production cross sections based on a consistent set of parameters, give realistic values which support the choice of particular systems for the synthesis of transfermium elements following the procedure used in Dubna (Oganessian 1976).

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Table 1 - Experimental (σ_{exp}) and estimated evaporation cross sections ($\sigma_{th}^{(1)}$ and $\sigma_{th}^{(2)}$) with the corresponding critical angular momenta $(\ell^{s}_{cr})_{th}$ and $(\ell^{s}_{cr})_{exp}$ determined by the rotating liquid drop model and respectively by reproducing the experimental data.

Reaction	Compound nucleus	σ_{exp} (cm^2)	$(\ell^{s}_{cr})_{th}$ (h)	$\sigma^{(1)}_{th}$ (cm^2)	$(\ell^{s}_{cr})_{exp}$ (h)	$\sigma^{(2)}_{th}$ (cm^2)
$^{203}Tl(^{50}Ti,xn)$	$^{253}103$	7×10^{-35}	65	1.1×10^{-27}	43	3.8×10^{-35}
$^{206}Pb(^{51}V,xn)$	$^{257}105$	5×10^{-35}	67	4×10^{-30}	40	4.5×10^{-35}
$^{209}Bi(^{54}Cr,xn)$	$^{263}107$	1×10^{-34}	49	3.3×10^{-34}	49	3.3×10^{-34}
$^{208}Pb(^{55}Mn,xn)$	$^{263}107$	5×10^{-35}	49	1.5×10^{-34}	47	0.5×10^{-34}

Table 2 - Estimated evaporation cross sections for the production of three isotopes of the 114 - element with critical angular momentum given by the rotating liquid drop model ($\ell_{cr} = 54\ \hbar$) and with the empirical one from transfermium region ($\ell_{cr} = 45\ \hbar$).

System	Compound nucleus	σ_{2n} (cm^2) $\ell_{cr} = 54\hbar$	σ_{3n} (cm^2) $\ell_{cr} = 54\ \hbar$	σ_{4n} (cm^2) $\ell_{cr} = 54\ \hbar$	σ_{2n} (cm^2) $\ell_{cr} = 45\ \hbar$	σ_{3n} (cm^2) $\ell_{cr} = 45\ \hbar$	σ_{4n} (cm^2) $\ell_{cr} = 45\ \hbar$
^{240}Pu+^{48}Ca	^{288}114	1.4×10^{-37}	3.4×10^{-33}	3.7×10^{-30}	1.2×10^{-39}	4.5×10^{-35}	8.5×10^{-34}
^{238}U+^{50}Ti	^{288}114	2.9×10^{-38}	1.1×10^{-33}	1.5×10^{-30}	6×10^{-40}	1.2×10^{-35}	4×10^{-34}
^{242}Pu+^{48}Ca	^{290}114	2.5×10^{-37}	3.3×10^{-35}	2.2×10^{-31}	2×10^{-38}	4×10^{-37}	3×10^{-35}
^{244}Pu+^{48}Ca	^{292}114	2.3×10^{-39}	9.4×10^{-35}	5.6×10^{-32}	6.5×10^{-41}	2×10^{-36}	4×10^{-35}

FIGURE CAPTIONS

Fig. 1 Potential energy values of various target-projectile combinations leading to the compound nucleus $^{253}103$ vs projectile mass (upper part). Complete fusion cross sections calculated for various target-projectile combinations forming the $^{253}103$ compound nucleus vs projectile mass (lower part).

Fig. 2 Same as fig. 1 but for the $^{257}105$ compound nucleus.

Fig. 3 Same as fig. 1 but for the $^{263}107$ compound nucleus.

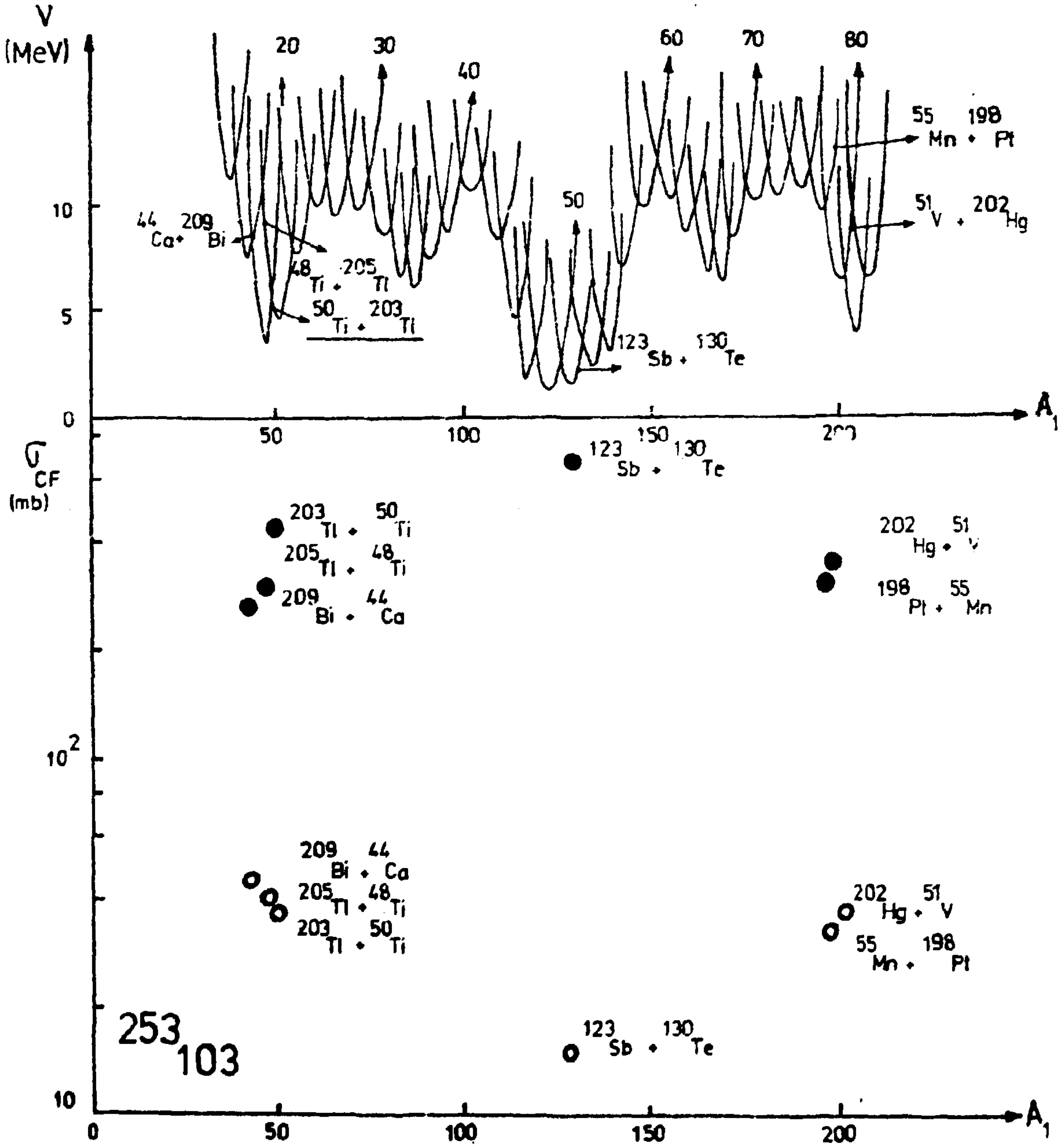

V (MeV)
10
5
0
20
30
40
50
60
70
80
^{44}Ca + ^{209}Bi
^{48}Ti + ^{205}Tl
^{50}Ti + ^{203}Tl
^{123}Sb + ^{130}Te
^{55}Mn + ^{198}Pt
^{51}V + ^{202}Hg
A_1
50
100
150
200
σ_{CF} (mb)
10^2
10
^{203}Tl + ^{50}Ti
^{205}Tl + ^{48}Ti
^{209}Bi + ^{44}Ca
^{202}Hg + ^{51}V
^{198}Pt + ^{55}Mn
$^{253}_{103}$
0

Fig.1

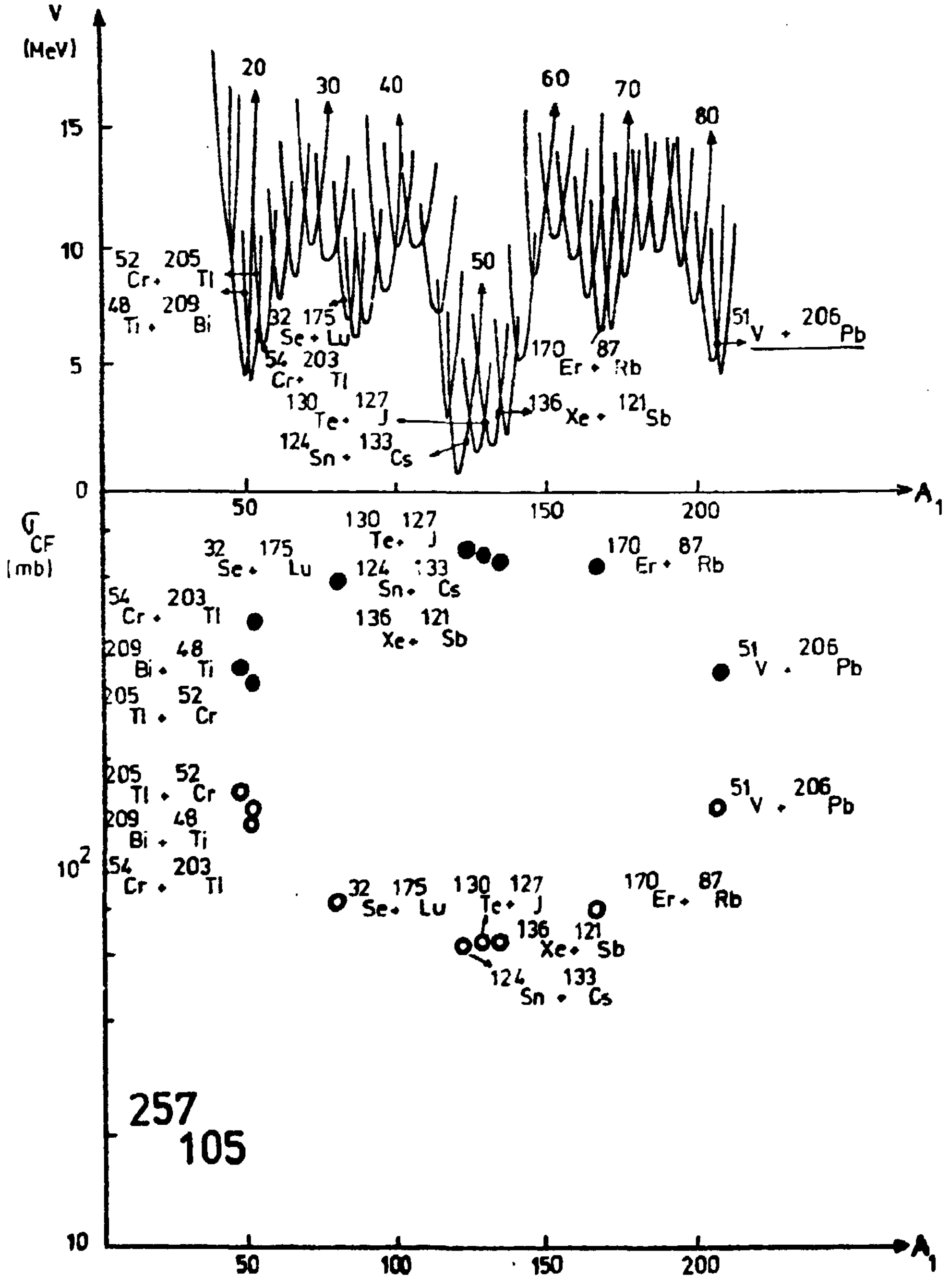
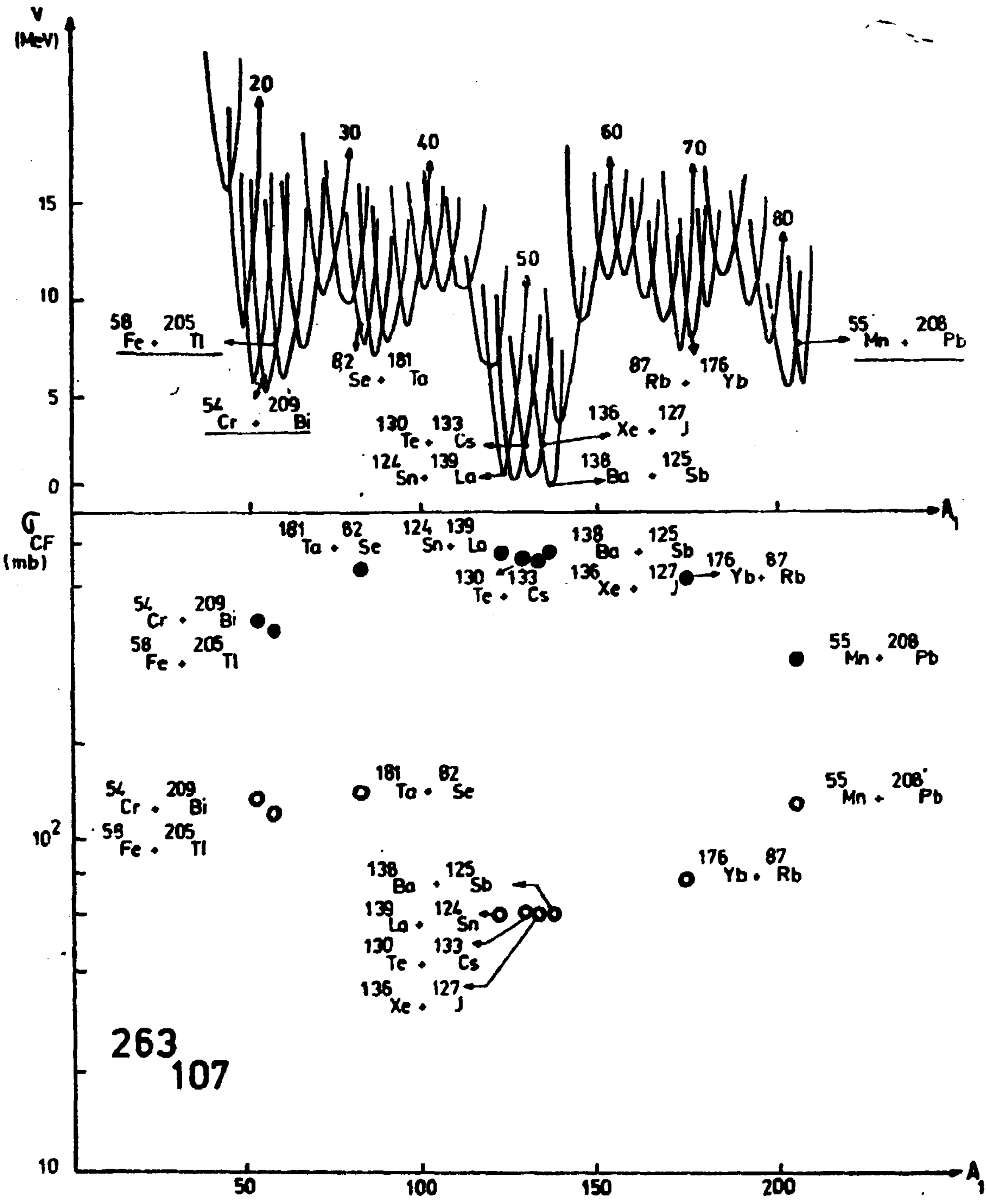

V (MeV)
15
10
5
0
20
30
40
50
60
70
80
52 Cr + 205 Tl
48 Ti + 209 Bi
32 Se + 175 Lu
54 Cr + 203 Tl
130 Te + 127 J
124 Sn + 133 Cs
136 Xe + 121 Sb
170 Er + 87 Rb
51 V + 206 Pb
A1
50
150
200
σCF (mb)
130 Te + 127 J
32 Se + 175 Lu
124 Sn + 133 Cs
170 Er + 87 Rb
54 Cr + 203 Tl
136 Xe + 121 Sb
209 Bi + 48 Ti
51 V + 206 Pb
205 Tl + 52 Cr
205 Tl + 52 Cr
209 Bi + 48 Ti
51 V + 206 Pb
10^2
54 Cr + 203 Tl
32 Se + 175 Lu
130 Te + 127 J
170 Er + 87 Rb
136 Xe + 121 Sb
124 Sn + 133 Cs
257 105
10
50
100
150
200
A1

Fig.2



V
(MeV)
15
10
5
0
20
30
40
50
60
70
80
58 Fe + 205 Tl
54 Cr + 209 Bi
82 Se + 181 Ta
130 Te + 133 Cs
124 Sn + 139 La
136 Xe + 127 J
138 Ba + 125 Sb
87 Rb + 176 Yb
55 Mn + 208 Pb
A_1
σ_{CF}
(mb)
181 Ta + 82 Se
124 Sn + 139 La
138 Ba + 125 Sb
130 Te + 133 Cs
136 Xe + 127 J
176 Yb + 87 Rb
54 Cr + 209 Bi
58 Fe + 205 Tl
55 Mn + 208 Pb
10^2
10
263
107
50
100
150
200
A_1

Fig. 3