High energy alpha particle emission as a challenging mechanism for synthesis of very heavy nuclei

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Abstract. Two experiments made with the MSP144 stepped pole magnetic spectrometer of FLNR-JINR Dubna measured the energy spectra of α particles emitted at zero degree (collinear kinematic) in the reactions $^{40}$Ar(220 MeV) + $^{232}$Th and $^{48}$Ca(270 MeV) + $^{238}$U. The study was pursued up to the maximum energy the alpha particles may have in a two-body reaction, without excitation of the reaction partners, the so-called kinematic limit. The observed cross sections in the vicinity of the kinematic limits were of the order of µb. In the indicated reactions, the heavy partners of the recorded alpha particles in the exit channel were respectively $^{268}$Sg and $^{282}$Db. At the kinematic limit, the heavy partners have excitation energies close to zero, therefore a high probability to survive.

1. Introduction

The study of superheavy elements attracted and continues to attract a lot of interest both theoretically and experimentally. The reason is the need to find an answer to some fundamental questions like where are the limits of stability of the heaviest elements and for what reason. Moreover, the idea of islands of stability immersed in a sea of unstable heavy elements was advanced by theorists and some experimental hints of their existence exists already.
Despite the substantial efforts to go beyond $Z=118$, no positive news appeared for already quite some time. There are reasons for such a situation. After a long and successful campaign that mostly used $^{48}\text{Ca}$ as primary beam, things become more and more difficult as the possible heavy targets for synthesis become highly radioactive (Cm, Bk, Cf). Further target candidates $^{254}\text{Es}$ and $^{257}\text{Fm}$ will be very difficult to obtain.

Another limiting aspect is that the available combinations lead to neutron deficient nuclei and that synthesis of odd nuclei is generally preferred due to the alpha emission hindrance.

The sensitivity of these experiments is outstanding: they operate with cross sections at the $\text{pb}$ level and soon at the $\text{fb}$ level (e.g. SHE Factory at FLNR-JINR Dubna). These very low cross section levels are theoretically understood and are mostly due to the fierce competition of the fusion-evaporation (FE) reactions with the quasi fission and/or fast fission processes.

2. Some experimental facts

In the following we will try to point to an alternative to the FE reactions issued from the study of light particle emission in heavy ion reactions at close to barrier energies. We refer to two experiments [1,2] performed at the MSP144 magnetic spectrometer in FLNR-JINR Dubna. The reactions are:

\[ ^{40}\text{Ar (220MeV)} + ^{232}\text{Th} \rightarrow ^{4}\text{He} + ^{268}\text{Sg} \text{ and } ^{48}\text{Ca (270MeV)} + ^{238}\text{U} \rightarrow ^{4}\text{He} + ^{282}\text{Ds} \]

at zero degree.

Noticeably, in both reactions the targets are alpha active nuclei. The alpha spectra measured with the MSP spectrometer are shown in Figs. 1 and 2 taken from [1] and [2] respectively. These spectra have a common important feature, namely they are measured up to a value of alpha particle energy close to the maximum one allowed by the conservation laws in a two body reaction. We will call this energy the kinematic limit. This limit is obtained when the reaction products have zero excitation energy and are readily obtained from a simple kinematic calculation involving only the geometry (collinear in this particular case) and masses of the reactants. While for alpha particle this is to be expected, their accompanying heavy residue (HR) are the heavy elements Sg ($Z=106$) and Ds ($Z=110$).

The measured cross sections near the kinematic limit are of the order of $\mu\text{b}$. It follows that the two body reactions provide us with the means of obtaining unexcited heavy residues or having a very small, controlled excitation energy. As it was demonstrated in [3] using energy conservation arguments, below the kinematic limit, for at least 20-25 MeV, there are no other reactions possible except two body ones. On the other hand, for alpha energies slightly smaller than the kinematic limit, the heavy residue will gradually accumulate excitation energy. If the excitation energy is below the fission barrier $B_f$ and also below the neutron separation energy $S_n$, the heavy residue will survive but as can be seen from the figures, the cross section steeply increases for such a situation (to the left of kinematic limit).

Without speculating about the mechanisms governing these two body reactions, the fact is that the HR are created with the observed cross section for alphas which is at least three orders of magnitude higher than for fusion-evaporation reactions leading to the same final nucleus.

Obviously, after observing these facts we thought of recording with the MSP spectrometer also the heavy residue. It turned out that this is almost impossible in the actual configuration due to the large noise level created by the beam entering the spectrometer and all its charge states and accompanied inelastic scattering. This is not a danger for the alpha particles because they have the highest magnetic rigidity. For detecting the heavy residue, it will be necessary to use the standard hardware for SHE detection which is usually a gas filled magnetic spectrometer GFMS). These devices have the advantage that the HR charge states obtained at the exit from the target are concentrated in one, the equilibrium charge state in the rarefied gas of the GFMS. Unfortunately, all GFMS are very busy with experiments on SHE synthesis by fusion-evaporation reactions. However, if one experiment will be aimed at using a GFMS with a two body reaction, the logically expected positive result will open a wide avenue for SHE synthesis, seriously modifying the present approaches. One should only mention...
that measuring coincidences alpha-heavy residue at the appropriate energies will be an irrefutable proof for the creation and identification of the aimed for SHE. In a preparatory phase, alpha particle spectra should be measured close to the kinematic limit for projectiles above $^{48}$Ca and at various incident energies. In particular, Ni and Zn have a long range of isotopes, some with a substantial neutron excess, giving access to the synthesis of less neutron deficient SHE. We remark in particular the combination $^{66}$Zn+$^{232}$Th which leads to the heavy residue $^{294}$Og, the last discovered SHE and the cross sections could then be compared. As for the incident energies, while the fusion evaporation reactions are studied at incident energies leaving the compound nucleus with an excitation energy allowing 2-4 neutrons emission (30-40 MeV excitation energy), in the two body reactions the excitation energy of the heavy residue is controlled by the alpha particle energy and could therefore be very small, close to zero. Which is the optimum incident energy for obtaining the highest cross section for alpha emission close to kinematic limit for a given target-projectile combination remains an open question to be solved by systematic dedicated experimental studies. However, the many reactions studied in [1,3,4] seem to indicate that incident energies slightly above the Coulomb barrier are giving the highest cross sections for the alpha particles emitted with energies close to the kinematic limit. Importantly, one should also notice that the use of alpha decaying targets (used in the presented experiments) increases the observed cross section at the kinematic limit when compared with other combinations.

Figure 1: $\alpha$ differential cross section measured in the $^{40}$Ar + $^{232}$Th reaction performed at 220 MeV incident beam energy (picture taken from Ref. [1]).

An often-asked question is: if the cross section of these two-body reactions is so high compared with the fusion-evaporation reactions, why the so produced heavy residues were not observed in the already measured combinations? Before answering this question, few observations are in order. For the same input channel, the heavy residue partner of alpha particle has a substantially smaller kinetic energy than that of the compound nucleus. This is easy to understand in terms of momentum conservation: for the two body reactions, alpha particle takes away an important quantity of energy and momentum to the detriment of the heavy residue.

For the reaction examples presented above, to our knowledge, the Ar+Th reaction was not used for the synthesis of Hs isotopes. The other reaction however, was successfully used by the Dubna group [5] for the synthesis of Cn isotopes, in particular $^{283}$Cn after 3$n$ evaporation. The experiment was done
at the Dubna Gas Filled Spectrometer (DGFS). Few bombarding energies were used, among them 234 MeV giving a rather large number of events. In the two body reaction measured at the MSP spectrometer [2], the bombarding energy was 270 MeV; therefore we don’t know the cross section for alpha production at the kinematic limit if the incoming energy would have been 234 MeV. Nevertheless, we can consider for comparison a similar level of the cross section. If the two body reaction is induced by $^{48}$Ca ions with energy of 234 MeV, the expected energy of the heavy residue, $^{282}$Ds is 29.5 MeV when the alpha has an energy near the kinematic limit. Of this energy, considering that targets are 0.3mg/cm$^2$ thick and the reaction happens in the middle of the target and also that the entrance window of DGFS is 1.5 um Ti, we arrive to an energy of 14.6 MeV for $^{282}$Ds before entering the magnetic field. Calculating the average charge state following the prescription of the methodic paper [6] on the DGFS and also the recipe indicated there for the magnetic rigidity calculation, we find a value of 2.79 Tm. A similar calculation for $^{283}$Cn indicates a value of 2.58 Tm. The value of Ds is almost 11% higher, which, considering the dispersion of 7.5mm Brho indicated in the same paper, results in a shift in position by 82.5 mm, while the energy recorded by the silicon detectors will be very different in the opposite direction. The time of flight detector in front of silicon implantation detector will reject Ds as too slow compared to the expected Cn. Indeed, the difference of velocity before energy loss in the spectrometer gas and windows of the time of flight detector is already 25% and will increase when the last two mentioned (unknown to us) will be taken into account.

![Figure 2: α differential cross section measured in the $^{48}$Ca + $^{238}$U reaction performed at 270 MeV incident beam energy (picture taken from Ref. [2]).](image)

Another possible question may refer to the contribution of target impurities to the high energy region of the alpha particle spectrum. This can indeed be a serious issue, especially considering the low level of cross sections close to the kinematic limit. In the case of Th, we used fresh metallic targets. In the case of $^{238}$U however, the targets were made of uranium oxide on Al support. Aware of the impurities problem, the last point measured in fig. 2 is at an energy slightly beyond the kinematic limit where alpha particles may be produced only on the target impurities. No counts were recorded and the indicated cross section is the estimated upper limit for the impurity contribution in the region of the kinematic limit.
When this interesting phenomenon was first observed, we tried to understand the mechanism behind this two body process [1,3,7]. One should say that besides alphas, other particles are emitted: p, d, t, ³He and no doubt neutrons (we could not observe them with the setup used for experiments). The spectra of all these particles had something in common: a maximum cross section in the region dominated by evaporation from an excited nucleus, followed by an exponential decrease where the main contribution is due to pre-equilibrium emission and the last part of the spectrum for which the slope becomes steeper when approaching the kinematic limit. For some of the studied combinations projectile-target, the kinematic limit was reached at the expense of more than 7 orders of magnitude loss in the measured cross section. The results mentioned in the present paper are produced in reactions with alpha active nuclei and the bombarding energy was close to the barrier; may be these two particularities led also to a relatively high level of the cross section in vicinity of the kinematic limit.

Various aspects of the phenomenon of light particle emission in heavy ion induced reactions are presented in the review paper [8] which provides also a vast literature. However, the mechanism behind these two body reactions is not yet clear and consequently is not available to explain or even less predict the level of cross section close to kinematic limit.

3. Conclusion

We presented some already obtained experimental data in a new light, indicating that using a two body reaction may lead to substantially higher cross sections than fusion-evaporation reactions commonly used for the synthesis of SHE. This fact needs a convincing experimental proof, preferably re-synthesizing an already discovered element, such as to make possible a comparison of the obtained cross sections. If this proof gives a positive result - which is logically to be expected, then a more optimistic perspective for the SHE synthesis may open. Moreover, coincidence experiments alpha-heavy residue may change substantially the experimental approach, allowing an unambiguous identification for heavy elements without the need to recur to the decay filiations ending in an already known element. Besides, the life time limit for observation of a SHE can be lowered to the level of few dozens of microseconds. Success of such an experiment will boost the theoretical efforts to understand the mechanism of these two body reaction near the kinematic limit.

References
[1] C. Borcea et al., Nucl. Phys. A351, (1981), 312
[2] C. Borcea et al., Proc. Int. Symp. On Exotic Nuclei 2016 Kazan, Russia, World Scientific ISBN 978-981-3226-53-1, p. 132
[3] C. Borcea et al., Nucl. Phys. A391, (1982), 520
[4] C.Borcea et al., Nucl. Phys. A415, (1984), 169
[5] Yu. Ts. Oganessian et al., Phys. Rev. C70, 064609 (2004)
[6] Yu. Ts. Oganessian et al., Phys. Rev. C64, 064309 (2001)
[7] Yu. E. Penionzhkevich et al., Soviet Journal of Particles and Nuclei, i Vol 17, issue 2, p. 165, 1986
[8] V. I. Zagrebaev and Yu. E. Penionzhkewich, Prog. Part. Nucl. Phys. Vol. 35, p 575, 1995