Author(s): Pulcini, A.; Vardaci, E.; Kozulin, E.; Ashaduzzaman, M.; Borcea, C.; Bracco, A.; Brambilla, S.; Calinescu, S.; Camera, F.; Ciemala, M.; Canditiis, B. de; Dorvaux, O.; Harca, I. M.; Itkis, I.; Kirakosyan, V. V.; Knyazheva, G.; Kozulina, N.; Kolesov, I. V.; La Rana, G.; Maj, A.; Matea, I.; Novikov, K.; Petrone, C.; Quero, D.; Rath, P.; Saveleva, E.; Schmitt, C.; Sposito, G.; Stezowski, O.; Trzaska, Wladyslaw; Wilson, J.

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Year: 2018

Version: Published version

Please cite the original version:

Pulcini, A., Vardaci, E., Kozulin, E., Ashaduzzaman, M., Borcea, C., Bracco, A., Brambilla, S., Calinescu, S., Camera, F., Ciemala, M., Canditiis, B. D., Dorvaux, O., Harca, I. M., Itkis, I., Kirakosyan, V.V., Knyazheva, G., Kozulina, N., Kolesov, I. V., La Rana, G., . . . Wilson, J. (2018). Gamma rays as probe of fission and quasi-fission dynamics in the reaction 32S + 197Au near the Coulomb barrier. In G. Mandaglio, A. Trifirò, & M. Trimarchi (Eds.), NRNN 2017 : International Workshop "Nuclear Reactions on Nucleons and Nuclei" (Article 012013). IOP Publishing. Journal of Physics : Conference Series, 1014. https://doi.org/10.1088/1742-6596/1014/1/012013

Gamma rays as probe of fission and quasi-fission dynamics in the reaction ^{32}S + ^{197}Au near the Coulomb barrier

To cite this article: A Pulcini *et al* 2018 *J. Phys.: Conf. Ser.* **1014** 012013

Gamma rays as probe of fission and quasi-fission dynamics in the reaction ^{32}S + ^{197}Au near the Coulomb barrier

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Abstract. Compound nucleus fission and quasi-fission are both binary decay channels whose common properties make the experimental separation between them difficult. A way to achieve this separation could be to probe the angular momentum of the binary fragments. This can be done detecting gamma rays in coincidence with the two fragments. As a case study, the reaction ^{32}S + ^{197}Au near the Coulomb barrier has been performed at the Tandem ALTO facility at IPN ORSAY. ORGAM and PARIS, two different gamma detectors arrays, are coupled with the CORSET detector, a two-arm time-of-flight spectrometer. TOF-TOF data were analyzed to reconstruct the mass-energy distribution of the primary fragments coupled with gamma multiplicity and spectroscopic analysis. Preliminary results of will be shown.

1. Introduction

In reactions where fusion cross-section has to be estimated, it is important to get insight on the possible exit channels. When massive nuclei are involved, at energies around the Coulomb barrier, because of the substantial increase of the Coulomb repulsion, the quasi-fission mechanism (QF) happens to be the most important process counteracting complete fusion (CF) [1]. At the same time shell effects become very important at this energy range [2].

QF is a mechanism in which the composite system separates into two main fragments without forming a compound nucleus. The common properties between QF and compound nucleus fission (FF) make their experimental separation difficult. A few methods have been developed to decompose fission-like fragments into the FF and QF components, mainly based on comparing the experimental properties of the fragments in reactions leading to the formation of the same composite system but having different entrance channel properties. In the lack of a comprehensive theoretical model it is necessary to proceed empirically by searching for correlations between observables and extrapolating the systematics to unknown regions.

Typical pattern of the mass-TKE distribution which suggest the onset of the QF appears as the entrance channel mass symmetry and the reaction coulomb factor $Z_1 \cdot Z_2$ increases. From a mass distribution with a near Gaussian shape, typical of the fusion-fission described by the LDM, the increase of the two parameters above changes the mass distribution of the binary fragments quite remarkably: the mass distribution deviates from the LDM predictions with a more prominent asymmetric component. The average TKE and the variance of the TKE distributions also reflect the same progression.

While in the asymmetric region of the mass distribution it is usually possible to disentangle, to some extent, the component of QF and asymmetric fission modes thanks to the different nature of these two mechanisms, in the symmetric region the two components are overlapped. On one side the LDM cannot predict the relative strength of the CN fission to the total distribution; on the other side QF and FF fragments might have overlapping TKE distributions. The overlap of the two mechanisms in the symmetric mass region constitutes an inescapable problem when CN fission cross section has to be estimated [1].

That being said, it appears clear that a disentanglement of CN fission and QF processes is very hard to achieve and possible only in specific cases. Mass, TKE and angular distributions with their variances are not a good set of observables for the correct disentanglement of the two processes and there isn’t still a complete picture on what are the factors which determine the QF process.

In the next section the new approach proposed in this work will be discussed. In section 3 the studied reaction and the experimental setup will be discussed. In section 4 preliminary results will be shown.

2. Gamma ray probe

In the scenario described in the previous section, the search for a possible pathway to disentangle the two process starts from the identification of an additional observable or a new set of observables. The known differences between these two processes can help us finding the way: on one side there is CN fission, a slow process passing through an equilibrium stage; on the other side there is quasi-fission, a faster process with considerable mass transfer and energy dissipation, strongly governed by shell effects. It is reasonable to think that for the slower process the whole orbital angular momentum is transferred into internal degrees of freedom of the compound nucleus and so the two fragments following FF can reach spins higher than those of the fission-like fragments produced by quasi-fission.

A possible way to probe angular momentum of the two fragments is to detect gamma rays. Moreover, with gamma rays it is possible to identify the fragments atomic numbers and to directly investigate shell effects, the physics of the scission point (excitation energy and angular momentum), and the connection between fission modes and feeding of the fragments. Information about angular momentum can be extracted from discrete gamma transitions as well as from gamma multiplicity, M_γ, that is the average number of gamma emitted per event.

Recent studies were performed using modern gamma ray detector arrays and fission decay in reactions on thick targets to stop the recoiling fission fragments. The advantage of this method is that the Doppler broadening is absent if the recoiling fission fragments stop before emitting gamma rays, providing the maximum resolving power for the very dense spectra of gamma ray transitions from hundreds of nuclear species. The disadvantage of this approach is the impossibility to directly correlate gamma rays with fragments mass or TKE. In addition, only states with lifetimes longer than the stopping time for the recoiling fission fragments can be studied.

The drawbacks of the thick-target technique can be overcome by the fragment-gamma coincidence technique, which adds mass selectivity as well as identification from which fission fragment the gamma ray originates. It significantly improves the discrete gamma ray selectivity. The downside is that measurements arising from this technique are affected by gamma rays' energy shift and peak broadening, both due to Doppler effect, so energy corrections are needed [3] for which the measurement of the fragment velocities is required with the highest possible resolution.

Therefore, gating on high angular momentum gamma rays in coincidence with masses and TKE, it should be possible to see that some fragments are more populated in the fission region than in others and this could tentatively lead to a separation of CN fission and QF products even in the symmetric split mass region.

This method of correlating the high angular momentum population with the time scale of a reaction channel can be tested first by using the quasi-elastic channel. If the hypothesis is valid, the gamma transitions measured in coincidence with the quasi-elastic component should come from nuclei populated to lower angular momentum regions and the gamma multiplicity should be smaller than the one in coincidence with the fragments in the symmetric mass region. This would prove the concept and would open the road to experiments to distinguish between QF and CN fission in the symmetric region by employing an additional probe.

3. Experimental setup

To explore the concept described above, the reaction ^{32}S + ^{197}Au, at the energy near the Coulomb barrier, E_{lab} = 166 MeV, was performed at the Tandem ALTO accelerator at IPN Orsay (France). This reaction is characterized by a large fusion-fission cross section, and a negligible contribution from QF. The mass-TKE distribution is therefore characterized by a dominating component from fusion-fission process and the population of high angular momentum regions of the nuclei detected in coincidence with the mass symmetric fragments would therefore be not polluted with components from processes of nearby time scale.

Binary reaction products are detected in coincidence by the two-arm TOF spectrometer CORSET [4]. Each arm consists of a START detector, placed at 60 mm from the target, and a position-sensitive STOP detector, placed at 210 mm from the START. The two arms of CORSET were placed at 68° and 66.5° from the beam axis. These angles were chosen to detect symmetric fragments (the symmetric mass region for this reaction corresponding to 70° in the laboratory frame) and some asymmetric fragments, considering that the angular coverage of each STOP detector is about 10°.

Four beam monitor detectors are placed into the reaction chamber at 18° from the beam axis and at 40 mm from it. The four monitors are placed at angles of 90° with respect to each other.

The prompt gamma rays are detected with ORGAM and PARIS detectors. ORGAM is an array of high-resolution Ge detectors, each surrounded by BGO anti-Compton shields. 10 Ge detectors have been used, all located at backward angles. PARIS is a high efficiency array detector composed by LaBr3 (Ce)-NaI(Tl) phoswich base units. 10 units have been used, 9 packed together plus a single unit, all located at forward angles. The two detector arrays have similar photopeak efficiency in the low energy range, ~1% for ORGAM and ~1.5% for PARIS. ORGAM has better energy resolution (~4 keV at 1408 keV) than PARIS (~60 keV at 1332 keV), however PARIS compensate with a larger dynamical range (up to 20 MeV), compared to ORGAM (up to 2.4 MeV).

START and STOP signals are fed to logic unit modules which generate a trigger if there are two stop signals and at least one start signal. Start and stop signals are used for the measurement of TOFs for the two arms, while coordinates of the hit point on the STOP detectors are obtained as the difference between the time intervals STOP-trigger and coordinate-trigger. Gamma detectors are slave detectors. The readout of the PARIS was accomplished with the LaBrPRO module [5], the rest of the electronic is composed by commercial VME and NIM modules. The energy and time signals of the three setups were all fed into the Vipers [6] data acquisition.

4. Preliminary results

The ultimate goal for the experimental program is to investigate potential differences in the gamma ray properties depending on the reaction mechanism: fusion-fission or QF. This kind of study does not require a sorting of the data according to fragment masses and TKE, but widely profits from mass gating. In this first stage of the analysis, the goal is to check if it is possible to identify fission-like fragments by their deexcitation gamma rays from the spectra, gating on masses and gamma rays two-fold coincidences and verify that higher angular momenta are populated in the FF region of masses.

4.1. Binary fragments

The velocity vector of a fragment flying in a CORSET arm is obtained computing the flight path of the fragments (in the hypothesis that the fragment originates in the center of the target) and the TOF. Velocity vectors are needed to obtain the mass distribution as well as to perform Doppler correction. Only full momentum transfer binary events were taken into account in this analysis, so the mass of the primary fragments can be obtained using mass and momentum conservation laws. Masses and energies thus obtained need to be corrected due to the energy loss of the fragments along their path towards the detectors. From the TOF-TOF data, the mass-TKE matrix was reconstructed, as shown in figure 1. In the mass-TKE matrix it is possible to distinguish the typical loci for a fusion-fission process. The two lateral parts are elastic and quasi elastic events; the central part is mostly fusion-fission.

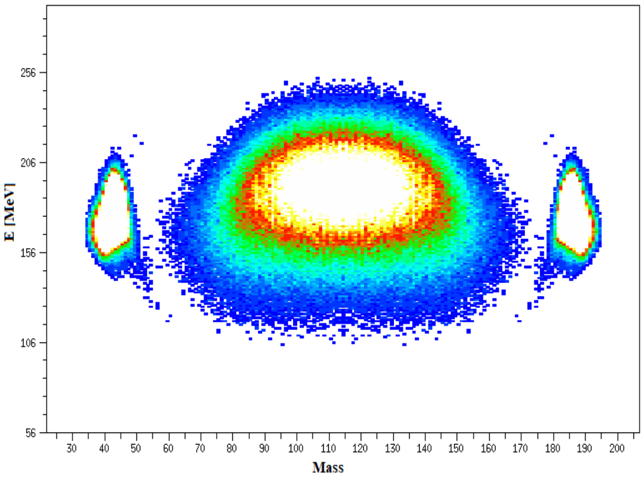

Figure 1. Mass-TKE matrix.

4.2. Gamma rays

From a first gate on the central part of the mass-TKE distribution, gamma energy lines corresponding to target and projectile levels should disappear. This is shown in figure 2. The upper curve represents the total spectrum recorded with the ORGAM array while the lower one represents the total spectrum gated on the fusion-fission part of the mass-TKE distribution. The most visible peaks of the total spectrum, identified as ^{197}Au transitions (figure 2) disappear almost completely in the gated spectrum.

Considering the good separation of the two components in the gamma spectrum coming from elastic and quasi-elastic events or CN fission, gamma multiplicities associated to the two regions of the mass-TKE distribution have been compared. Figure 3a shows the gamma rays multiplicity, detected with the PARIS array, for the two different regions: full triangles represent the gamma ray multiplicity of elastic and quasi-elastic events; full circles represent the multiplicity of fusion fission and deep inelastic events. Counts are normalized for comparison and are shown in logarithmic scale. It appears evident that the multiplicity associated with the quasi-elastic events drops faster than in the case of the fusion fission events. Furthermore, the multiplicity extends up to 7 in fusion-fission and up to 1 in quasi elastic. These trends are the proof that a faster process gives rise to less angular momentum in

the final fragments. We have to point out that the gamma multiplicity in Fig. 3a is still not corrected for the geometrical efficiency, but the trend is expected to be the same even after applying the correction.
An additional advantage of the present experimental method is that excitation energy regions can be scanned by taking windows of TKE values: a higher TKE value corresponds to less excitation energy available for the fragments (hence, lower multiplicity) and viceversa. Figure 3b shows the average multiplicity versus TKE. The average multiplicity exhibits a clear trend, decreasing as the TKE increases, in agreement with our assumption. This provides an additional gating condition to isolate weak transitions in the sea of the gamma rays measured.

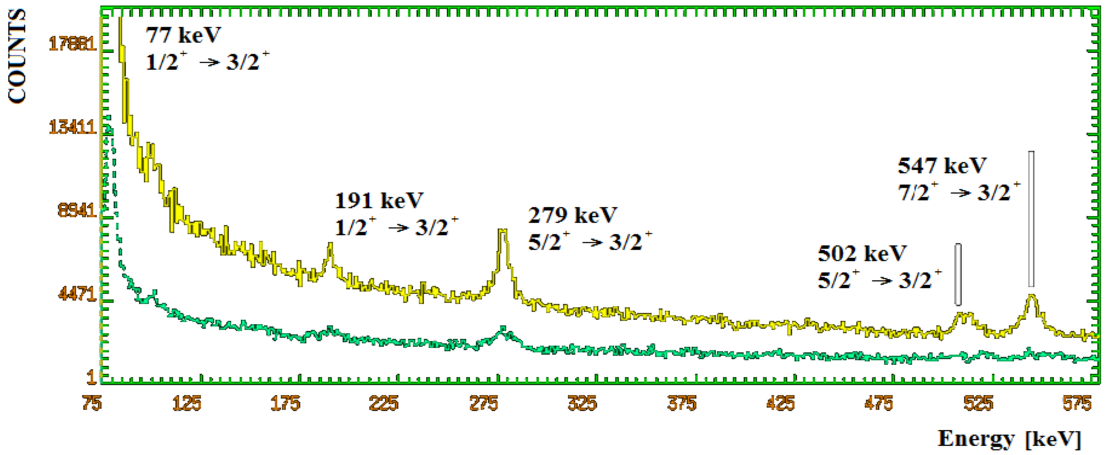

Figure 2. The total spectrum recorded by ORGAM detectors, upper curve, compared with the spectrum relative to the central part of the mass-TKE distribution, lower. The ^{197}Au transitions identified in the total spectrum are marked with their energy and angular momentum.

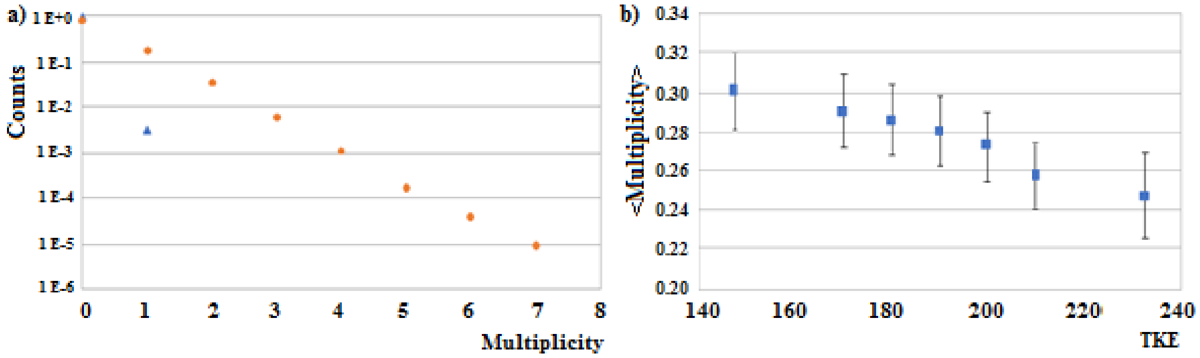

Figure 3. a) Multiplicity distributions for elastic and quasi-elastic channel (full triangles) and for fusion-fission channel (full circles); b) Average gamma multiplicity in coincidence with fission fragments versus their TKE.

A further prove in support of this conclusion could be to find gamma transitions between levels with high angular momentum in coincidence with masses in fusion-fission region. For this kind of analysis Doppler correction is mandatory. The energies of the gamma rays have to be corrected for both fission fragments, being impossible to know in advance from which fragment a gamma ray originates. Therefore, two gamma spectra are produced from one gamma spectrum after Doppler correction and must be analyzed separately [7]. An entire set of gamma transitions have been found for the nucleus ^{129}La connecting the level with $E^* = 5934.2$ keV and $J_\pi = 39/2+$ to the level with $E^* = 3420.6$ keV and $J_\pi = 27/2+$. Figure 4 shows the gamma ray energy spectra detected with the ORGAM array, in coincidence with both the mass (130 ± 3 a.m.u.) and one low lying transition (270 ± 5 keV) of the ^{129}La isotope ($E_{\gamma 1}$=269.7 keV), Doppler-corrected for the ^{129}La fragment. Although statistics precludes unambiguous identification of the gamma transitions, these results and the previous ones confirm the expectation that in the FF process higher angular momentum levels can be produced. Consequently, we can support the idea that processes with longer time scales can convert much more orbital angular momentum into the fragments. The different regions of angular momentum populated in FF and QE, at least for the ions selected so far, confirms this conclusion. On the same foot, we can reasonably expect the same effect also in QF and FF. Hence, these results give support to our initial expectations.

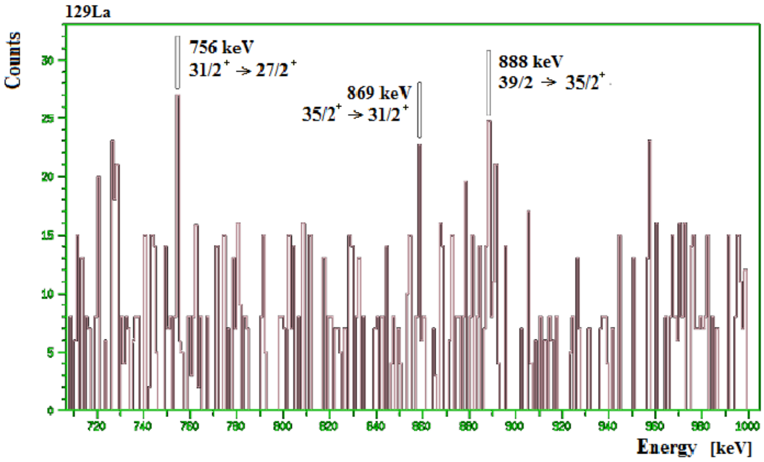

Figure 4. Some high angular momentum transition gamma rays of ^{129}La.

As a final comment we observe that, ^{129}La is a proton rich nucleus, and thus the partner must be the neutron rich nucleus ^{100}Sr whose level scheme is only fairly known. This means that looking for more proton rich nuclei (for instance the partner of the well-known ^{127}La is the unknown ^{102}Sr), with FF or QF reaction channels it might be possible to populate unknown neutron-rich nuclei and that the reconstruction of their level scheme can be pursued by using fragment-fragment coincidences. This is a very important result because there is no other known mean to produce such nuclei. At the same time, it is clear that these preliminary data need further processing to identify other possible unknown isotopes.

5. Conclusions

The preliminary results discussed in this work confirm that the gamma probe can play a very important role in disentangling FF and QF in the regions of the mass-TKE matrix where they are overlapped. Figure 3 is the key result of this work and shows how, gating on high multiplicity processes, favors the selection of slower processes. However, we must stress that these are preliminary results. The multiplicity distributions need to be corrected for the geometrical efficiency. For instance, even though only three gamma rays are detected in an event, they may come from events of larger multiplicity. Mass-TKE distributions also need correction for the energy losses: these corrections will improve the mass-TKE distribution and, most of all, the energy resolution of gamma energy spectra, affected by the errors introduced in the Doppler corrections. In any case, all of the mentioned corrections do not affect the main result of this work.

Yet, also high angular momentum spectroscopy can be performed by populating nuclei in level regions not accessible with usual fusion-evaporation reactions. As a by-product of this analysis, we have discovered that neutron-rich (possibly unknown) nuclei can be populated as partners of proton-rich nuclei. This means that a completely new spectroscopy can be accessible by using fragment-fragment coincidences. Still, the analysis is only at the beginning of a long process. After the mass-

TKE distributions correction for the energy losses, it would be very important to narrow the window of masses to reduce the gamma background and to look for unknown nuclei.

For the future plans, it is crucial to test this method in condition of major interest: when FF and QF are overlapped with the same intensity in the same mass region. It would also be important to benefit of these results and take advantage of the properties of the QF and FF to populate unknown neutron-rich nuclei. Reactions can be chosen carefully to populate neutron-rich regions of the nuclide chart of specific interest, like the one of interest from the r-process. However, it is clearly evident that the experimental condition must be kept at the optimum and that much larger gamma ray efficiency is necessary to reach a sufficient statistics.

6. Acknowledgement

This work was supported by FLNR, JINR, INFN, the IN2P3-JINR Agreement No 14-90, the ENSAR2 project "N-SI-88", by the financial contribution of Romania to the Joint Institute of Nuclear Research, Dubna, Russia to the project no. 03-5-1094-2010/2016, by the Polish National Science Centre under Contract No. 2013/08/M/ST2/00257 and the French LEA COPIGAL project.

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