Dynamical effects in the region of Heavy and Super-Heavy nuclei

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The transfer-induced fission channel has been studied in the collision of 340 MeV $^{28}\text{Si}$ on $^{232}\text{Th}$ as a function of the atomic number of the projectile-like fragments (PLF) by using a $4\pi$ detector array. The average excitation energy of the target-like fragment (TLF) is derived from the measured energy loss, whereas its angular momentum has been obtained from the angular distribution of fission fragments. The measured ratio of transfer-fission yield to PLF singles, $Y_f$, first increases up to a net charge transfer $\Delta Z = 4$, then shows a plateau around the values $Y_f = 0.4 - 0.6$. This ratio can be identified as the cumulative fission probability of the populated nuclei for net charge transfer $\Delta Z \leq 6$, suggesting a significant survival probability against fission of these TLF nuclei, in marked disagreement with the standard statistical model predictions. The observed survival probability implies that there is a strong hindrance to fission in the early stages of the deexcitation, such effects are important in the population of nuclei in the heavy and superheavy mass region by transfer reactions. Moreover pre- and post-scission multiplicities of neutrons and alpha particles have been simultaneously measured for the fission-like channel of the same reaction. Dynamical model calculations using HICOL code predict that 90\% of the observed events are of quasi-fission type while the remaining 10\% are from compound nucleus fission decay. From a comparison of PACE2 Statistical Model predictions with the measured pre-scission neutron multiplicity, the fission delay is estimated to be of $5^{+7\%}_{-3\%} \times 10^{-20}$s, which overlaps with the average duration of fission-like process from the contact to the scission point ($2 \times 10^{-20}$s) as determined from HICOL-based dynamical calculations.

\section{Introduction}

The synthesis of super-heavy elements (SHE) through heavy ion reactions has generated a great interest in recent years and extensive work has been carried out, both theoretically and experimentally, to study those rare production processes.\textsuperscript{1–6} It has been shown that the production cross-section of SHE depends upon the product of the compound nucleus formation cross-section and the survival probability against fission during the decay of the excited compound nucleus.\textsuperscript{4} Since the bulk of the excited super-heavy compound nuclei are expected to immediately decay by fission, the probability for the formation of a super-heavy evaporation residue is extremely low. It is important to better understand the fusion and fission mechanism...
involved. In particular it is important to study the reaction dynamics in the fission channel, that is essential for determining the optimum entrance channel parameters, such as target-projectile mass asymmetries and projectile bombarding energies, to maximize the cross-section for the formation of a super-heavy compound nucleus. It is well established that the fission process is dominated by effects due to nuclear viscosity, which produce a strong hindrance to fission, with the result that the number of neutrons emitted in the pre-scission stage is much larger than that expected on the basis of the Statistical Model. Extensive studies have been carried out in the past to obtain information on fission time scales ($t_{\text{fiss}}$) from the measurements of pre-scission neutrons, protons, alpha particles and electric dipole $\gamma$ ray, in fusion-fission reactions.\textsuperscript{7)–10) All these studies gave a strong indication of the dynamical delay in the fission process and that the measured fission probabilities, ($P_{\text{fiss}}$), depend on the entrance channel mass asymmetry and fissility of the fissioning system. To this respect transfer reactions on heavy targets offer the possibility to populate a wide range of target-like fragments (TLF) nuclei at varying excitation energies, which can be used to study in a systematic way the fission reaction mechanism. In particular, the study of fission probability of TLF nuclei is interesting because it gives a direct measure of the probability of survival of the populated TLF, thus it can be of particular interest when these nuclei lie in the mass region of heavy and super-heavy elements.

A further point to be taken into account is that the reaction used in the search for super-heavy elements include in most cases contributions from quasi-fission/fast-fission events. In these cases, the reaction dynamics is more complicated as compared to compound nucleus fission. It is therefore of interest to determine the dynamical times in reaction dominated by the quasi-fission/fast-fission processes.

Fission dynamics is one of the research topics currently under investigation by the $8\pi$LP charge particle detector system at Laboratori Nazionali di Legnaro. As a first step, the fission dynamics in transfer induced fission reaction for the system $^{28}\text{Si}$ on $^{232}\text{Th}$ at 340 MeV has been studied. Moreover the fission dynamics in the formation and decay of the nucleus $^{260}\text{Rf}$ populated in the fusion channel for the same reaction, have been investigated.

\section*{Experimental details}

The experiment has been performed at the XTU Tandem-ALPI Superconducting LINAC accelerator complex of the Laboratori Nazionali di Legnaro. A 340 MeV $^{28}\text{Si}$ beam, having about 1 \text{pA} intensity, was used to bombard a self-supporting $^{232}\text{Th}$ of 1.5 mg/cm$^2$ thickness.

The $8\pi$LP array\textsuperscript{11) employed consists of two detector subsystem made of $\Delta E-E$ telescope: the WALL and the BALL. The WALL is placed at 60 cm from the target covering from $\theta_{\text{lab}} = \pm 10^\circ$ to $\theta_{\text{lab}} = \pm 26^\circ$, where $\theta_{\text{lab}}$ indicates the angle between each detector and the beam direction. The BALL has a spherical geometry around the target with a 15 cm internal radius and covering, in this experiment, from $\theta_{\text{lab}} = \pm 51^\circ$ to $\theta_{\text{lab}} = \pm 163^\circ$. Each telescope is made of a transmission Silicon detector 300 \text{\textmu m} thick followed by a CsI(Tl) crystal, 15 mm or 5 mm thick for WALL and
BALL respectively. The $\Delta E$-E and time-of-flight techniques are used for particle identification in the WALL telescopes, with an energy threshold of 0.5 MeV/A. The same low-energy threshold characterizes the BALL telescopes, for which particle identification is obtained by using a combination of $\Delta E$-E and pulse shape analysis technique.\textsuperscript{12} In the present experiment the BALL detectors were used to detect fission fragments as well as light charged particles.

Projectile-like fragments (PLF) were detected using a $\Delta E$-E telescope, made of 40 $\mu$m and 400 $\mu$m thick silicon detectors, placed around the grazing angle ($\theta_{lab}$ = 39.5°) with a solid angle coverage of 1.3 msr. An aluminum foil 200 $\mu$m thick was placed in the front of the WALL to avoid the radiation damage of the silicon detectors.

Two NE213 liquid scintillator, 10 cm diameter and 5 cm thick, were used as neutron detectors and placed at a distance of 115 cm from the target at $\theta_{lab}$ = 60°, $\phi_{lab}$ = 0° and $\theta_{lab}$ = 136°, $\phi_{lab}$ = 20°, where $\phi_{lab}$ = 0° defines the horizontal plane.

The trigger of the acquisition system was generated by the detection of a particle in the PLF telescope or a twofold event in the BALL in single or in coincidence with neutron detectors.

\section*{§3. Experimental results}

3.1. Transfer-induced fission results

From the observed energy spectra of PLF, the average energy loss $\langle EL \rangle$, as a function of different fragment atomic number $Z_{PLF}$, has been deduced and compared with calculated energy loss for the case of complete damping of kinetic energy, i.e., corresponding to the Coulomb energy in the exit channel between two touching spheres. The energy loss increases with the net charge transfer $\Delta Z$, as commonly seen in two-body collisions around this bombarding energy. For low values of $\Delta Z$ the inelasticity is quite low, as in quasielastic collisions, while for $\Delta Z > 5$ (i.e. $Z_{PLF} < 9$) the energy dissipation approaches the 80% of the full damping limit.

The same transition from a quasielastic regime to deep-inelastic collisions has shown by the observed yield of PLF nuclei as a function of $\Delta Z$. However, the production yield for $Z_{PLF} = 6$ appears to be enhanced with respect to the neighboring elements and it cannot be explained by a simple two-body collision mechanism. It can be due to an additional reaction mechanism during (as projectile breakup) or after (as sequential PLF decay) the reaction.

From the measured energy loss, the excitation energy of the reaction partners, $E_x$(PLF) and $E_x$(TLF), has been extracted. It has been evaluated that the energy sharing between the fragments evolves in a continuous way from the quasielastic regime to fully relaxed events. The derived average excitation energy $\langle E_x \rangle$ of TLF fragments with $Z_{TLF} = 90 - 96$ ($\Delta Z \leq 6$) it was found to increase up to about 100 MeV.

To get information on the angular momentum in the fission channel, we have looked at the fission fragment angular distributions with respect to the recoil axis of the fissioning system, and to the fission fragment anisotropy $[W(0^\circ)/W(90^\circ)]$. The
observed angular distributions were fitted to deduced the angular anisotropies for different \( Z_{PLF} \). It appears that the anisotropy increases with increasing the net charge transfer, as qualitatively expected from simple considerations of angular momentum transfer to TLF’s. However, this trend shows a discontinuity around \( Z_{PLF} = 9 - 10 \). To deduce the TLF angular momentum, calculations of fission anisotropy were performed with the GANES code\(^{13}\), which simulates the fission of the recoiling TLF at different angular momentum values taking into account the geometry of the apparatus. A comparison of the experimental data with these calculations indicates an increase of TLF angular momentum, in the region of the quasielastic reaction, up to \( Z_{PLF} = 10 \). For higher \( Z \) transfers, the angular momentum then features an apparent drop at \( Z_{PLF} = 9 \) and then rises again in the region of deep-inelastic products, saturating at values around 40ℏ. The above estimates of the angular momentum transferred to TLF are in agreement with the findings of previous works in this field\(^{14},\!^{15}\).

The ratio of fission yield to PLF singles yield, \( Y_f \), has been then determined by integrating the measured angular distribution of fission fragments with respect to the recoiling TLF. The observed \( Y_f \) values as a function of the projectile-like atomic number \( Z_{PLF} \) are reported in Fig. 1.

It is shown that \( Y_f \) first increases with increasing net charge transfer up to \( \Delta Z = 4 \) then reaches a plateau around the values \( Y_f = 0.4 - 0.6 \) followed by a decrease for the higher \( Z \) transfers. The initial rise of fission yield is qualitatively expected due to the significant increase of the average TLF angular momentum and excitation energy as well as to the decrease of fission barriers, with increasing \( \Delta Z \).
The reported results suggest that the reconstruction of the undetected TLF parameters can be reliably achieved only in the case of small charge transfer, i.e., $\Delta Z \leq 6$. Consequently, we confine ourselves to the $\Delta Z \leq 6$ channels in the discussion of the observed transfer-induced fission yield. It is clear that only if the first step of the reaction is characterized by a two-body collision, the observed $Y_f$ correspond to the fission probability $P_f$ and therefore can be compared with the model estimates. Fission probabilities were calculated by using the statistical model code PACE2 with the level density parameter $a_\nu = a_f = A/12 \text{ MeV}^{-1}$. The average values of $P_f$, calculated for each $Z_{PLF}$ taking into account the spread in the EL distribution, are shown as a solid line in Fig.1 together with the limits on the average values due to the spread in the TLF parameters (dashed and dotted lines). These calculated average values of $P_f$ are compared with the observed values of $P_f$ for $\Delta Z \leq 6$. The calculations predict a rapid rise of $P_f$ with increasing $\Delta Z$, being close to the limiting value of 1 already for $\Delta Z \geq 3$. These results show that TLF nuclei with atomic number $Z = 90 - 96$ populated in transfer reactions exhibit substantially reduced fission probabilities as compared to the statistical model predictions.

In Fig. 2 the measured $P_f$ data are compared with earlier results from Gavron et al.\textsuperscript{16} for nuclei at lower excitation energies. All the nuclei studied exhibit a steep rise of $P_f$ at the fission barrier, followed by a slight decrease, due to neutron evaporation competition in the second chance fission. These results indicate that there is not much increase in the $P_f$ value for all systems above 20-30 MeV of excitation energy.
that means that the fission width at these higher excitation is much smaller as compared to the neutron width. Such a behavior is considered to be a consequence of a large dynamical hindrance to fission due to viscosity effects. From calculated neutron lifetimes as a function of the excitation energy of TLF nuclei it appears that these heavy nuclei will predominantly decay by neutron emission at excitation energies above 30-50 MeV, if fission dynamical times are assumed to be of the order of 10-100 zs.

3.2. Fusion-Fission channel

Neutrons and alpha particles energy spectra were measured simultaneously, in coincidence with fission fragments. Fission events were selected gating on couples of detectors located in the reaction plane at folding angle corresponding to full momentum transfer ($\theta_{FF}^{lab} = 135^\circ$). It is important to note that, due to the angular opening of the Ball detectors ($\Delta \theta \sim 18^\circ$), there is a large acceptance in the folding angles, consequently the selected events are not entirely associated with the full momentum transfer, but it is also possible a contributions from incomplete momentum transfer events.

Fourteen laboratory neutron energy spectra, selecting various fission fragment-neutron correlation angles, were constructed. The neutron spectra corrected for the detector efficiency, were simultaneously fitted by assuming three moving sources corresponding to the pre-scission composite nucleus and post-scission two fission fragments. The pre-scission neutron multiplicity and temperature $M_n^{pre}$, $T_n^{pre}$ and the post-scission fragment neutron multiplicity and temperature $M_n^{post}$, $T_n^{post}$ (where $M_n^{post}$ refers to the neutron multiplicity from both fragments) were determined from the fits. Best fit values of the parameters are found to be $M_n^{pre} = 8.7^{+2.0}_{-2.0}$, $M_n^{post} = 8.6^{+2.0}_{-2.0}$, $T_n^{pre} = 2.4^{+0.1}_{-0.1}$ MeV, $T_n^{post} = 1.3^{+0.1}_{-0.1}$ MeV. The experimental neutron spectra with the results from the moving source are shown in Fig. 3. The dotted, dashed and solid lines correspond to the pre-scission, post-scission and total neutron yield, respectively.

The alpha particle spectra in coincidence with the above defined fission fragment-fission fragment trigger have been derived for a number of the $8\pi$LP telescopes. The moving source fits to the experimental alpha spectra were performed by adjusting empirically the emission barriers. The best fit parameters obtained from the analysis are found to be $M_\alpha^{pre} = 0.22^{+0.08}_{-0.08}$, $M_\alpha^{post} = 0.1^{+0.03}_{-0.03}$ ($M_\alpha^{post}$ corresponds to the emission from both fragments), $T_\alpha^{pre} = 2.4^{+0.2}_{-0.2}$ MeV, $T_\alpha^{post} = 1.0^{+0.2}_{-0.2}$ MeV.

Dynamical model calculations have been performed based on the HICOL code, developed by Feldmeier$^{17}$, in which dynamical evolution of the two colliding nuclei is described by a sequence of shapes, consisting of two spheres connected by a conical neck. These calculations show that 90% of the observed events are of quasi-fission type which correspond to an orbital angular momentum window of $47h$ to $155h$, while the remaining 10% are from compound nucleus decay which correspond to orbital angular momenta only up to $46h$. HICOL calculations give also the fission time scale as a function of orbital angular momentum. The average fission time derived by averaging over $l$ distribution is about $2 \times 10^{-20}$ s, which should be compared
with the fission time derived from the statistical model analysis of the observed pre-scission neutron component.

We have then performed Statistical Model calculations using PACE2 code to determine the dynamical time needed to emit the observed pre-scission neutrons from the nucleus $^{260}_{104}$Rf, assuming standard level density parameters $a_\nu = a_f = A/10$ MeV$^{-1}$. It is found that a delay time of $5^{+7}_{-3} \times 10^{-20}$ s is required to account for the observed number of pre-scission neutrons. This delay, that is in agreement with the systematics reported in the work of Hinde et al.\cite{Hinde18}, is also consistent with the results from HICOL dynamical calculations. It is to note that for the same delay time $5 \times 10^{-20}$ s the pre-scission alpha multiplicity predicted by PACE2 are significantly larger than the experimental values. The difficulties in reproducing simultaneously the experimental neutrons and alpha particles multiplicities by using the same fission delay, already reported in the past by Lestone et al.\cite{Lestone19} and Ikezoe et al.\cite{Ikezoe20}. These difficulties might suggest that, since the alpha particles are mainly emitted from very elongated shapes, the deformation effects are not taken correctly into account in the Statistical calculations or that alpha particles are emitted only by a subset of configurations with respect to the neutron decay channel.

§4. Summary and conclusions

In the present work, the multinucleon transfer-induced fission reactions have been studied for the system $^{28}$Si on $^{232}$Th at 340 MeV. The estimated excitation energy and angular momentum transferred to the target-like fragments increase with increasing net charge transfer $\Delta Z$. It is inferred that one can reliably reconstruct the
charge, excitation energy and angular momentum of the fissioning TLF nucleus only for the transfer channel up to $\Delta Z \leq 6$. For the corresponding TLF nuclei statistical model calculations predict a very high fission probability. On the contrary, the measured ratio between transfer-fission and PLF singles $Y_f$, which can be identified as fission probability $P_f$ in the case of $\Delta Z \leq 6$, shows a saturation in the range of $Y_f = 0.4-0.6$ implying that there is a sizable survival probability of TLF nuclei with $Z = 90-96$ against fission. This result can be explained only by invoking large fission dynamical times of about 10-100 zs, indicating that although the composite system was populated at high excitation energies, the fission mostly take place from a rather cold nucleus after a substantial neutron emission. It would therefore be of interest, in order to maximize the cross section for the synthesis of heavy and superheavy elements, to consider the use of neutron-rich radioactive beams at above barrier energies on actinide nuclei, since the fused system is expected to cool down by neutron evaporation rather than by fission in the initial stage.

Moreover, for the same system pre-scission neutrons and alpha particles multiplicities have been simultaneously measured for the fission-like channel. From the multisource fits to the measured neutron and alpha particle spectra, pre- and post-scission multiplicities and temperatures have been deduced. Dynamical model calculations, based on HICOL code, suggest that only $\sim 10\%$ of the fission yield is due to compound nucleus fission being the dominant part due to quasi-fission or fast-fission reactions. The overall average dynamical time integrated over all $l$-values is estimated to be $\sim 2 \times 10^{-20}$ s. This value is consistent with the delay time of $5^{+7}_{-3} \times 10^{-20}$ s determined from a comparison of pre-scission neutron multiplicity with PACE2 statistical model code.

References

11) G. Prete et al., Nucl. Inst. and Meth. A422 (1999), 263.