Observation of selective γ decay of fission-like fragments in the $^{32}S+^{58}Ni$ reaction at 143 MeV

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The γ decay of energy relaxed fragments has been studied as a function of the mass asymmetry in the exit channel for the $^{32}S+^{58}Ni$ reaction at 143 MeV. γ-multiplicity and γ-anisotropy data as well as $\langle Q \rangle$ values from fragment inclusive measurements show the differences between the deep-inelastic and the "fission-like" regimes. The role of the deformation in the symmetric splitting is outlined for medium mass ($A \sim 100$) composite systems.

The symmetric splitting of medium mass ($A \sim 100$) composite systems was already observed in some heavy-ion reactions at bombarding energies for which compound nucleus fission is supposed to be negligible.[1] These "fission-like" reactions represent an intermediate stage between deep-inelastic and compound nucleus processes and may provide valuable information on the dynamics of heavy-ion collisions.[1,2]

Recent work on "quasi-fission" reactions induced by ^{238}U has shown that the observed relaxation of the mass asymmetry degree of freedom is in agreement with the one-body dissipation picture.[3] It is suggested[3] that the driving force responsible for the mass drift for heavy systems vanishes at $A \sim 100$ because of the disappearance of the minimum at symmetry in the liquid drop potential energy surfaces.

A different approach to the symmetric splitting has been proposed for medium-light nuclei ($A \leq 56$).[4] A correlation has been found between the cross sections for fission-like events in the $^{16}O + ^{40,44}Ca$ reactions and the $^{28}Si + ^{28}Si$, $^{30}Si + ^{30}Si$ large angle elastic scattering.[5] This result may be connected[4] to the predicted existence of secondary minima at extremely large deformation in the potential energy surface of the composite system calculated by a microscopic-macroscopic method. Consequently the occurrence of symmetric splitting could be related to the microscopic structure of the dinucleus.

The influence of the composite system shape, treated as a macroscopic variable, on the mass asymmetry relaxation has been outlined also by the trajectory calculations for reactions of ^{238}U on ^{48}Ca and ^{27}Al targets.[6]

In this Brief Report we present data for the $^{32}S + ^{58}Ni$ reaction at 143 MeV which show how the γ-ray multiplicity and anisotropy of energetically fully relaxed events depend on exit channel mass asymmetry. We have found evidence for selective γ decay of the fission-like reaction products ($Z=20-23$) characterized by a decrease of the γ multiplicity and a strong, correlated, increase of the in-plane to out-of-plane γ-ray anisotropy $W(90°)/W(0°)$. Such a high γ-ray anisotropy is not a known feature for reaction products in this mass region, and it suggests strong fragment deformations at scission.

The experiment was performed at the XTU tandem facility of the Legnaro National Laboratories. The 144.3 MeV ^{32}S beam was focused onto a thin (0.2 mg/cm^2) foil of ^{58}Ni, 99% enriched. Projectile-like fragments (PLF) and fission-like fragments were detected by a position-sensitive Bragg curve ionization chamber[7] at $\theta_{lab}=+30°$ with an opening angle $\Delta\theta=7°$ in plane and $\Delta\Phi=3°$ out of plane. The resolving power $Z/\Delta Z \geq 50$ at $Z=16$ allowed a clear separation of elements up to the highest detected nuclear charge ($Z=23$). The reaction Q value was evaluated from the measured energy and position using two body kinematics with average masses.

The γ rays were detected at 40 cm from the target by four shielded 10 cm$\times$10 cm NaI(Tl) crystals, three of which were in the reaction plane ($\theta_{lab}=+60°, +135°, -105°$), and the fourth perpendicular to the reaction plane. The measurements covered the range $E_\gamma=0.2-8.0$ MeV, and absolute detection efficiencies were determined *in situ* using calibrated sources. Ionization chamber singles and ionization chamber NaI(Tl) coincidences were recorded.

For individual detectors the average γ multiplicity M_γ was evaluated from the ratio of fragment-γ coincidences to fragment singles, with corrections for the γ-detection efficiency. The in-plane γ-ray anisotropy was found to be rather weak (less than 20%) as expected,[8,9] and therefore the in-plane data were averaged. The in-plane to out-of-plane anisotropies $W(90°)/W(0°)$ were used to obtain M_γ values integrated over all angles.

Figure 1 shows the average Q value, $\langle Q \rangle$, versus ejectile Z as extracted from the fragment singles. The experimental data are compared in Fig. 1 with calculations of the energy loss of spherical nuclei having the Coulomb repulsion energy V_C as kinetic energy in the exit channel. As usual for these reactions, the inelasticity increases as a function of the net charge transfer. The $\langle Q \rangle$ values for fission-like fragments $(Z \geq 20)$ lie on the calculated curve. This is normally taken as an indication of the fragment deformation if the rotational energy contribution to the $\langle Q \rangle$ value has to be accounted for.[10] Strong particle evaporation would shift $\langle Q \rangle$ towards lower values, but this seems not to be the case because of the low excitation energy per fragment in the symmetric splitting region $(E_x < 15$ MeV if $E_x = \langle Q \rangle /2)$.

Figures 2 and 3 show the measured M_γ and $W(90°)/W(0°)$ values as a function of the ejectile Z for the kinetic energy window $V_C \pm 10$ MeV so that only events involving total relaxation are included. The error bars in the figures represent only the statistical errors.

The experimental data for PLF $(Z \leq 20)$ show the known features of deep inelastic reactions. The total transferred spin derived from M_γ (Ref. 11) for PLF is in good agreement with the sticking condition calculated for spherical nuclei at $l = 56\hbar$, which is an average value of the l window available for two-body reactions. The γ-energy integrated anisotropy values $W(90°)/W(0°) \sim 1$ for PLF reflect more the mixing of γ multipolarities (and/or of stretched and nonstretched transitions) than the degree of spin alignment of the fragments. In fact, sizable anisotropies $W(90°)/W(0°) \geq 2$ have been measured with Ge detectors for $E2$ transitions in coincidence with $Z = 16, 15, 14$ in the same experimental configuration.[12]

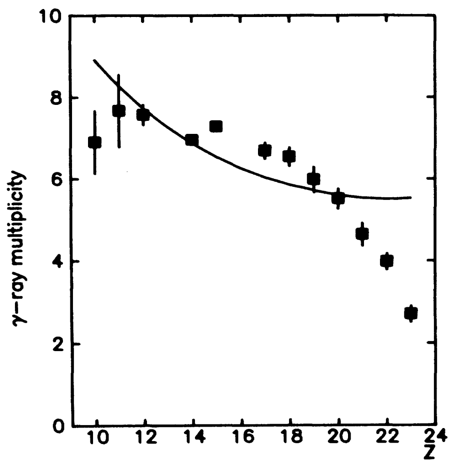

FIG. 2. Angle integrated M_γ vs fragment Z for the kinetic energy window corresponding to $V_C \pm 10$ MeV. The calculated M_γ (solid line) refers to spherical nuclei at sticking $(l = 56\hbar)$ using the relationship between total transferred spin and M_γ taken from Ref. 11.

In the fission-like region there is a surprising decrease of M_γ clearly correlated with a strong increase of the in-plane component of the γ radiation.

The M_γ trend with the mass asymmetry in the exit channel is opposite to the observations for heavier systems,[13] where M_γ reaches a maximum at symmetry. In that case, anisotropy values $W(90°)/W(0°) \sim 1$ have been reported showing a small increase $(< 25\%)$ at symmetry. Furthermore, nuclei around $Z = 22$ populated by inelastic reactions do not show preferential γ emission in the reaction plane for a wide range of spin and excitation energy combinations: for ^{16}O- and ^{32}S-induced reactions on Ti

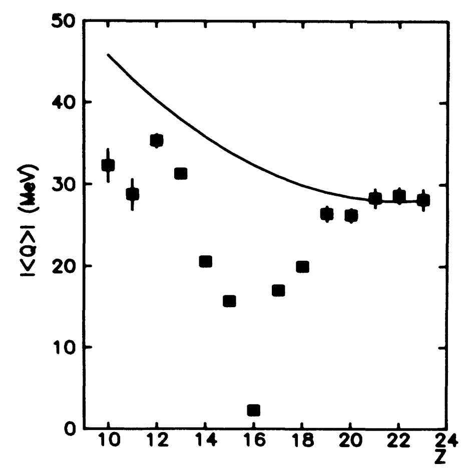

FIG. 1. $\langle Q \rangle$ values versus fragment Z. The solid line shows $Q = E_{c.m.} - V_C$ for spherical nuclei.

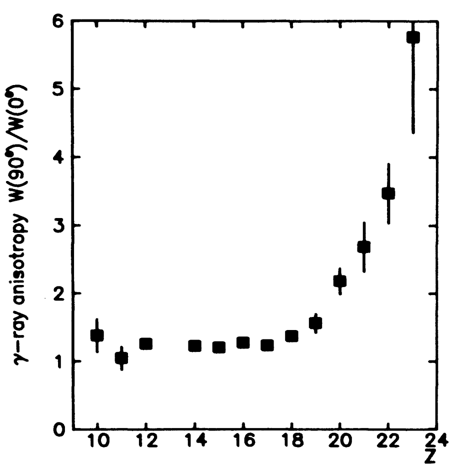

FIG. 3. γ energy integrated in-plane to out-of-plane anisotropy versus fragment Z for the energy window of Fig. 2.

isotopes,[14,15] the γ anisotropy is $W(90°)/W(0°)\sim 1$ for different PLF and Q windows. A dominance of in-plane emission is instead expected in the decay of deformed nuclear states by stretched $E2$ transitions.[16]

To explore the influence of the deformation on the other observables, the $\langle Q \rangle$ and M_γ values for fragments with $Z=22$ have been calculated assuming two prolate ellipsoids at the sticking condition having a variable axis ratio a/b and a separation distance $d=1.5$ fm. The experimental data are reproduced assuming $a/b=1.7$. This deformation is larger than that determined from the Q-value analysis of the $^{16}O + ^{48}Ti$ deep-inelastic reaction.[14] The present data (Figs. 2 and 3) clearly indicate a difference in deformation between symmetric splitting fragments and deep inelastic ones.

The selective population of deformed states in the exit channels of the symmetric splitting reactions has an important consequence for the dynamics of the mass asymmetry relaxation in the mass $A\sim 100$ region. The phase-space available for the fragments at scission may be determined not only by the dissipated energy and transferred angular momentum, but also by the degree of deformation. Therefore the occurrence of the symmetric splitting should be related, through the deformation, to the microscopic structure of the nuclei. The reported results raise questions about the nature of the final states populated by these reactions.

The observed selectivity in the γ decay should be connected with the production of well-defined fragments and/or class of states in the exit channels. In this work the isotopes responsible of the unexpected decay are not identified, but Q_{gg} arguments suggest $^{44,45,46}Ti$, $^{42,43}Sc$, and $^{40,41}Ca$ as the most probable primary fragments of the symmetric splitting. There are theoretical predictions of local minima in the $l=0$ potential energy surfaces, calculated by the macroscopic-microscopic method, at large prolate deformations $(a/b\sim 2)$ in ^{40}Ca and ^{44}Ti at excitation energy $E_x = 11-17$ MeV.[17] These minima reflect the occurrence of shell structure in the single-particle level scheme at certain deformations. A possible explanation is that the selective γ decay may be associated with the excitation of this class of states.

We note that the sequential decay of primary fragments populated in the symmetric splitting cannot at present be clarified because the coincident γ-ray spectra were low in statistics. The average energy of those γ-ray events is $\langle E_\gamma \rangle \sim 1$ MeV so the γ cascade accounts for only a small portion of the total excitation energy. The emission of at least one particle is, therefore, expected. It is surprising that in the presence of particle decay, large γ anisotropies are also found.

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