Observation of fusion-like residues in energetic nuclear collisions at the Celsius storage ring

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Recent experiments at the CELSIUS storage ring of Uppsala, Sweden, have revealed the existence of high momentum transfer target-like fragments contrary to expectations. Recoiling heavy fragments in the reaction of 250 MeV/nucleon \(^{14}\)N on \(^{131}\)Xe have been measured at 10\(^{\circ}\) with respect to the beam direction with specially designed recoil telescopes. Simulations with the Boltzmann-Uehling-Uhlenbeck (BUU) transport equation are not able to reproduce the experimental observations. Intermediate mass fragments (IMF: \(3 \leq Z \leq 8\)) were also measured using three elements of the CHICSi \(\Delta E - E\) telescopes. Single energy spectra of IMFs suggest that the larger fragments \((Z = 7, 8)\) are preferentially emitted from a single equilibrated, but very hot source \((T \approx 9\) MeV).

Keywords: Nuclear physics, nuclear reactions.

We report in this article the direct measurement and surprising observation of fusion-like residues \(i.e.\) residues with substantial linear momentum) from collisions of \(^{14}\)N and \(^{131}\)Xe at 250 MeV/nucleon.

Experimental

The experiment was carried out at the CELSIUS heavy ion storage ring of the The Svedberg Laboratory in Uppsala, Sweden. A beam of \(^{14}\)N delivered by the Gustav Werner Cyclotron was injected, accelerated to an energy of 250 MeV/nucleon, electron cooled and stored for periods of five minutes before being dumped. The target was thin gas jets of \(^{131}\)Xe with a thickness of \(\sim 10^{13}\) atoms/cm\(^2\) resulting in an average luminosity of \(4 \times 10^{28}\). Data was acquired only with the fully accelerated and cooled beam, about 208 seconds of the full (300 s) cycle. The detailed operation of the storage ring and the gas jet target system has been discussed elsewhere [4].

A time of flight-energy telescope [5] especially designed to have very low energy threshold \(\sim 35\) keV/nucleon) yet meet the highly demanding UHV environment of storage rings was placed at 10\(^{\circ}\) with respect to the beam direction.
to measure slow-moving recoil fragments. The recoil telescope consists of two micro channel plates (MCP) of the Busch electron mirror type with 20\(\mu\)g/cm\(^2\) C foils, followed by a 2 \(\times\) 2 cm\(^2\) p-i-n diode Si detector. The two MCPs give a start and stop signal which is used to measure the time of flight (TOF), and hence, the velocity of the fragments, while the Si detector measures the energy. By combining the velocity and energy measurements, it is possible to reconstruct the mass of the fragments. A spontaneous fission \(^{252}\text{Cf}\) source was used to calibrate the detector system by using the Schmitt calibration procedure \cite{6} and matching well-known average masses and energies of the heavy and light fragment groups. The energy and mass were reconstructed in an iterative process as the built-in correction for pulse height defect depends on the mass of the fragment.

Three elements of the future CHICSi barrel \cite{7} were put at 60\(^\circ\), 80\(^\circ\) and 100\(^\circ\) with respect to the beam, in the same plane as the recoil telescope, to measure IMFs. One of these CHICSi elements consist of a thin \(\Delta E\) (12\(\mu\)m thickness) Si detector, a thicker \(E\) (300\(\mu\)m) Si detector followed by a veto detector (300\(\mu\)m Si detector). A source of \(^{228}\text{Th}\) was used to calibrate the \(\Delta E\) and \(E\) detectors.

Both the recoil telescope and CHICSi elements were protected from UV light from the interaction region by a 50 \(\mu\)g/cm\(^2\) Ni foil placed in front of the first elements facing the target. Appropriate corrections for energy losses in the Ni foils were performed event-by-event.

Results

A total of 203 fragments with masses 20 < \(A\) < 150 were measured in the recoil telescope. Figure 1 shows the average linear momentum of the fragments as a function of their mass. Error bars are statistical. For low mass fragments (\(A < 70\)), the behavior of increasing linear momentum can be ascribed to the properties of fission fragments. To show this, we have performed a simple calculation in which we assume a fissioning nucleus is moving along the beam-line with a certain velocity and then fissions. The kinetic energy of the fission fragments is calculated using the systematics of total kinetic energy release of fissioning systems at rest. The

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Observed mean linear momenta of residues as a function of mass from the interaction of \(^{14}\text{N}\) and \(^{131}\text{Xe}\) at 250 MeV/nucleon. Solid line shows the predictions of BUU and a statistical decay model. Dashed lines shows the prediction of fission fragments resulting from events with 5\% and 25\% momentum transfer, respectively.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Single kinetic energy spectra of IMFs with \(Z = 7, 8\). Solid lines are moving source fits assuming a single equilibrated source.}
\end{figure}
laboratory linear momentum of these fragments is then evaluated at an emission angle of 10°. The dashed lines in Fig. 1 shows such a calculation assuming the projectile transfers on average 5% and 25% of its momentum to the fissioning nucleus, respectively. It is clear that fission occurs for rather peripheral collisions. Heavy residues (A > 80), on the other hand, seem on average to result from collisions where the projectile transfers a substantial part of its linear momentum. Using the massive transfer model, the momentum transfer amounts to ∼ 39% of the incoming projectile momentum. This finding is unexpected. Simulations with the BUU transport equation [8] and a statistical decay model calculation as after-burner is not able to reproduce the experimental observations (solid line).

The single laboratory kinetic energy spectra of IMFs at the three measured angles were fit with a moving source parametrization assuming emission from a single equilibrated source. Fits to Z ≤ 6 fragment spectra could not be done with sufficient goodness, indicating additional sources may exist. Figure 2 shows the singles kinetic energy distributions of IMFs with Z = 7, 8 and respective moving source fits (solid lines). The goodness of the fits give us confidence that these fragments are emitted preferentially from a single equilibrated source. It is, hence, tempting to associate this source with the fusion-like residues observed in the recoil telescope, given the source velocities extracted from the fits. Furthermore, the temperatures derived from the slopes of the Z = 7, 8 spectra are about 8.8 MeV which corresponds to an excitation energy of about 950 MeV for an A = 137 primary TLF with 40% momentum transfer. This excitation energy is close to the maximum attainable by a bound nucleus. The apparent survival of highly excited primary fragments by the emission of Z = 7, 8 IMFs and other charged particles is very surprising and needs further investigation. Experiments scheduled to use the full CHICSi barrel, fifteen recoil telescopes and a projectile-like fragment (PLF) forward wall will hopefully fully clarify these interesting findings by measuring IMFs, PLFs and fusion-like residues in coincidence.

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