Search for Heavy and Superheavy systems in $^{197}$Au + $^{232}$Th Collisions near the Coulomb Barrier

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Abstract. The reaction $^{197}$Au + $^{232}$Th at 7.5 AMeV was studied using the BigSol spectrometer at Texas A&M. Theoretical calculations suggest that this reaction could be used as an alternative method to produce heavy and superheavy elements. During the short interaction time, heavy systems of interacting nucleons are formed and, due to the strong energy dissipation, a large number nucleons can be transferred. The larger the lifetime of the decaying giant system, the larger the possible number of transferred nucleons. Moreover shell effects may help in the formation of heavy nuclei in the region of the island of stability. Reaction products emitted in an angular range from 6 to 16 degrees were collected at the entrance of the BigSol spectrometer and detected at the focal plane using a segmented ionization chamber. Four position sensitive PPAC detectors placed along the ion’s flight path were used to track the product trajectories and measure the times of flight. The experimental results are presented and compared with theoretical calculations performed with the Constraint Molecular Dynamics code.
1. Introduction

The synthesis of superheavy elements (SHE) has been an important topic in both theoretical and experimental nuclear science for many decades. There are two standard experimental methods of SHE production: the “cold” and “hot” fusion reactions. “Cold fusion” reactions with Pb or Bi targets [1] produce SHE which are neutron deficient and have short half-lives. The excitation energy of the compound nucleus (CN) is in the range $E_{\text{CN}}^* = 10 - 20 \text{ MeV}$. In these reactions the formation cross-section for SHE decreases very quickly with increasing charge of the projectile and becomes less than 1 pb for CN with $Z>112$. The “hot fusion” reactions, with actinide targets and $^{48}$Ca beams [2], produce SHE with more neutrons, but still very far away from the predicted neutron shell closure $N=184$ for the SHE “island of stability”. The excitation energy of the CN is in the range $E_{\text{CN}}^* = 30 - 50 \text{ MeV}$. SHE with atomic number $Z$ in the range (113-118) have been produced with this method. The cross-section for $Z=118$ is about 0.5 pb, whereas for elements heavier than $Z=118$ is expected to drop to the fb level.

Two body reactions involving very heavy nuclei can be considered as an alternative method to produce SHE along the “island of stability”. Deep inelastic reactions involving two $^{238}$U nuclei at energies around the Coulomb barrier have been studied over the years by several authors from the theoretical [3-5] and the experimental [6-9] point of view. Though SHE have not been yet detected in such experiments the results indicate that the observed fragments originate from the binary break up of a rather long living and highly deformed di-nuclear system (DNS). In this work we investigate the reaction $^{197}$Au + $^{232}$Th at 7.5 MeV/nucleon. The experiment was performed at the BigSol time of flight spectrometer of Texas A&M. The energy and the charge distribution of the reaction products were measured. We correlate the energy, mass and Z distributions of the detected events in order to understand the evolution of the DNS. A theoretical estimation of the reaction products was also performed using the Constrained Molecular Dynamics code (CoMD) [3] at the projectile energies 6, 6.75, 7.5AMeV. Following the time evolution of the reaction this code predicts that 3% DNS with $Z$ about 164 survive for more than 3 $10^{21} \text{ s}$. In these cases a large exchange of mass is expected. Experimentally some surviving events with atomic number about $Z=100$ were detected, however further improvements to the experimental setup are needed in order to increase the detection sensitivity and confirm those events.

2. Experimental setup

The experiment was performed using the BigSol Superconducting Solenoid time of flight spectrometer at the Texas A&M. A complete description of this device can be found in ref [10]. The lay-out of the beam line as used in this work is shown in Fig. 1.

![Figure 1: Experimental Setup. See the text for details.](image-url)
plane detector station is placed. A beam blocker is placed just after the target to stop the beam and select the reaction products emitted at angles larger than 6°. The acceptance of the spectrometer is therefore in the range 6°-16°. Four position sensitive Parallel Plate Avalanche Counters (PPAC) are used to reconstruct fragment trajectories between the production target and the focal point. A 16 segment annular PPAC with a 2.5 cm central hole (PPAC1) is placed 25 cm downstream from the target. Three other PPAC detectors are positioned at 3.3 m (PPAC2), 5.1 m (PPAC3), 6.15 m (PPAC4).

The detector system located at the focal point includes PPAC4 and a multi-anode Ionization Chamber (IC), used either as a stopping detector for slow heavy reaction products or as a transmission detector for faster fragments. The IC has an active area of 6.5x6.5 cm$^2$ and is equipped with 8 parallel anodes, each having a width of 4.65 cm along the beam direction.

The experimental setup provides a number of redundant time measurements. These time measurements consist of independent measurements of the time difference between PPAC3 and PPAC4, PPAC2 and PPAC3, PPAC2 and PPAC4 and between PPAC1 and PPAC4. All time measurements are required to be consistent in order to accept an event. We also implemented a pileup rejection scheme in which we require the measured time between two events in PPAC4 to be more than 8 μs or the event is rejected. The energy loss in each of the IC anodes is measured using both a peak sensing ADC after signal shaping as well as sampling the raw signal using a flash-ADC. The analysis of the flash-ADC signals provided a powerful method to reject spurious events.

The BigSol magnetic field was tuned in order to optimize the transmission of the low energy heavy fragments. The estimated transmission efficiency based on a simulation of the trajectories in the magnetic field gives an average efficiency of 60% and 5% for the projectile-like fragments and their fission fragments respectively.

Time and energy calibrations of the system were obtained by using different heavy ion beams ($^{40}$Ar, $^{84}$Kr, $^{131}$Xe, $^{197}$Au, $^{238}$U) at different energies (7.5 and 15 AMeV) directly into the detectors with the beam blocker removed. During the measurements calibration runs with the direct $^{197}$Au beam were repeated at regular time intervals. The energy losses in the detectors were calculated using a new effective charge parameterization [11] developed to calculate the stopping powers and the energy loss of the reaction products. This parameterization is based on the existing energy loss data of several heavy ions with 18<Z<92 in the energy range 0.1-15 MeV/nucleon, in the detector materials (mylar and isobutane) and can be used to extrapolate the stopping powers for very heavy elements.

The atomic number identification of the reaction products is obtained by comparing stopping powers measured in the eight sectors of the IC as a function of the velocity with the values predicted by our extrapolation. The resolution dZ/Z is about 3.5% (FWHM) for the 7.5 AMeV $^{197}$Au beam.

In a first approximation, a provisional mass of the fragments is assigned simply by requiring that the A/Z ratio of the entrance channel is conserved. For the ions stopped in the IC, the mass is also reconstructed by dividing the total energy measured in the IC and PPAC4 by the energy in MeV/nucleon measured from the time of flight between PPAC3 and PPAC4. Even if the experimental mass resolution is poor, Fig.2 shows a rather good agreement between the provisional mass and the reconstructed one.

The initial energy of the fragments is calculated by correcting the energy measured by the time of flight by the energy losses in the PPACs and in half the target thickness.
3. Result and Discussion

3.1. Atomic number distribution of the reaction products

Fig. 3 shows the atomic number distribution of the reaction products emitted in the angular range (6-16°) measured at the BigSol focal plane. Different regions in the plot correspond to different reaction mechanisms. The events with 60<Z<100 result mainly from the break-up of an initial DNS in two fragments. They show a broad peak around the Z=80 corresponding to projectile-like fragments produced in the deep inelastic reaction with a tail between Z=60 and Z=70 probably resulting from the charged particle evaporation from the primary excited deep inelastic fragments or from the fission of the very heavy systems. The events with Z<60 are fission fragments from the excited projectile-like or target–like nuclei formed in the deep-inelastic reaction. We note that in our experiment the Coulomb barrier for spherical nuclei in the exit channel is about 680 MeV. Since the 232Th target was very thick the total center of mass energy of the entrance channel drops from 799 MeV to 629 MeV as the beam passes through the target.

The Z distribution of the reaction products calculated using the CoMD code, was obtained by following the evolution of the system up to 5000 fm/c and considering relatively central collisions with impact parameter from fm 0 to 1 fm. This selection is made in order to maximize the reaction products going into our acceptance angles. Different projectile energies were considered in the calculation (6, 6.75 and 7.5 MeV/nucleon). The simulated charge distributions are also shown in Fig. 3 and compared with the experimental data. The results of the simulation show that the number of reaction products populating the region from Z=60 to Z=70 increases with increasing the projectile energy. This suggests that increasing the energy of the projectile plays against the survival probability of the more excited reaction products.

The Z distribution calculated with a projectile energy of 6.75 MeV/nucleon (the average of the beam energy before and after the target) fairly agrees with the experimental charge distribution.
Figure 3: Z distribution of the reaction products. Points show experimental data, lines refer to CoMD calculations (dashed line at 6 MeV/nucleon, solid line CoMD at 6.75 MeV/nucleon, dotted line CoMD at 7.5 MeV/nucleon).

Few events (5) with high atomic number $97<Z<102$ survived the pileup-rejection filters. Unfortunately the energy of those events at the entrance of the IC is about or below 1 MeV/nucleon. At this energy the Z resolution of our detector is relatively poor. More accurate measurements are required in order to improve the result. A rough estimation of the reaction cross section for these very heavy elements gives an upper limit of about 11 nb/event.

3.2. Energy distribution of the reaction products

In order to understand the origin of the detected reaction products we analyzed their energy distribution. In deep inelastic reactions the kinetic energy of the entrance channel is transformed into internal excitation of different degrees of freedom of the DNS. Selecting the products emitted in the angular range from 6 to 16 degrees in the laboratory framework we intend to filter out relatively central collisions characterized by longer survival time of the DNS and larger energy dissipation compared to peripheral deep inelastic collisions. With our experimental setup we can detect only one of the reaction products and therefore we cannot obtain a direct measure of the total kinetic energy after the reaction. The energy of the fragments is obtained from the measured time of flights after correction for the energy loss in the PPACs and half of the target thickness. Figure 4 shows the energy of the detected fragments in the center of mass as a function of the atomic number. The elastically scattered gold particles are cut by the magnet settings, therefore the detected fragments come mainly from the central collisions. The low kinetic energy of the products in the Z range 70-85 suggests that they might be originated by relatively long lived systems. The data analysis is still in progress.
4. Conclusions

The reaction $^{197}$Au+$^{232}$Th at 7.5 AMeV has been investigated by using the BigSol time of flight spectrometer at Texas A&M. Large mass transfer is observed in the detected reaction products, giving rise to some nuclei with atomic number larger than 97. We estimate the cross section for those events at about 50 nb level. The Z resolution of the system for those events is worse than 10% because their energy is very much degraded before the IC. Therefore a precise identification of the nuclei is not possible. Further improvements of the experimental setup are needed in order to reduce the energy loss of the ions in the detectors. A higher granularity of the IC is also recommended in order to improve the efficiency of the pileup rejection. The results obtained so far suggest the possibility of producing nuclei with Z about 100, however confirmation by decay measurements or other techniques would be required to be certain of this conclusion.

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