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NEW EXPERIMENTAL APPROACH FOR HEAVY AND SUPERHEAVY ELEMENT PRODUCTION

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In this article we present a new experimental approach for production of heavy and superheavy elements (HE, SHE). Nuclear reactions at low incident energies induced by heavy ion (HI) projectiles on fissile target nuclei are investigated. Dedicated detection setup is presented and the preliminary results for the reaction $^{197}Au(7.5\ \mathrm{MeV}/u)+^{232}Th$, studied at the Cyclotron Institute of Texas A&M University, are given.

1. Introduction

The synthesis of HE and SHE elements through complete fusion (CF) reactions has been an important and successful subfield of nuclear physics research for more than fifty years. Presently the focus is on superheavy element production using two basic techniques i.e. "cold" and "hot" fusion reactions. Those two approaches successfully led to the discovery of many new elements among them Z=112 and 118.[1,2] The heart of a typical SHE detection setup is a velocity filter which transmits the synthesized superheavy nuclei to the detector system. There, they undergoes subsequent radioactive α-decays or spontaneous fission (SF). Detection of these decay chains serve to unambiguously identify the parent (implanted) nucleus. However, cross sections involved ($\sigma \sim$1 pb) are at the limit of the sensitivity achievable with the current technology.

2. New SHE Production Approach

In this context we propose a new approach in which it is suggested to investigate nuclear reactions at low incident energies (near the Coulomb barrier) induced by heavy projectiles e.g.: ^{172}Yb, ^{197}Au on fissile target nuclei e.g: ^{232}Th, ^{238}U.[3]

A possible scenario for such reactions is that they might lead to massive transfers into regions where shell effects on the underlying potential energy surface might lead to SHE production. Does the superheavy system survive as a ground state nucleus? This depends on the excitation energy and angular momentum brought into this system during the transfer process. The lower its excitation energy and angular momentum, the larger the chance that the system emits only few neutrons.

In the proposed reactions a relatively long interaction time is needed to transfer the massive fragment to the projectile. As a result, quite high excitation energies of the reaction partners can be generated and consequently the survival probability of the produced heavy and superheavy nuclei can decrease dramatically. On the other hand, the second reacting partner can be considered as a reservoir for energy and orbital angular momentum with respect to the rest of the system. Besides, if the transfer process of the massive fragment takes place in a more peripheral collision the resulting system might be formed with small excitation energy and consequently its survival probability will increase.

After test experiments, (^{136}Xe, ^{172}Yb, ^{198}Pt (15 A MeV) $+^{238}U$; ^{84}Kr, ^{172}Yb (15 A MeV) $+^{232}Th$; ^{238}U (15 A MeV) $+^{238}U$, ^{198}Pt, ^{238}U, ^{232}Th; ^{84}Kr (24.8 A MeV) $+^{232}Th$; ^{84}Kr, ^{129}Xe, ^{197}Au (7.5 A MeV) $+^{232}Th$), we choose to study ^{197}Au (7.5 A MeV) $+^{232}Th$ reaction. Characteristics of the fission of Th suggest that one can explore three regions of SHEs: Z≈112, Z≈136 for low excitation of Th target and Z≈124 for higher excitation (more violent collisions).

The objective of the research was to test experimentally the possibility that HE/SHE elements might be produced in massive transfer processes and to establish cross sections or cross section limits for these processes. In this way we hope to answer the question of whether this method can be competitive with the standard CF approach.

3. Experimental Setup Overview

In cold or hot CF reactions, the synthesized SHE have a well defined velocity, v_{ER}, which is very close to that of the compound nucleus. The "classical" velocity filter is set to isolate ions with velocities within a narrow window around v_{ER} in order to transmit SHE ions to the detection system while the beam and other reaction products are rejected. The filter also has a small angular acceptance (≈30 msrad).

In our approach, the scenario presented in the previous section assumes that the HE/SHE nucleus can be produced in peripheral as well as in more violent collisions between reaction partners. As a consequence, the velocity spectrum of heavy and superheavy nuclei can be broad and not well known. We can not use in this case a "classical" velocity filter. Instead, one has to use a filter that can accept a wide range

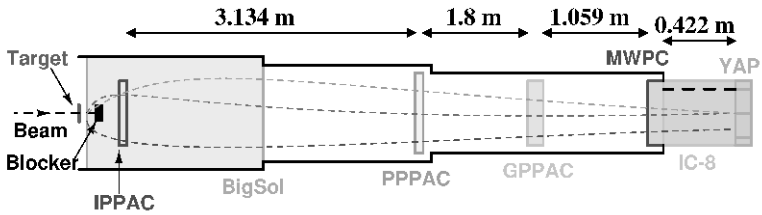

Fig. 1. The detection system of heavy and superheavy elements at Texas A&M.

of HI velocities and has a large angular acceptance. Such a device is installed in the Cyclotron Institute. It is an efficient magnetic velocity filter - superconducting solenoid (BigSol) constructed at the University of Michigan.[4]

Given the axial symmetry of the solenoid the primary beam must be stopped just after the target. That done, the subsequent beam line must be instrumented to identify heavy and superheavy nuclei. Below it is discussed how this was done.

The filtering and the detection system presented in Fig. 1 includes (from the left to the right): a blocker (circular piece of metal) placed after the target in order to stop the beam and reaction products emitted at angles smaller then 1-6 degrees (depending on blocker choice), the previously mentioned superconducting solenoid and a multi-element detector system.[5] The detector system is composed of three parallel plate avalanche counters (IPPAC, PPPAC and GPPAC), a multi-wire proportional counter (MWPC), an ionization chamber (IC-8) and 14 Yttrium Aluminum Pervoskite[6] (YAP) inorganic scintillators that form a wall.

The magnetic field of the BigSol separates spatially different charged HIs in a case when they have the velocity component perpendicular to the Z (beam) axis (3 trajectories in Fig. 1). It is also adjusted to focus HIs in the region approximately 4 meters beyond the BigSol where the IC-8 and YAP detectors are situated.

Three transmission detectors IPPAC, PPPAC and GPPAC are segmented with different geometries and are used to measure the time of flight (ToF) of HIs and their position in each detector, in plane (X-Y) perpendicular to the beam axis. The MWPC is a consecutive transmission detector which measures time tag for ToF determination, X, Y position and the energy loss, ΔE_M, of heavy ions. It is also a trigger unit in this setup. The chamber IC-8 is composed of 8 independent sections. Each section measures energy loss ($\Delta E_{ICi},\ i = 1, ..., 8$) of HI along its path in the detector. All above detectors were filled with isobutane gas. The YAP scintillators served to measure residual energy (if any) of the HIs.

Below we will describe in more details only one of the main component of the detection system which is the IC-8 chamber, Fig. 2. Each section has 4.65 cm length with the anode situated at the left side wall, facing the beam direction, of the box section. This way, the anodes generate the electric field that is perpendicular to the trajectory of ions passing through the chamber. The charges collected by the anodes are proportional to the energy losses of an ion that goes through individual

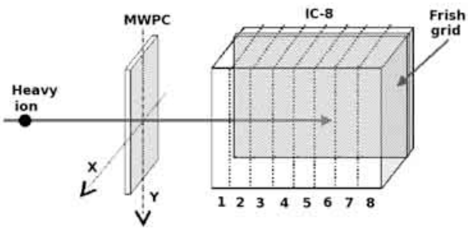

Fig. 2. Schematics of the ionization chamber. In its direct vicinity, the MWPC is mounted.

sections. Additionally, a Frish grid is placed near the anodes to ensure the pulse height (collected charge) independence on the HI trajectory location in consecutive sections. All eight sections are placed in one aluminum cylinder, filled with gas under the pressure 30 mbar.

This multi-element detector was setup to use the technique $(\Delta)E$ vs ToF to identify superheavy elements.

Because our BigSol filter accepts a broad spectrum of velocities of HIs, one observes large counting rates (∼200 counts/second) of heavy ions and light charged particles at the focal plane. It may happen that during the time the acquisition needs to process all signals for a given event, another HI enters the detection setup and detectors will produce additional pulses (pileups) which will be mixed up with the pulses of the triggering, primary ion. The pileup events can mimic detection of very heavy nuclei. Due to this background effect, special attention was given to the detection and electronic setup, in order to minimize the number of such events.

3.1. *Pileup rejection*

Two types of pileup rejection systems were installed. The first applied the electronic logic with a TAC system connected to the MWPC counter. For the second, we have connected Flash ADCs (FADC) to each detector output signal. In case of the PPPAC, GPPAC and MWPC, 10 ns/ch FADCs were connected while 80 ns/ch FADCs were used for each segment of the IC-8 chamber. Time window of all FADCs was adjusted to the dead time of the acquisition system.

Besides, we have developed special procedures of FADCs pulse shapes analysis to eliminated double hits (pileup) events by off-line software.

3.2. *Calibration of the experimental setup*

ToF signals from pair of detectors: PPPAC - MWPC (T_{PM}), GPPAC - MWPC (T_{GM}), PPPAC - GPPAC (T_{PG}) and energy loss signals from the IC-8 and MWPC (ΔE_{ICi}, i = 1...8, ΔE_M) were calibrated by using direct beams (DB) (no target and BigSol switched off) of ^{40}Ar, ^{84}Kr, ^{129}Xe, ^{172}Yb, ^{197}Au and ^{238}U with energies 15, 15, 15, 15, 7.5/15 and 7.5 A MeV, respectively.

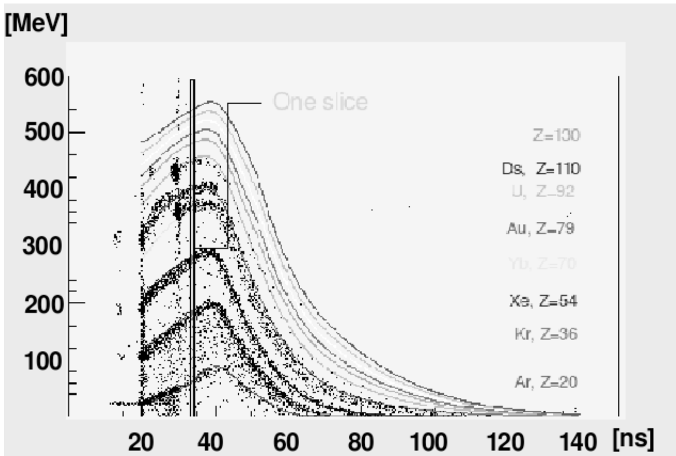

Fig. 3. 2-dimensional (calibrated) spectrum of E_{ICtot} vs T_{GM} for beams listed at the beginning of Subsec. 3.2. The points are the data while the lines represents different atomic numbers. The lines below U are the fit to the data. Lines above U are taken from the extrapolation procedure.

In the calibration procedure we applied the energy loss SRIM code to calculate ΔE_{ICi}, ΔE_M and all ToFs of DB ions for each detector of our detection setup.[7,8]

The identification technique, i.e. $E_{ICtot} = \sum \Delta E_{ICi}$ vs e.g.: T_{GM}, for SHE candidates permits atomic number determination of detected heavy residue. However, due to the poverty of literature experimental data on energy losses of ions heavier then Z=92 we had to develop extrapolation procedure for Z=[93, 130]. For that we have used extrapolations of the data from direct beams. We divided the T scale (T_{GM}) into slices of 0.5 ns wide, Fig. 3. Next, for each slice total energies, E_{ICtot}, in the IC-8 chamber are taken for ions that represent each beam and extrapolation of those values are made with a quadratic fit to higher Z's. The result of such extrapolation (Z>92) is shown in the Fig. 3.

4. Heavy and Superheavy Candidates in the Reaction $^{197}Au(7.5\mathrm{A}MeV) +^{232} Th$

The ions impinged on a Th target (6.3 mg/cm^2) that was rotated 45 degrees with respect to the beam direction. In such a thick target, the energy loss of the gold ions serves to spread the initial beam energy. This is necessary because we only have the approximate estimation (from the results of the previous test runs) of the optimal collision energy that should be used in peripheral reactions with Th nuclei to produce the HE/SHE elements with relatively low excitation energies. The beam energy in the target drops from the initial 7.5 A MeV at the beginning of the target to 6.3 A MeV at the exit of the target.

The first selection of the reaction products is accomplished with the help of a 6^o blocker. Products that are emitted at angles greater than 6 degrees pass through the transmission detector (Italian PPAC), enter the BigSol filter and after it, the ions pass through the three ToF detectors and finally enter the IC-8 ionization chamber where they can stop or they continue to stop in one of the YAPs.

To obtain the identification of the heavy reaction products we primarily use the velocity/ToF from the transmission detectors (e.g. T_{GM}) and the energy losses of heavy ions (HI) measured in the segmented ionization chamber IC-8.

As it is seen from the Fig. 4 region of heavy and superheavy elements is located in the upper part of the E_{ICtot} vs T_{GM} spectrum. This region was marked by contour $C1$. All events located in the $C1$ were analyzed while we required the following pileup rejection criteria: no pileup is observed in TAC, in FADCs of PPPAC, GPPAC, MWPC and IC-8 detectors. Additionally, the condition on the well determined position in GPPAC and MWPC of detected heavy ion (HI) was applied.

With those selections we could isolate *6 real events* that may correspond to the detection of ions much heavier then the Au nuclei, large points in Fig. 4. Those six candidates we named superinteresting events (SIE) because, at the moment, one must be cautious in claiming the real atomic number of those HIs. From our Z-extrapolation procedure (Fig. 3) we can estimate that those events correspond to Z≈110.

Several other groups of events can be identified in the figure. The thick banana-like groups of events correspond to the detection of Au-like ions. Transfer reactions in collision of the Au with the Th nucleus have a large cross section and due to this, the products of such transfers are still abundant at the end of the detection line, despite the selection made by the BigSol filter and the 6^o blocker. It is manifested

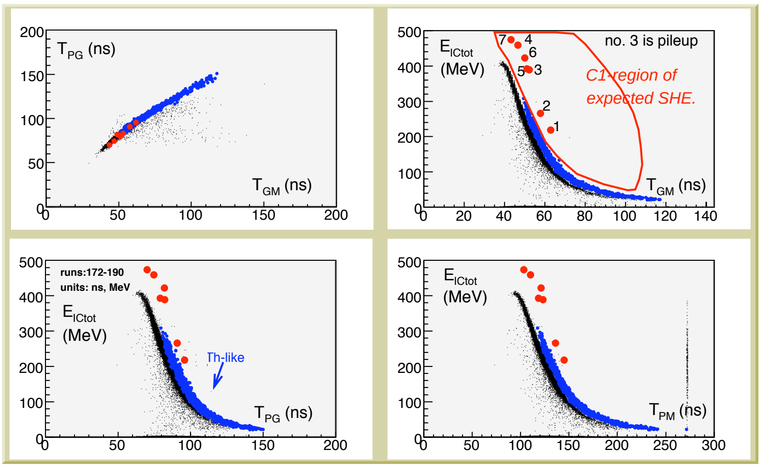

Fig. 4. Upper left panel: time of flight 2-dimensional spectrum of T_{PG} vs T_{GM}, three other panels represent E_{ICtot} vs T_{GM}, T_{PG} and T_{PM}, respectively. The studied reaction is $^{197}Au(7.5\text{A}MeV) +^{232} Th$. The contour $C1$ is the region of expected heavy and superheavy elements. Six cases of superinteresting events were found (see text for details).

Table 1. Characteristics of six SIE cases. Columns from left to right are the SIE number, velocity of the heavy ion between PPPAC and GPPAC, between GPPAC and MWPC counter, energy loss in the MWPC, total energy loss in the IC-8 chamber and finally calculated mass of the SIE events and calculated energy loss in GPPAC detector. SIE number is the same as in Fig. 4

SIE no.	V_{PG} (cm/ns)	V_{GM} (cm/ns)	ΔE_M (MeV)	E_{ICtot} (MeV)	A^{Calc} amu.	ΔE_G^{Calc} (MeV)
1	2.13	1.66	155.8	219.0	262.4	242.3
2	2.24	1.80	169.1	267.5	260.0	239.6
4	2.77	2.23	123.8	459.5	$\gg$ 226.0	$>$ 316.3
5	2.58	2.01	176.8	390.9	$\approx$ 271.0	$\approx$ 367.5
6	2.50	2.06	196.3	420.2	$\approx$ 280.3	$\approx$ 291.5
7	2.92	2.37	139.8	474.4	$\gg$ 211	$>$ 318.2

by the events that are located on the left of the banana and they extend to the lowest energies E_{ICtot}. Of course, those events correspond to the detection of ions lighter (Z <79) than the gold nuclei. Here different kinds of heavy ions should be located. Although it is not possible to identify those products according to their atomic number, nevertheless one can expect here, the fragments of the fission of Th nuclei and also deep inelastic reaction products. It is also possible to identify a group of events that correspond Th-like nuclei. Those events are located just on the right of the Au and they are quite abundant.

Main measured characteristics of the six SIE candidates are cited in table 1. Using measured values of $V_{GM} = 105.9/T_{GM}$ and $\Delta E_M + E_{ICtot}$ one can estimate masses of SHE candidates. We use the formula $A^{Calc} = 1.389^2(\Delta E_M + E_{ICtot})/V_{GM}^2$. However, this prescription gives only the lower limit of A^{Calc} because the kinetic energy of that formula in fact is equal to the sum $\Delta E_M + E_{ICtot} + E_{mylar}$, where E_{mylar} is the energy loss of heavy ion in the detectors (MWPC and IC-8) windows. In case of event no. 4 and 7 the SIE ions punch through the ionization chamber (IC-8) so here we missed some residual energy not only E_{mylar} as for other cases. Such estimated masses seem to be low compared what one can expect for ions with Z≈110 but one should remember our estimation is only a lower limit for masses of these SIE ions. We are currently reviewing all energy calibrations. It is also interesting to note the energy per nucleon of those six cases is located in the region between 1.5 MeV/u and 3 MeV/u.

5. Conclusions and Plans

It should be stressed that results presented in the last section, for the reaction $Au+Th$, are preliminary. The cross section for the production of the six SIE events we estimate at the level of 10-100 pb. To calculate more exact value for the cross section a more precise simulation are needed to determine BigSol filter efficiency. More exact mass estimations of the detected SIE events are in progress by taking into account energy loss of heavy ions in mylar windows of the detector setup.

This research will be continued at Texas A&M University. The emphasis will be placed on a more accurate calibration of heavy ion energy losses in the MWPC and the ionization chamber (IC-8). We will work to further improve the detection setup to eliminate pileup events. Using baffles in BigSol one can also expect to achieve a lower background and to use silicon position detectors instead of YAP detectors to detect radioactive decay (α or spontaneous fission) of the implanted products.

In summary, results presented in this article show that our experimental apparatus is capable to isolate and detect very heavy nuclei when they are produced.

Acknowledgments

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