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Extending studies of the fusion of heavy nuclei to the neutron-rich region using accelerated radioactive ion beams

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One of the stated goals for proposed and existing facilities that produce and accelerate radioactive ion beams is to explore and achieve a new understanding of the reactions mechanisms leading to the synthesis of the heaviest nuclei. Nuclear synthesis of two large nuclei into a single entity is a complex multistep process. The beam intensities of radioactive ions accelerated at present day facilities are not sufficient to synthesize super heavy elements. However the study of the iso-spin dependence of nuclear synthesis and the many processes competing with it can be carried out at present day facilities. Of special interest are cases where the interacting nuclei and the synthesized product are extremely neutron-rich. The effects of neutron excess on the reaction processes leading to the formation of the synthesized nucleus that emerged in earlier studies are poorly understood and sometimes counter intuitive. Results from measurements performed at HRIBF, as well as our plans for future measurements and the equipment being prepared will be presented.

Keywords: Fusion reactions; superheavy synthesis; radioactive ion beams.

Uno de los objetivos declarados de los laboratorios que producen y haces acelerados de iones radioactivos es el de explorar y obtener un Nuevo entendimiento de los mecanismos de reacción que conducen a la síntesis de núcleos más pesados. La fusión de dos núcleos pesados en una sola entidad es un proceso complejo de varios pasos. Las intensidades de los haces radioactivos acelerados actualmente no son suficientes para sintetizar elementos superpesados. Sin embargo, el estudio de la dependencia de isoespín de esta síntesis nuclear y los muchos procesos que compiten puede llevarse a cabo con los haces existentes. De interés especial son los casos donde los núcleos en interacción y los productos sintetizados son extremadamente ricos en neutrones. Los efectos del exceso de neutrones en los mecanismos de reacción involucrados en la síntesis de nuevos núcleos, continúan siendo pobremente entendidos, e incluso llegan a ser contra intuitivos. Aquí presentamos resultados de medidas llevadas a cabo en HRIBF, así como nuestros planes para medidas futuras y el equipo que para ese efecto se está preparando.

Descriptores: Reacciones de fusión; síntesis de núcleos superpesados; haces de iones radioactivos.

PACS: 25.70.Jj; 24.60.Dr; 25.60.Pj

1. Introduction

The unique Radioactive Ion Beams (RIBs) available exclusively at the HRIBF facility at ORNL [1] provide us with the opportunity to study the evolution of nuclear fusion as a function of neutron excess in the nuclei entering the collision. The fusion of heavy nuclei is a massive rearrangement of nuclear matter and should exhibit a pronounced dependence on bulk properties of nuclei. Data taken at extreme values of iso-spin will enhance our understanding of these properties and provide additional tests for models of nuclear matter. The fusion and the subsequent fission of very heavy neutron-rich nuclei have a bearing on the rate and terminus of neutron-rich element creation in the stellar r-process [2]. The role extra neutrons may play in the synthesis of heavy elements is also a topic of current interest [3].

The synthesis of heavier nuclei is pursued mostly via fusion of the relatively light but neutron-rich ^{48}Ca nucleus with a variety of heavy targets [4]. Reaching the region of long-lived super heavy nuclei (SHE) will require use of nuclei with a larger number of neutrons than those available by combining ^{48}Ca with heavy actinides. Neutron-rich radioactive nuclear beams may become an option to synthesize SHE in spite of the lower beam intensities expected for RIBs.

2. Fusion and fission in reactions induced by neutron-rich radioactive ion beams

It has been realized for some time that the complete fusion of two nuclei is a multi-step process.

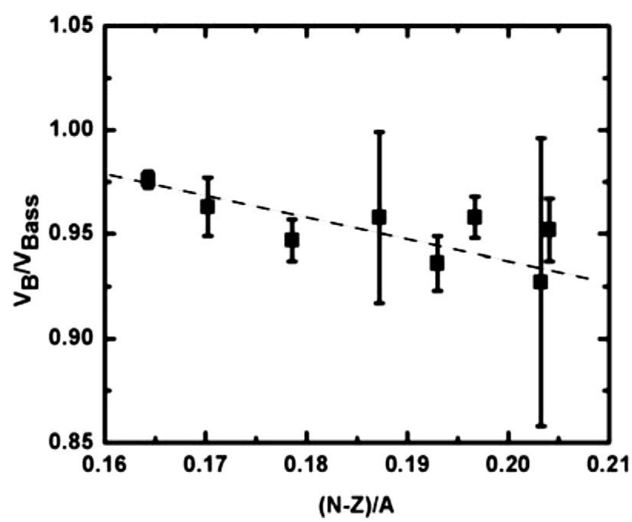

FIGURE 1. Normalized interaction barriers measured from collisions employing neutron-rich RIBs.

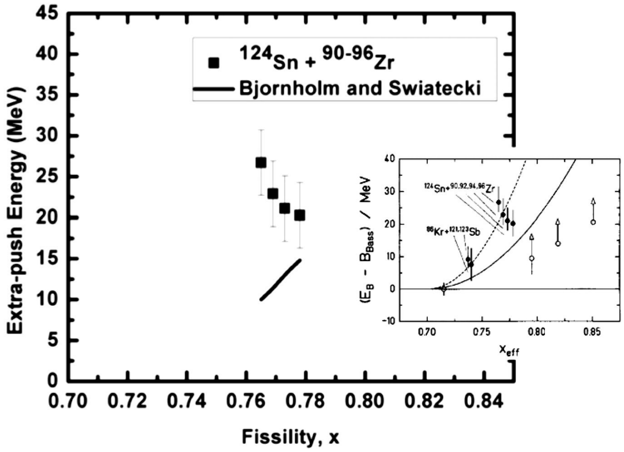

FIGURE 2. The extra push energy calculated for a set of 4 isotopes of Zr fusing with ^{124}Sn. The inset shows the response over a large range of fissilities.

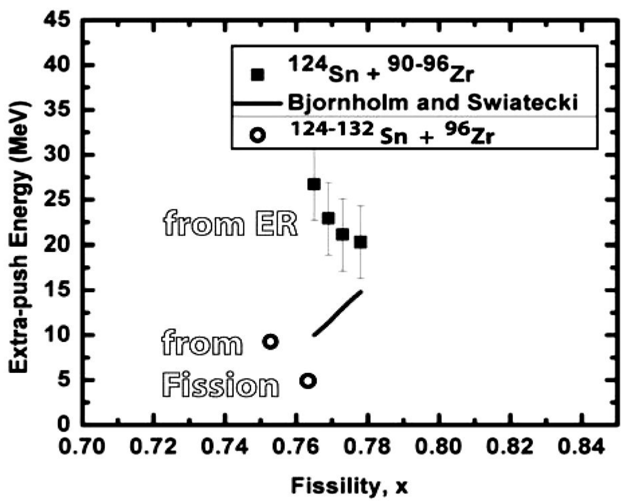

FIGURE 3. The extra push energies derived from the evaporation residue data and from our capture data.

1. The nuclei must first overcome the Coulomb and centrifugal repulsion and join to form a (rotating) dinuclear system.

2. Following further dissipation of kinetic energy and the migration of nucleons, the dinuclear system stands a chance to amalgamate into a single larger nucleus.

The first step requires that the nuclei surmount the interaction barrier and the second step involves passing the fusion barrier. The extra energy required to surmount this "inside" fusion barrier is called the extra push energy [5].

The experimental determination of interaction barriers requires measurements at several beam energies near and below the barrier where cross sections for fusion are small. Therefore, although neutron-rich RIB beams have been available for some time, interaction barriers were measured only for few systems [3]. Figure 1 shows the collection of much of the world's data on normalized interaction barriers. The barriers are compensated for the variation of the nucleus-nucleus

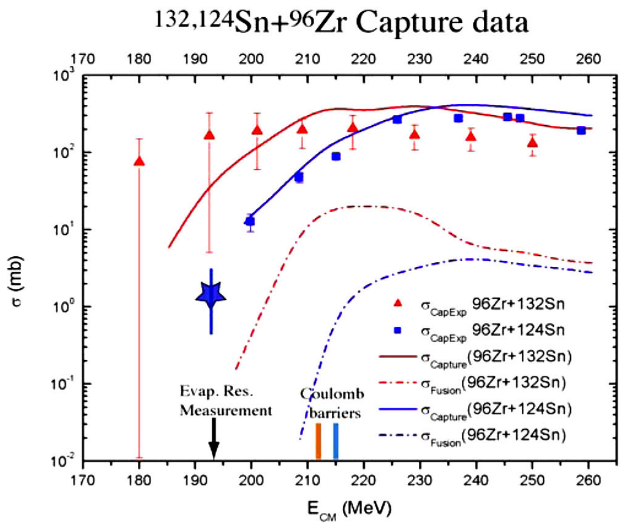

FIGURE 4. Separating nucleus-nucleus capture from other processes such as deep inelastic scattering requires good energy and particle ID. In the experiment ion mass was determined through measurement of energy and time of light (TOF). As a result, phase space coverage of the outgoing products was minimal (<1% efficiency) resulting in large statistical uncertainties.

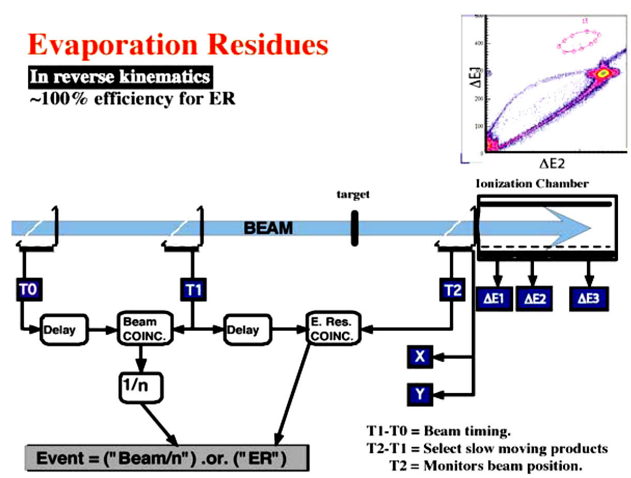

FIGURE 5. The system designed to measure evaporation residues that was optimized for the study of reactions with inverse kinematic conditions and is limited to use with low intensity beams. The inset shows a typical energy loss spectrum from the ion chamber.

Coulomb barrier, contained in V_{bass}, and the increase in nuclear size due to the increase in mass number. One may discern a trend toward lower barriers for more neutron-rich systems but a constant ratio of 0.95 would do as much justice to these data. Better data on interaction barriers between heavy targets and neutron-rich RIBs are needed. The detector system described later is designed to perform this specific task.

We next examine the situation with the extra push energies needed to nudge the dinuclear complex to merge and form a single compound nucleus. Results from the studies of collisions between heavy stable nuclei indicate that the extra push energy required for surmounting the fusion barrier increases with the increase of effective fissility [5]. Fissility

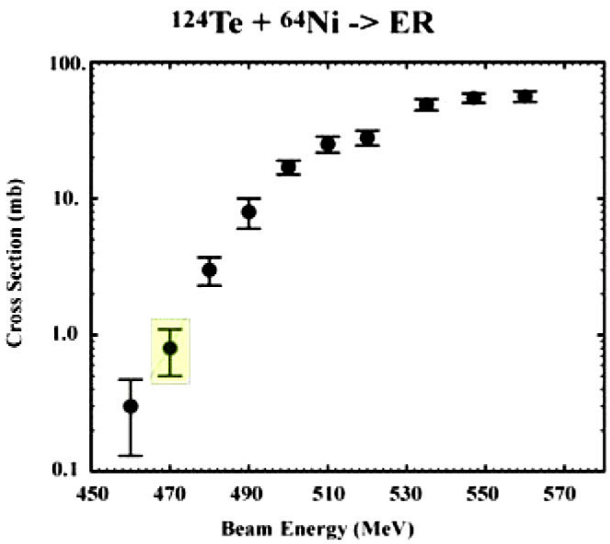

FIGURE 6. Measured excitation function for ER production in collisions of ^{132}Te+^{64}Ni

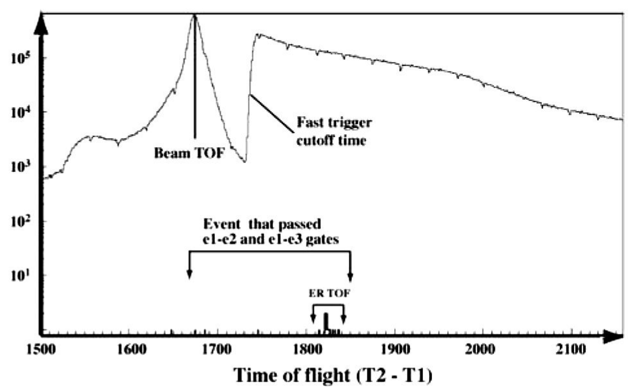

FIGURE 7. Time of flight spectra of events associated with the 0.8 mb cross-section data point highlighted in Fig. 6.

is the tendency of a compound nucleus formed in the collision to fission, and is proportional to Z^2/A (Z is the number of protons and A the mass number of the compound nucleus). Effective fissility (x in Fig. 2) also takes into account the N-Z asymmetry as well as the masses of the colliding nuclei. The naive expectation would be that the excess of neutrons (the nuclear "glue") in these heavy nuclei brings about an increase in probability that the di-nuclear system will fuse.

Data taken on several systems that differ from each other only by the number of neutrons show behavior that is opposite to what one may expect [6]. Figure 3 shows data on the extra push energy required to fuse a ^{124}Sn nucleus with a series of Zr isotopes ranging from 90 to 96 in mass displaying a trend opposite to model prediction. It must be emphasized, though, that what is shown here is a complex comparison. The data measured were evaporation residues. The fusion cross section was calculated using reaction models and the extra push energy is then calculated as a difference between the fusion barrier and a model dependent interaction barrier.

The results from these few measurements demonstrate the need to measure many more systems and extend the measurements toward more extreme values of iso-spin using neutron-rich RIBs and to do it with better precision. The beams presently available at the HRIBF facility make such measurements possible.

3. Further measurments on the Sn + Zr system

With high purity ^{132}Sn beams available at HRIBF we have to opportunity to extend the Sn+Zr data to a more neutron-rich combination [7]. We bombarded a ^{96}Zr target with ^{124}Sn and ^{132}Sn beams and measured the cross section for capture into the dinuclear complex. Model calculations are used to deduce the fusion cross-section and the required extra push energy [8]. The results are shown in Fig. 3. Although our data shows the same trend, a comparison of the two sets of ^{124}Sn+^{96}Zr data show what degree of uncertainty we are dealing with. We can discern the level of uncertainty in our results from Fig. 4. The ^{132}Sn+^{96}Zr data near and below the barrier have large error bars. Also the calculated capture cross sections missed some of the data measured above the barrier. The same model was, in turn, also used to calculate the fusion cross section.

An efficient system to measure evaporation residues in reactions with low intensity neutron-rich RIBs [9] is shown in Fig. 5. It owes its high efficiency to the forward focusing of the fast moving compound nucleus formed in a collision between a target and a heavier beam. Background rejection and data acquisition trigger are obtained by using fast, high transmission, timing detectors. Events that move slower than the beam (between target and T2) provide a valid trigger. For normalization purposes a small sample of beam triggers is also collected. Energy loss signals in the three ion chamber anodes also help in separating residues from beam like particles.

Figure 6 shows data taken with stable beams and Fig. 7 shows the raw data used to extract the ER cross section data at 0.8 mb (marked in Fig. 6). The degree of background rejection achieved with this setup is apparent in Fig. 7. It shows the level of selectivity achieved with the 3 energy loss signals and the addition of the constraints on flight time.

We now turn our attention to the ^{132}Sn+^{96}Zr ER data. Based on trends established from previous data with stable beams we expected low ($<$100 mb) cross sections. Rather then rely only on calculated energy loss to identify the evaporation residues we "calibrated" the detector with a ^{238}U beam. The results from our measurements are shown in Fig. 8. The data shown were acquired following the bombardment of ^{96}Zr by 1.6 billion ^{132}Sn beam ions (22 hours at an average intensity of 20KHz). Two events could be identified and the extracted cross section is 1.5 mb, much larger then expected on the basis of the measurements reported in Ref. 6. The star in Fig. 4 shows the evaporation residue cross section measured by us. It far exceeds the cross sections for total fusion predicted by the model calculation combined with our nucleus-nucleus capture data. Rather than a

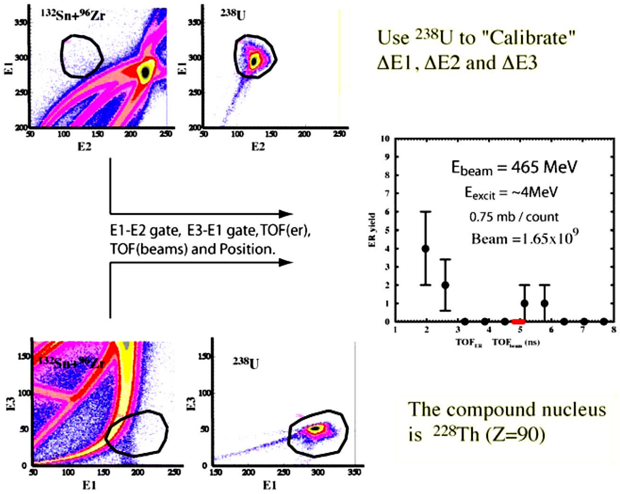

FIGURE 8. Identification of evaporation residues from the fusion of ^{132}Sn+^{96}Zr. The two-dimensional displays show signals generated by the ^{238}U calibration beam and the gates drawn on the E1 vs. E2 and E3 vs. E1 displays. The time of flight relative to the beam TOF is shown on the far right after filtering through both gates.

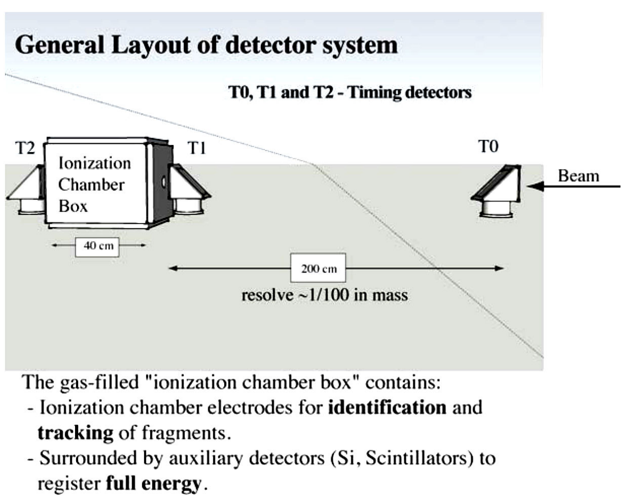

FIGURE 9. Future experimental setup optimized to detect and identify binary product from reactions of neutron-rich RIBs with heavy targets at near barrier energies. The beam traverses the detector and exits the thin window registering a hit in the T0, T1 and T2 timing detector.

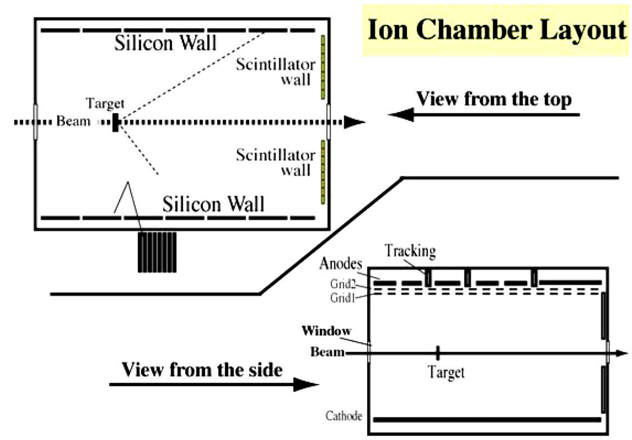

FIGURE 10. The "ionization chamber box" from Fig. 9 houses a multi anode ionization chamber that is designed to provide energy loss and tracking information of fragments formed in the collision. The front and side walls are paved with solid state detectors that will stop the fragments and record their residual energy.

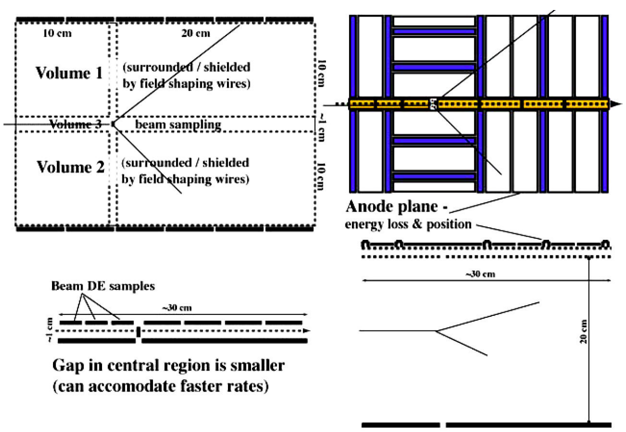

FIGURE 11. The upper right figure shows a possible layout of the anode plane. Energy loss and position signals along the projection of the fragment's track on this plane are recorded (as shown on the upper left side). Positions in the plane perpendicular to the anode plane are record by measuring the drift time of electrons from the track position to the grid (start time is provided by T1 timing detector).

requirement for an extra push we see a large enhancement in the probability for fusion. We plan to confirm our tentative ER cross section measurement for this system with longer running times and obtain data points with more events and measure an excitation function of this production cross section.

4. A detector system for studying fission with neutron-rich RIBs

The data shown in Fig. 4 demonstrate the need for a (dedicated) system to measure binary products from heavy ion collisions with neutron-rich RIB beam. Such a system should provide good energy and angle information on the outgoing products as well as particle ID. Since it is intended for use with low intensity RIBs the detector should cover a large part of phase space for the outgoing products. It should be able to handle beam intensities up to ∼1 MHz and allow for tagging of isobaric or isotopic contaminants. Figures 9-11 and their captions provide a description of the detector system that we designed and are building in collaborations with scientists at University of Mexico, Oregon State University and University of Notre Dame [10].

The detector system is designed primarily to work with heavy targets bombarded by lighter neutron-rich radioactive ion beams produced in fission of p+^{238}U but it can be used with any combination of beam and target. The detector's special features are summarized below.

1. It is comprised of three electrically independent volumes (Fig. 12).

- a Two large sections on both sides of the beam (volume 1 and 2 each having a 10×20 cm cross section) will be used to track and identify the two fragments from the collision.
- b The center volume (3) through which the beam passes is a long grid-less ionization chamber with anode and cathode in close proximity ($\sim1\times1$ cm cross section). This may allow for count rates close to 1 MHz that provide usable energy loss signal for beam isobar tagging.

2. Full three-dimensional tracking will be provided by vertical drift time and several position sensitive proportional wire counters embedded in the anode plane.
3. Full energy of fragments that were not stopped in the gas volume will be recorded by solid state detectors mounted on the front and side walls of the detector.
4. Fast and thin timing (and position sensitive) detectors (see Fig. 9) will provide:
   - a Passive and active collimation of the beam and isotope tagging if needed.
   - b Beam position as it enters and exits the detector.
   - c A fast trigger veto signal when beam passes the detector without interacting. A sampling of these triggers can be used of normalization and beam composition analysis.

The main limitation is the beam count rate that the system can sustain and yet provide some energy loss information (<1 MHz but hopefully not much less owing to the small cathode to anode gap). Differentiating between products from nuclear reactions initiated by beam and target and beam and nuclei in the gas molecules filling the detector can be accomplished, to first order, by using the tracking information (tracking back to the target location). Further differentiation can be done by exploiting the difference in kinematics for beam + heavy target interactions and beam + light detector gas target nuclei interactions.

5. Conclusion

While the synthesis of super heavy nuclei with radioactive ion beam is presently a goal out of reach we plan to use the existing detector system and the new one being built to understand and eventually be able to predict the role that neutron excess can have on the probability of heavy nuclei to fuse. With some extended capabilities [10] the detector system we plan to build can be used to study the fission of neutron-rich (unstable) actinides. The detector system can also be operated as an active target though this mode of use is not planned at present since there are several such detectors being constructed at a number of laboratories around the world [11].

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