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Searching the Stabilizing Effects of Neutron Shell Closure via Fusion Evaporation Residue Studies

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***Abstract*—**Searching the "Island of stability" is a topic of extreme interest in theoretical as well as experimental modern physics today. This "island of stability" is spanned by superheavy elements (SHE's) that are produced in the laboratory. SHE's are believed to exist primarily due to the "magic" stabilizing effects of nuclear shell structure. SHE synthesis is extremely difficult due to their very low production cross section, often of the order of pico barns or less. Stabilizing effects of shell closures at proton number Z=82 and neutron number N=126 are predicted theoretically. Though stabilizing effects of Z=82 have been experimentally verified, no concluding observations have been made with N=126, so far. We measured and analyzed the total evaporation residue (ER) cross sections for a number of systems with neutron number around 126 to explore possible shell closure effects in ER cross sections, in this work.

***Keywords*—**Superheavy element, fusion evaporation, evaporation reside, compound nucleus.

I. Introduction

EVEN though the periodic table of stable elements was completed 70 years back, the quest for the synthesis of new elements continues as a hot topic in modern physics. The "island of stability", the region where the superheavy elements span at present, provides extreme landscapes to test our fundamental understanding of quantum many-body theory governing nuclear matter. SHEs are synthesized via nuclear fusion reactions [1], [2]. SHE synthesis is very difficult due to their very low production cross sections, often of the order of pico-barns or less [1], [2]. SHE's are often identified as heavy evaporation residues (ER) in the laboratory, which, subsequently decay via alpha particle emission.

An important hurdle in SHE synthesis is the presence of a non-equilibrium process called quasifission [3], [4], which severely hinders the formation of a compound system after the capture of the target-projectile system. In quasifission, the projectile and the target after capture re-separate much before achieving a complete equilibration in all degrees of freedom. This hindrance to fusion thus manifests as a reduction in ER cross section. Being a dynamical process, complete modeling of quasifission is not yet developed. Extensive theoretical and experimental studies are going on to map the characteristics of quasifission, as it can provide guidance to choose the best projectile-target combinations for SHE synthesis.

The barrier against spontaneous fission provides the macroscopic limit for the existence of a nucleus. According to liquid drop model, for example, spontaneous fission dominates in nuclei with $Z^2/A > 39$, which sets the upper limits of nuclei around Z=100, where Z is the atomic number and A is the mass number of the nucleus. However, SHEs have been produced in the laboratory with Z up to 118 [1], [2], contradicting the expectations from a pure-macroscopic model. SHEs are thus expected to exist primarily by the microscopic stabilization of nuclear shell structure, as the macroscopic fission barrier will be zero in such heavy systems.

Stabilizing effects of Z=82 have been proved experimentally, and investigations are being conducted to observe similar effects for N=126. A study carried out a few decades back [5] did not report any conclusive evidence of neutron shell closure effects for N=126. However, many theoretical models speculate strong stabilizing effects of N=126. A positive result with N=126 would be a milestone achievement in SHE synthesis, as shell model predicts the next magic number at N=184.

In order to understand the stabilizing effects of shell structure in the region around N=126, we measured the total ER cross sections for $^{16,18}O+^{194}Pt$ systems forming the compound nuclei $^{210,212}Rn$. Results are compared with $^{18}O+^{194,198}Pt$ reactions [2] and other data sets available in literature, for a better understanding.

II. Experimental Details and Analysis of Results

The ER measurements were carried out at the Inter University Accelerator Centre (IUAC), New Delhi, India. The measurement of ER is extremely difficult as they are always forward focused in nature and are accompanied by an intense beam background. The ERs produced in this study were separated from the intense beam-like and target-like contaminations, using the recoil mass separator Hybrid Reaction mass Analyser (HYRA) spectrometer [6].

HYRA is a dual-mode, dual-stage separator that can be operated in vacuum mode as well as gas-filled mode. HYRA has QQ-MD-Q-MD-QQ configuration in its first stage, where Q stand for the magnetic quadrupole and MD stands for magnetic dipole. Since, the transmission efficiency of a RMS is a major concern in many ER experiments, to achieve required statistics in limited beam time, we operated HYRA in gas-filled mode in these experiments. Gas-filled mode yields better transmission efficiency due to their inherent velocity

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and charge state focusing. Helium gas at a pressure of 0.15 Torr was used in all measurements.

The ERs produced in the reactions were further cleaned from any possible contamination (originating from the scattering inside the beam-pipe) using a time-of-flight (TOF) technique. Pulsed beam from the 15 UD Pelletron accelerator was used to bombard the isotopic targets of Pt in all runs. The measurements were performed at energies around the Coulomb barrier. The ERs were detected at the focal plane chamber using a detection system consisting of a multi wire proportional counter followed by a two-dimensional silicon surface barrier detector. Two monitor detectors were used at ±22° with respect to the beam direction. The Rutherford yields registered in these detectors were used for absolute cross section normalization.

The ER cross sections were obtained from the ER yield recorded at the focal plane detectors, which were normalized by the Rutherford yield. The transmission efficiency of the separator was obtained by comparing the ER cross sections of known systems measured in these experiments [7]. Total ER cross-sections obtained for the 4 systems are shown in Fig. 1.

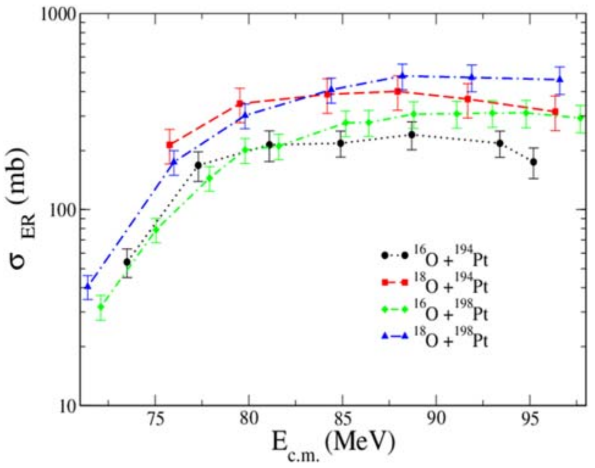

Fig. 1 Total ER cross sections for different o+pt systems

In order to test any possible role of neutron shell closure at N=126 in this reaction, statistical model calculations were performed to reproduce the experimental results.

III. Theoretical Analysis and Results

Statistical model calculations [8] have been performed for the systems under study using the conventional Bohr-Wheeler [9] fission widths first. The basic assumption in these calculations is that the system after capture forms a CN and decay via particle emission, gamma emission, and fission. Fission fragment angular distributions [10] and mass distributions clearly demonstrated that these systems proceed via true CN formation and non-compound nuclear process is absent. Major decay channels of the CN formed, viz., charged particle evaporation, neutron evaporation, gamma emission, and fission decay were thus considered in the model calculations, using their respective widths from Weiskopf's formula [11]. Calculations were performed using the free energy as the driving force, with shell corrected level density parameters. Igantyuk level density parametrization [12] has been used in this work.

The fusion spin distribution obtained from the coupled channels code CCFULL has been used as the standard input in statistical model analysis. These spin distributions were obtained by reproducing the total experimental fusion cross-sections. It is observed that the model calculations assuming Bohr-Wheeler fission widths clearly under predict the experimental ER cross sections. The difference is more pronounced at higher excitation energies. Experimental ER cross sections compared with model calculations assuming Bohr-Wheeler width is shown in Fig. 2

The failure of Bohr-Wheeler fission widths to reproduce the experimental data in this measurement clearly indicates the dynamical delay in fission process. This delay is originating from the dissipative nature of nuclear interactions. Bohr-Wheeler fission width does not incorporate dissipation in it. The delay in fission leads to an enhancement in particle evaporations and hence the ER cross sections.

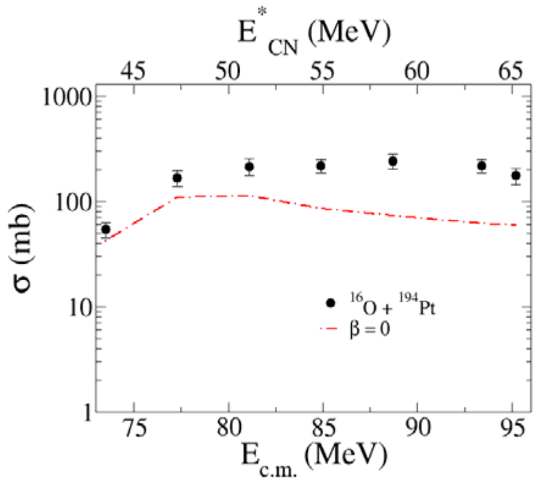

Fig. 2 Experimental ER cross sections for $^{16}O+^{194}Pt$ reaction compared with statistical model calculations assuming Bohr-Wheeler fission widths

In order to explore the possible effects of dissipation in enhancing the ER cross sections, we further calculated the ER cross sections using the fission widths from Kramer's [13] formalism. Kramers' formalism includes dissipative effects in fission width in a self-consistent manner. In this model, we used the dissipation strength (β) as a free variable to fit the experimental ER data. It is clearly observed that calculations assuming Kramer's fission width with a non-zero dissipation strength reproduce the experimental data reasonably well in all systems studied in this work. The model calculations using different β values for the $^{16}O+^{194}Pt$ are shown in Fig. 3. Similar calculations performed for $^{18}O+^{194}Pt$ reaction together with experimental results are shown in Fig. 4. Fusion cross sections calculated using CCFULL is also shown in the plot.

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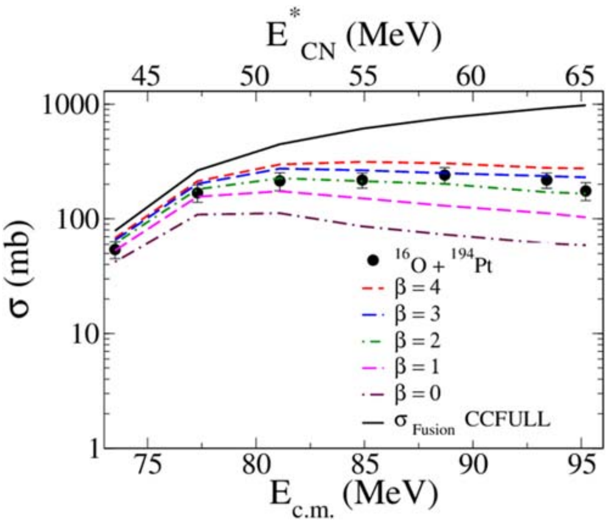

Fig. 3 The experimental ER cross section compared with model calculations assuming β different for the $^{16}O+^{194}Pt$ reaction

It is observed that Kramer's fission width with a non-zero dissipation strength is required for describing the ER data for all the systems presented in this work. We further analyzed a few other systems such as $^{16}O+^{186}Os$ and $^{18}O+^{192}Os$, of which the latter reaction again forms a CN with N=126. ER and fission data for these systems are available in literature [14], [15].

Model calculations assuming free energy as a driving force clearly shows that a non-zero dissipative strength is indeed required for O+Os reactions as well, indicating as a characteristic trend in all systems populating nuclei near mass region 200. Though the β value required for these systems varies slightly, their magnitudes reflect the relative magnitudes of their ER cross sections. It is a bulk property of the system in our work and has structural effects such as shell closure etc.

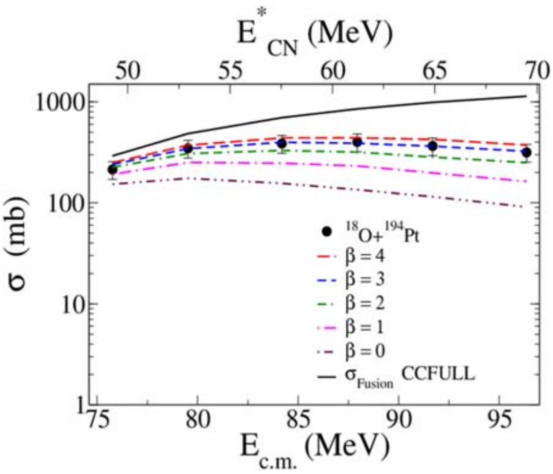

Fig. 4 The experimental ER cross section compared with model calculations assuming different β for the $^{18}o+^{194}pt$ reaction

IV. Discussion

In order to further investigate the role of shell closure, we plot the ER survival probability of different systems as a function of CN excitation energy (E*) in Fig. 5. The survival probability of the ER is defined as the ratio of ER cross section to total fusion cross section.

It may be noted that non-zero dissipation strength is required for fitting the ER survivability in all reactions, as shown in Fig. 5. The best-fitted β required for different reactions addressed in this work is given in Table. I. The dissipation strength represents the damping of collective motion associated with fission and is a bulk property of the system. In our work, we could not observe any significant difference in beta for systems forming a CN with N=126 (for example $^{18}O+^{194}Pt$,^{192}Os reactions) and systems without N=126.

Slight variation observed in the ER cross sections and hence in best-fitted beta values is due to the isotopic dependence of ER cross section. Slightly higher beta values required for reactions with heavier projectile or target nucleus may be understood from the larger ER survival probability with increasing mass in an isotopic chain of CN. Similar observations were reported earlier in this mass region [16].

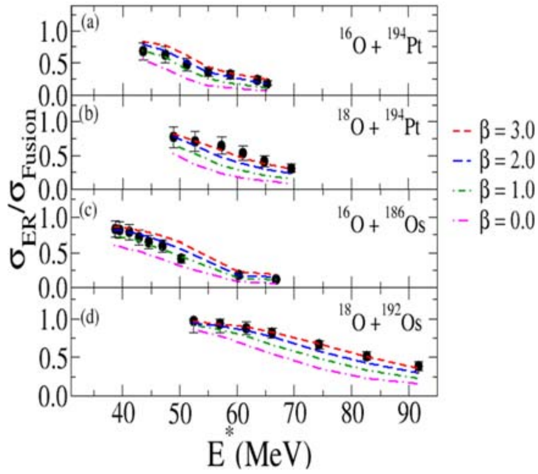

Fig. 5 ER survivability plot for different systems. The data are compared with calculations using different β values

TABLE I
Best Fitted β Values for Different Reactions Studied

Reaction	Best fitted (β) (unit of 10^{21} s^{-1})
$^{16}O+^{194}Pt$	2
$^{16}O+^{198}Pt$	1
$^{18}O+^{194}Pt$	3
$^{18}O+^{198}Pt$	2
$^{16}O+^{186}Os$	1
$^{18}O+^{192}Os$	2

One of the possible reasons for the absence of shell closure effects in reaction forming CN with N=126 (in ^{212}Rn and ^{210}Po, in this work) is the following. In our work, we measured the total ER cross sections, which is a sum of all possible evaporation channels. Fission may be happening straight from the CN formed, or from a daughter nucleus formed after a few particles emission. The fission system will have different excitation energy and angular momentum depending on whether fission happen at first chance itself or later. In such cases, the total fission cross section will be a cumulative effect of all such daughter nuclei at different excitation energies. Such a distribution may not leave any discernible shell closure effects in the experimental observables.

In summary, we studied the total ER cross sections of a number of systems populating CN with neutron number around the neutron magic number 126. Theoretical calculations assuming Bohr-Wheeler fission width could not explain the experimental data at higher excitation energies, clearly indicating the dissipative nature of nuclear force. Effects of shell closure are not observed in the total ER cross sections measured in systems with N=126, when compared with those without neutron number 126. A possible reason could be the cumulative effect of many-chance fission included in the total fission yield along with first-chance fission. More measurements, particularly ER cross sections of individual channels populated with shell closure may be required for clear understanding Microscopic shell stabilizations.

Acknowledgements

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