# Studies of Fusion Cross Sections of Te and Sn Isotopes with a $^{64}$Ni Target at Energies Near and Below the Barrier

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**Abstract.** Evaporation residue (ER) production from several isotopes of Sn and Te bombarding Ni targets at energies near and below the Coulomb barrier was measured. Measured ER data were compared with the predictions of sub-barrier fusion calculated in a WKB approximation. These comparisons are used to study effects of neutron excess and neutron transfer on the sub-barrier fusion cross sections for reactions induced by heavy nuclei.

**Keywords:** Radioactive Ion Beams, Fusion, Transfer, WKB, Sub-barrier
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## INTRODUCTION

The study of evaporation residues (ERs) formed in collisions between heavy nuclei at energies near and below the interaction barrier is of great interest. As pointed out in the initial studies, sub-barrier fusion is a sensitive probe of the structure of the nuclei entering the collision [1, 2]. Furthermore, fusion reactions are used to synthesize heavy elements and a great deal of effort has been put into finding optimal conditions that can lead to production of heavier and more exotic systems. The availability of accelerated neutron rich fission fragments from p+U at HRIBF enabled us to extend the measured ER data to very neutron-rich nuclei. We present some new data on ERs for Te and Sn isotopes fusing with $^{58}$Ni and $^{64}$Ni targets and summarize what we were able to learn so far.

## EXPERIMENTAL SETUP

The high efficiency setup to study ERs, constructed specifically to take advantage of the heavier exotic nuclei accelerated at HRIBF, can handle beam intensities up to $10^5$ ions/sec [3] (Fig. 1). A fast time-of-flight pre-trigger blocks all but a small sample of the

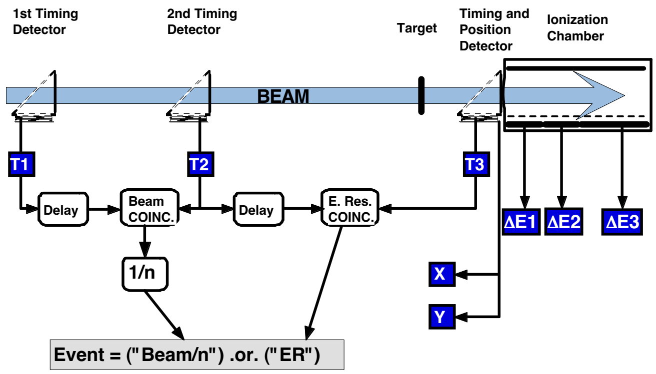


**FIGURE 1.** Experimental setup to measure evaporation residues

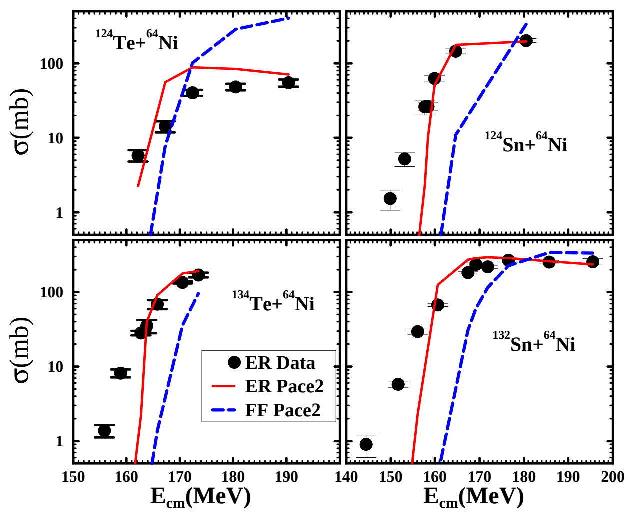


**FIGURE 2.** Measured evaporation residues for Sn and Te isotopes on $^{64}$Ni. PACE2 does not include quantum penetrability - calculation and data should be compared only above the barrier which is calculated using the Bass model potential.

direct beam from flooding the data acquisition system. This system was used to measure ERs from the collision of radioactive ion beams of $^{132,134}$Sn and $^{134}$Te with $^{64}$Ni. We also measured excitation functions of other systems in the same mass region for testing purposes. More details, appear in Ref. [3].

## EVAPORATION RESIDUE DATA

Data taken with different Te and Sn isotopes bombarding a $^{64}$Ni target are shown in Fig. 2. As expected ER cross sections increase with N/Z of the composite system. Also

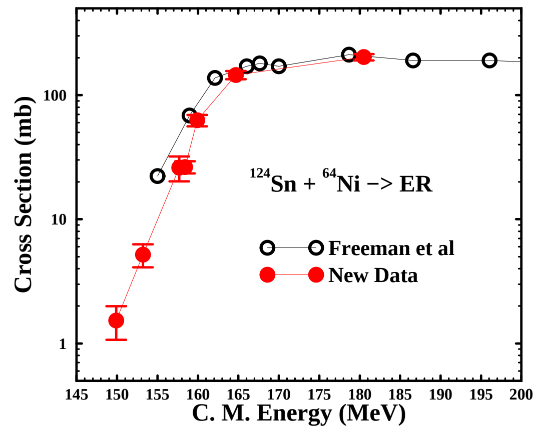


**FIGURE 3.** Measured evaporation residues for $^{124}$Sn+$^{64}$Ni.

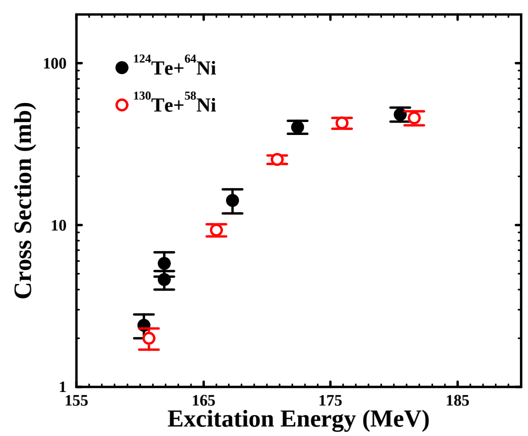


**FIGURE 4.** Measured evaporation residues for two similar systems populating $^{188}$Hg. Q value for CN formation are -127 MeV for $^{124}$Te+$^{64}$Ni and -117 MeV for $^{130}$Te+$^{58}$Ni.

shown are fusion-evaporation and fusion fission cross sections predicted with PACE2 [4] for these systems. A comparison of our measured cross sections for $^{124}$Sn+$^{64}$Ni to other published data [5] is shown in Fig. 3 The data in Fig. 4 show that ER cross sections for $^{124}$Te+$^{64}$Ni and $^{130}$Te+$^{58}$Ni populating the same excitation energy in $^{188}$Hg are about the same, as one might expect. Our aim is to investigate the effect the addition of neutrons to the colliding nuclei may have on the probability of nucleus-nucleus capture which could then lead to a compound nucleus [6]. The verdict from experimental results is mixed [6, 7, 8] so far. For the Sn+Ni combination we are able to study the effect of variation in neutron number using both existing data and new data on neutron-rich radioactive Sn isotopes. Fig. 5 shows neutron separation energies of different Sn isotopes; note the large range of neutron to proton ratio spanned for the isotopes shown.

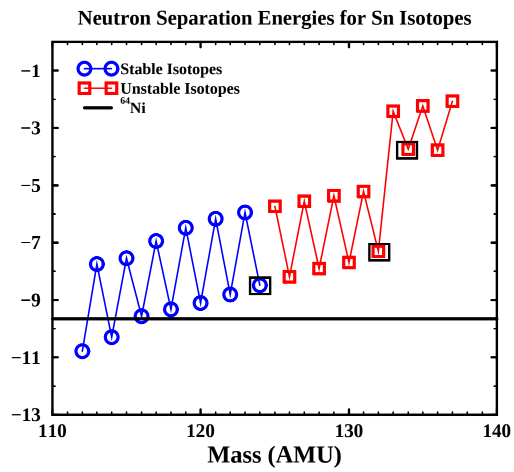


**FIGURE 5.** Neutron separation energies for Sn isotopes - large squares mark systems for which we measured ER data

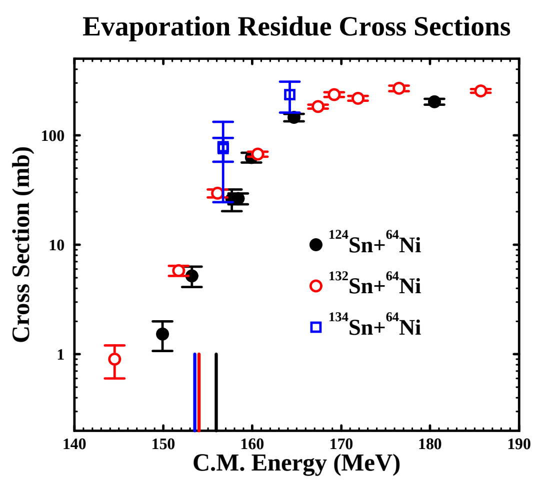


**FIGURE 6.** Measured evaporation residues for $^{124,132,134}$Sn on $^{64}$Ni. At 156MeV two measurements with $^{134}$Sn overlap but one has smaller error bars.

For some isotopes neutron separation energy in Sn is larger (more negative) than in $^{64}$Ni (the horizontal line) and the most neutron-rich one exhibit much smaller (less negative) neutron separation energy. ER data on the three systems marked in Fig. 5 are shown in Fig. 6. The only data set showing significant enhancement is that of $^{134}$Sn. This data set, however, is incomplete. The average beam intensity was around 1000 ions/sec and was a mixture of isobars of which only a 15% to 40% were $^{134}$Sn ions (see Fig. 7). Since $^{134}$Te was available with high purity, we measured its ER cross section alone, and subtracted that contribution from the total measured cross section. There is no pure $^{134}$Sb beam available at this time so the data shown combine the contributions of both $^{134}$Sb and $^{134}$Sn to the cross section. As shown in Fig. 7 the contribution of different isobars varies

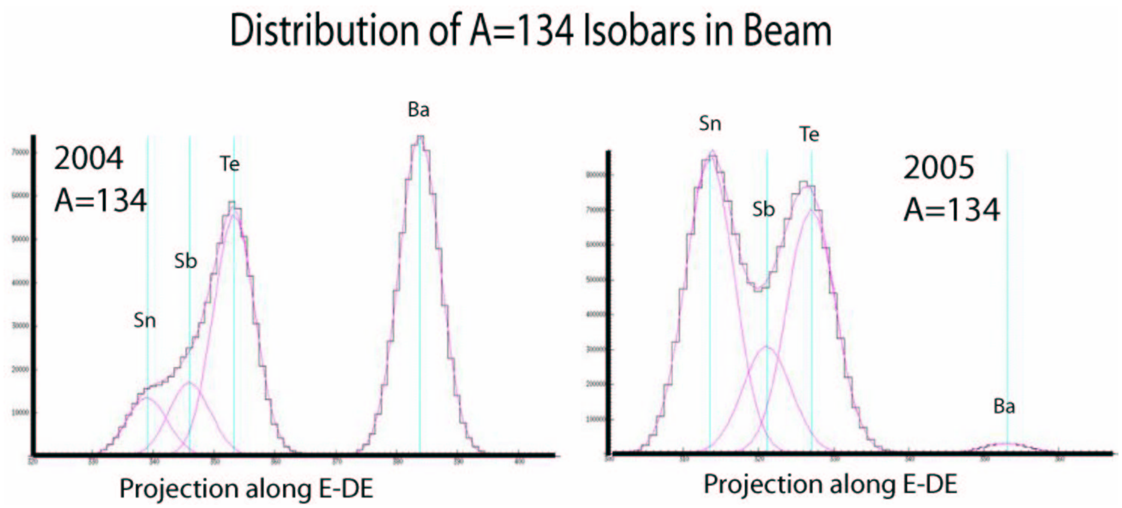


**FIGURE 7.** The distribution of A=134 isobars in the beam during two different experiments - projections were made over line of fixed E/DE ratio.

- therefore, repeating the measurement may help unfold the contribution of $^{134}$Sb from $^{134}$Sn as beam composition is sampled throughout the run. Two or more additional data points at lower energies will help to determine whether the larger cross section observed so far in that system is due to a larger than usual nuclear radius in the entrance channel, or other effects may be at play. Also, the contribution from isobars with higher charge (Z) is diminished.

## WKB CALCULATIONS FOR SUB-BARRIER FUSION

Measuring fusion cross sections for reactions between neutron-rich heavy nuclei could yield information about the magnitude of cross section enhancement one might expect when attempting to synthesize heavy elements using neutron rich radioactive ion beams. There are several models that predict enhancement of sub-barrier fusion well beyond size effects [9, 10, 11]. We implemented a WKB code that calculates, the cross section of two nuclei to get captured in the nucleus-nucleus potential well. In our code we follow the prescription suggested in Refs. [10, 11] with some differences. We opted to use global potentials derived from fits to a large body of fusion data [12, 13]. We also used a neutron transfer form factor that saturates at inter-nuclear distances where neutron flow [9] is initiated rather than at some arbitrary distance of closest approach. Further details and differences between our calculation and those of Refs. [10, 11] will appear in [14]. Fig. 8 presents calculated sub-barrier fusion cross sections for collisions between a $^{132}$Sn beam and $^{64}$Ni and $^{58}$Ni targets. Note that the calculations for $^{132}$Sn+$^{64}$Ni under-predict the measured cross section at the lowest energy point. Similar results were reported for coupled channel calculations which take into account neutron transfer as well as inelastic excitation [15]. Note that the same mechanism predicts a large enhancement in the fusion cross section for $^{132}$Sn+$^{58}$Ni where there are many neutron transfer channels with positive Q-values.

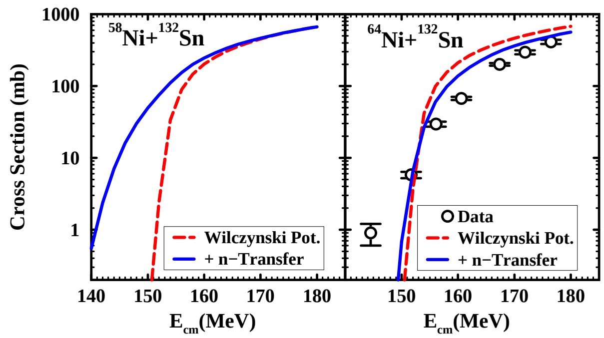


**FIGURE 8.** WKB predictions for capture of $^{132}$Sn with $^{64}$Ni and $^{58}$Ni target.

# SUMMARY

We presented newly measured ER cross sections from collisions of Te and Sn isotopes with Ni targets. The effect of neutron excess and neutron transfer probabilities on sub-barrier fusion cross section was studied by comparing calculated capture cross sections with the ER data. At sub-barrier energies ER cross sections account well for the capture process. However, at energies near and above the barrier, fission competes with ER production and comparison of capture calculations with ER data become less meaningful. Extending our studies to energies near and above the barrier requires measuring also fusion-fission and quasi elastic scattering. We are currently planning a "next generation" detection system that will measure these quantities simultaneously.

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