Physics with Heavy Neutron-Rich RIBs at the HRIBF*

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The Holifield Radioactive Ion Beam Facility (HRIBF) at Oak Ridge is the first ISOL-type facility to provide beams of accelerated radioactive fission products. To generate these beams, products of fission induced by proton bombardment of a uranium carbide target are ionized, charge-exchanged in Cs vapor, and injected into the HRIBF tandem. Using a single stripper foil in the terminal, they can be accelerated to about 3 MeV per nucleon, ideal for Coulomb Excitation studies. Alternatively, they can be accelerated to energies above the Coulomb barrier by means of double-stripping, at the expense of a factor of about five in lost beam intensity.

This paper reports on recent experiments using neutron-rich radioactive ion beams (RIBs) from the HRIBF facility. We have performed Coulomb excitation measurements of B(E2; $0^+ \rightarrow 2^+$) in ^{126,128}Sn and ^{132,134,136}Te, neutron transfer to single-particle states in ^{135}Te, and fusion-evaporation reactions on light targets to study evaporation residues with γ-γ-recoil coincidence spectroscopy.

To perform these types of measurements with heavy neutron-rich RIBs is inherently challenging. Any stopped or scattered beam that decays near the target can generate very high background rates for both the Ge and the CsI detectors. In this respect, the excellent beam quality provided by the HRIBF tandem accelerator turned out to be crucial. Since the beams are weak, the γ-ray singles and γ-γ-coincidence rates from the desired reactions are usually much lower even than the room background rates, necessitating the use of a selective trigger for the events of interest. Moreover, the beams are generally contaminated with isobars of different elements; that is, they are composed of "cocktails" of a single mass. The HRIBF injection system, as it is presently configured, does not provide complete isobar selection for these heavy beams. In addition, interesting experiments tend to require very inverse reactions, resulting in high velocities for recoiling reaction products and hence large Doppler broadening effects for the detected γ rays. To obtain good γ-ray energy resolution therefore requires the use of highly segmented detectors such as the CLARION array of segmented clovers.

The HRIBF is well-equipped for nuclear structure studies with RIBs. The experimental setup for the present work consisted of the CLARION Ge detector array and the HyBall CsI charged-particle detector array at the target. Foil-plus-microchannel-plate (MCP) ion detectors were used both to count the beam and to detect recoiling reaction products. Thick (4-5 mg/cm^2) metallic foils placed near the achromatic focus of the RMS [1] were also used to excite K vacancies in beam particles; detection of the resulting X rays provided a continuous measurement of the isobarric composition of the beam.

Coulomb excitation measurements have been performed using a natural carbon target of 0.83 mg/cm^2. Carbon ions scattered out of the target were detected in the HyBall, and provided a very clean gate for coincident γ rays. The C ions could be cleanly distinguished from other ions in the HyBall CsI detectors by means of pulse-shape analysis. The ratio of γ-HyBall coincidences to HyBall singles gives an excellent measure of the excitation probability of the beam during the collision. In this way, measurements of the B(E2; $0^+ \rightarrow 2^+$) have been obtained for the first time for the nuclides ^{126,128}Sn and ^{132,134,136}Te. Beam intensities of 3×10^5 to 10^7 ions/s and energies ~ 3 MeV/nucleon were used.

Gamma-ray spectra in prompt coincidence with carbons are shown in figure 1 for the five different masses. The Sn isotopes of interest are strongly contaminated with the Sb and Te isobars, and the ^{134,136}Te beams show significant components of the corresponding stable Ba nuclei. Analysis of the results to extract the final B(E2) values is in progress. Figure 2 shows *very preliminary* results together with the systematics for measured Sn, Te, Xe, Ba and Ce isotopes, taken from ref. [2]. The present results are shown as filled circles.

It is very interesting that our preliminary B(E2; $0^+ \rightarrow 2^+$) value for ^{136}Te is similar to, or perhaps even a little lower than, that for ^{134}Te. This is contrary to expectations from the shell model, and from extrapolating the systematics of heavier N$= 82, 84$ isotones. If this result stands after the final analysis, it could be interpreted as indicating that the shell-model parentage of the first 2^+ state in ^{136}Te is dominated by the 2ν state, *i.e.* the corresponding level in ^{134}Sn at 725 keV, with only a small component of the 2π (^{134}Te, 1279 keV) level. The weak mixing implied by this interpretation is somewhat surprising.

In another experiment, the inverse-kinematics transfer reaction ^{9}Be(^{134}Te,^{8}Be) at about 4 MeV per nucleon was used to identify single-neutron states in ^{135}Te. Unbound ^{8}Be products were detected in the HyBall CsI detectors as a pair of α particles, and could easily be distinguished from other types of charged particles on the basis of the pulse shape. Gamma rays in coincidence with the α pairs produce a very clean spectrum, shown in the top potion of figure 3. It is dominated by the single-neutron states of ^{135}Te; our *preliminary* assignments are indicated in the lower part of figure 3. The data shown were obtained in 16 hours, at a beam current of about 4×10^5 ions per second.

The 1180 keV level was first observed in the decay of a $\frac{19}{2}^-$ isomer populated by spontaneous fission, and the levels at 657, 1081, 1126 and 1180 keV have also been seen by Hoff *et al.* [3] in the beta decay of ^{135}Sb. Our observations strongly support the assignments of $\nu p_{3/2}$ and $\nu p_{1/2}$ single-neutron structure to the first two excited states as suggested by Hoff *et al.* [3], but the position of the $\nu f_{5/2}$ state is more ambiguous. Hoff *et al.* assign this as the 1126 keV level, but the systematics of N$= 83$ isotones suggest that our newly-observed state at 1400 keV could be a better candidate.

The feasibility of γ-γ coincidence spectroscopy coupled with fusion-evaporation reactions of heavy neutron-rich RIBs has been demonstrated, using beams of ^{118}Ag at $\sim 10^6$ ions per second. The data collected consisted of γ-HyBall coincidences, together with γ-γ-recoil coincidences where the recoil was detected in a MCP detector. A target of 0.6 mg/cm^2 natural C was bombarded at 500 MeV, and produced the known nuclides ^{125,126}I [4] (5n and 4n evaporation) and ^{126}Te (p3n), together with α3n evaporation to previously unobserved states in ^{123}Sb. A target of 1.25 mg/cm^2 Be was also bombarded at 455 MeV in an attempt to observe new levels in the 4n-evaporation product, ^{123}Sb. The γ-γ spectrum observed in coincidence with recoils was virtually identical to the α-gated γ-ray spectrum from the C target, confirming the assignment of the peaks to ^{123}Sb.

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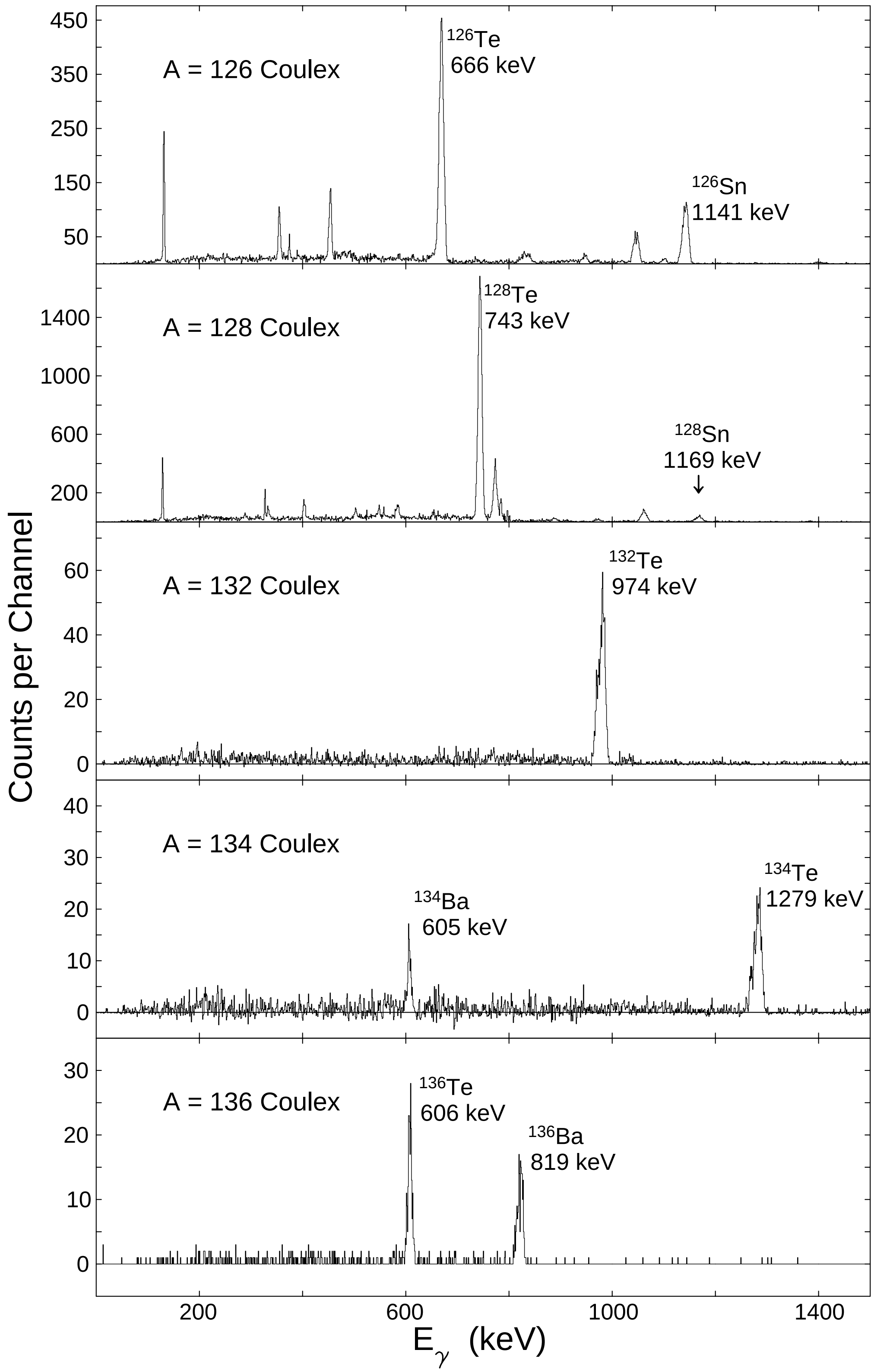

Figure 1: Gamma-ray spectra from Coulomb excitation of beams from the HRIBF, in prompt time coincidence with scattered carbon target ions detected in the HyBall CsI detectors. Some of the spectra have a small normalized random coincidence component subtracted. Unlabeled peaks in the spectra for masses 126 and 128 are believed to arise from Coulex of the odd-odd Sb isotopes to previously unobserved levels.

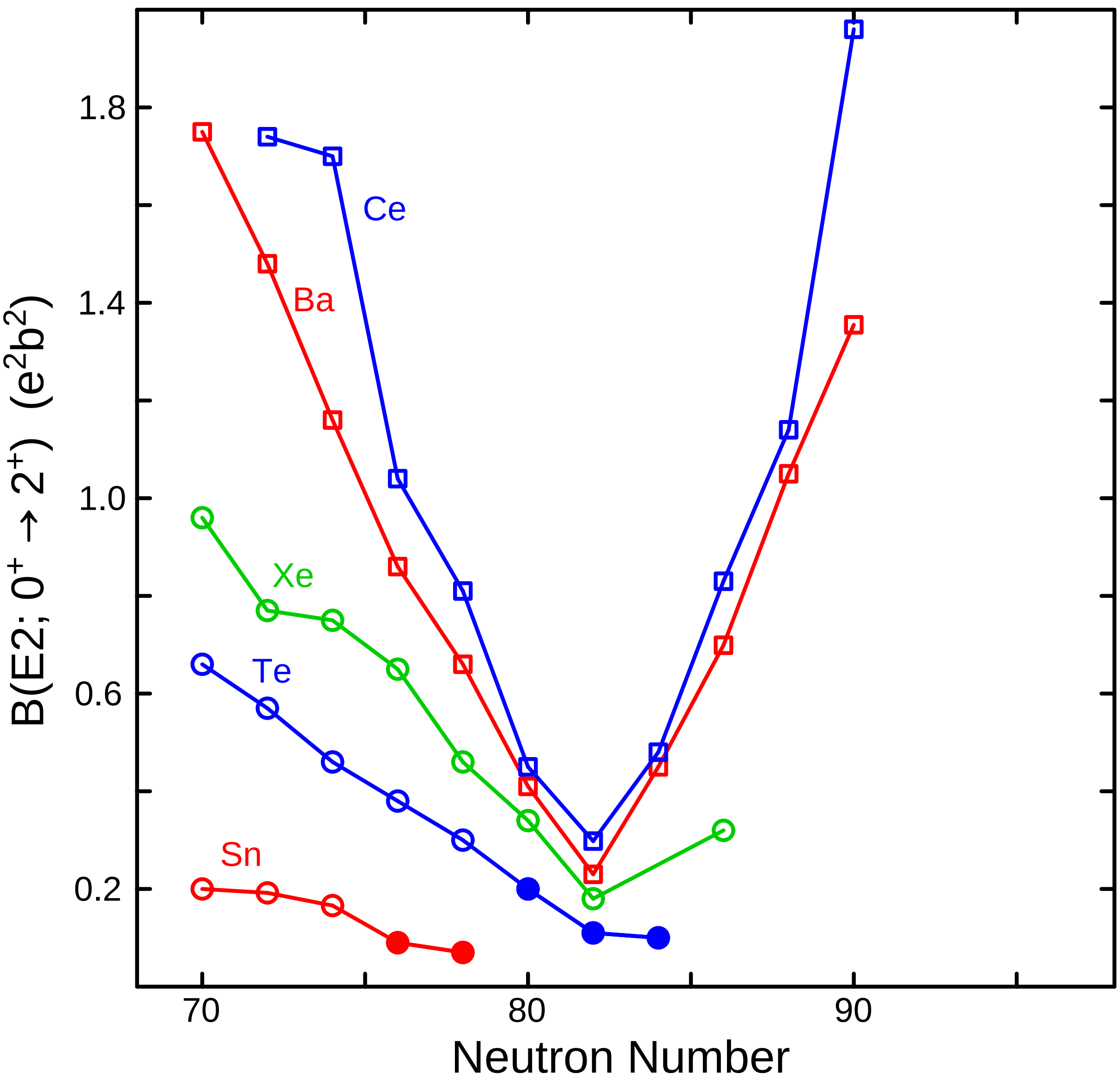

Figure 2: *Preliminary* values of B(E2; $0^+ \rightarrow 2^+$) extracted from the spectra of figure 1 (filled circles) together with systematics compiled in reference [2] (open symbols).

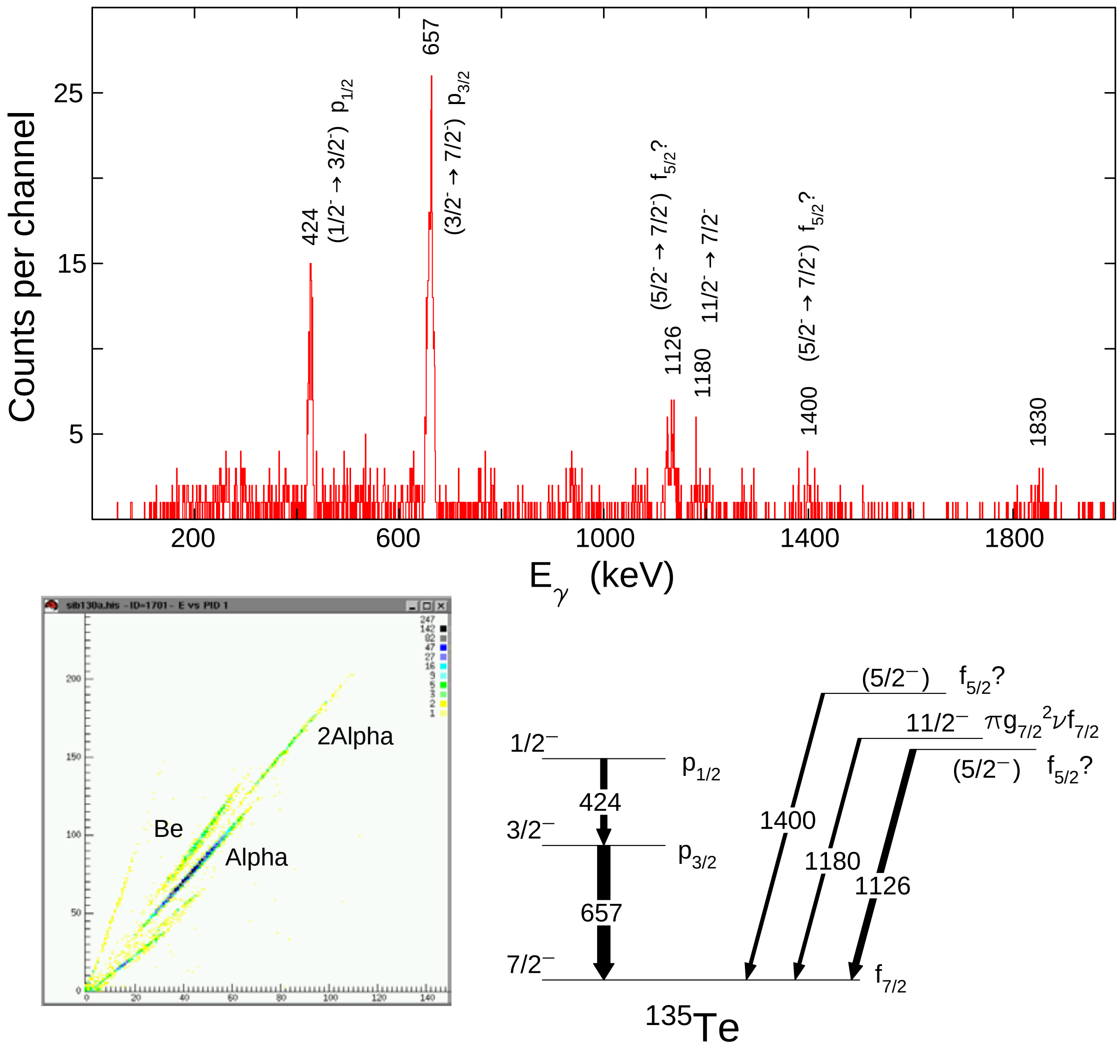

Figure 3: Top: Gamma-ray spectrum from the ^{9}Be(^{134}Te,^{8}Be)^{135}Te reaction in coincidence with 2α clusters detected by the HyBall. Bottom left: Particle identification spectrum for one of the CsI detectors. Bottom right: Partial level scheme for ^{135}Te, showing preliminary tentative configuration assignments.