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Coulomb excitation and transfer reactions with neutron-rich radioactive beams

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Abstract. Neutron-rich radioactive ion beams available from the HRIBF allow a variety of measurements around the ^{132}Sn region, including Coulomb excitation and single-nucleon transfer. The $B(E2; 0^+ \rightarrow 2^+)$ values for first 2^+ excited states of even-even neutron-rich $^{132-136}$Te and $^{126-130}$Sn have been measured by Coulomb excitation in inverse kinematics. Neutron transfer onto a ^{134}Te beam from ^{9}Be and ^{13}C targets, to populate single-particle states in ^{135}Te, has also been studied. Gamma rays from the ^{13}C(^{134}Te, ^{12}C) reaction were used to identify the $\nu i_{13/2}$ state in ^{135}Te, at an energy of 2109 keV. These and other results, and plans for future experiments with these neutron-rich beams, are presented.

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1 Introduction

At the Holifield Radioactive Ion Beam Facility (HRIBF), located at Oak Ridge National Laboratory (ORNL), heavy neutron-rich fragments from proton-induced fission in a uranium carbide target are extracted, ionized and charge-exchanged, and then injected into a 25 MV tandem electrostatic accelerator. This provides post-accelerated beams of over 100 radioactive species with at least 1000 ions per second on target; intensities for some beams are as high as 10^8 ions per second. In general, the beams are isobarically contaminated, *i.e.,* contain significant numbers of other nuclear species with the same mass. However, chemical techniques [1] can produce isobarically pure beams of a few selected elements, including Sn and Ge.

These neutron-rich radioactive ion beams (RIBs) open exciting possibilities for a wide range of new spectroscopic studies around doubly-magic ^{132}Sn, including $B(E2)$ measurements through Coulomb excitation in inverse kinematics, γ-ray spectroscopy following fusion-evaporation reactions, and neutron- and proton transfer reactions to investigate single-particle states. Experiments using these beams also provide an excellent training ground for developing techniques to be used at the future high-intensity Rare Isotope Accelerator facility, RIA. These novel experiments, however, involve significant technical and experimental challenges.

Even a small fraction of stopped or scattered radioactive beam close to the target can generate large backgrounds of γ and β radiation in γ-ray and charged-particle detectors. Good beam quality, such as provided by the HRIBF tandem accelerator, is therefore crucial. The low beam currents of these radioactive species implies that γ and γ-γ coincidence rates from induced reactions are small compared to background. A selective trigger for the events of interest is thus of vital importance. The heavy beam, coupled with the light targets required for most

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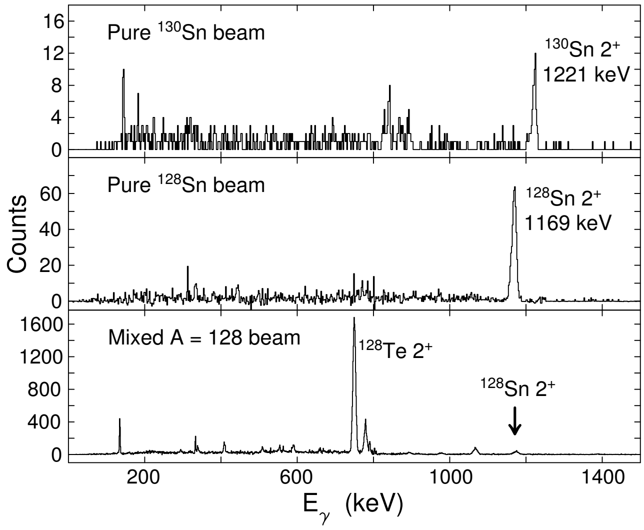

Fig. 1. Spectra of γ-rays from Coulomb excitation of ^{128,130}Sn beams using CLARION. $2_1^+ \to 0^+$ transitions are labeled.

experiments, yields excited nuclei with high recoil velocities, typically $\sim 0.07c$. This, in turn, generates significant Doppler broadening for γ-rays. A related problem is the extreme kinematic broadening of light-ion energies from inverse-kinematics transfer reactions close to the Coulomb barrier.

2 Coulomb excitation measurements with CLARION

We have developed a novel method [2] for measuring Coulomb excitation of RIBs, in which scattered target nuclei are detected at forward angles, and used both as a clean trigger for selecting γ-rays from the Coulomb-excited beam and to normalize to the integrated beam current through Rutherford scattering. This technique was first applied to measure the $B(E2; 0^+ \to 2_1^+)$ values for the first-excited 2^+ states of neutron-rich ^{132,134,136}Te and ^{126,128}Sn. Energetic carbon nuclei, from collisions of the beam in a natural carbon target, were detected in the HyBall array [3] of 95 CsI crystals. Gamma rays, detected by the segmented clover Ge detectors of the CLARION array [4], were recorded along with the HyBall data whenever they were in coincidence. The high 2^+ energies and low $B(E2)$ values yield low cross-sections for excitation, which together with the weak beam makes these experiments challenging. The Te results have been reported in ref. [2]. A measurement for the ^{132,134}Te beams also been performed at the HRIBF by Barton *et al.* [5] using a different method.

More recently, $B(E2; 0^+ \to 2_1^+)$ measurements were made for ^{128,130}Sn beams [6], using the new isotopically purified beams formed from molecular SnS^+ [1]. Beam intensities were about 3×10^6 s^{-1} and 5×10^5 s^{-1}, respectively. The Sn ions were primarily in their 0^+ ground states, but 8.5% and 11% were in the metastable 7^- state for ^{128}Sn and ^{130}Sn, respectively. Isobars of

Table 1. $B(E2; 0^+ \to 2_1^+)$ values (e^2b^2) measured in the present work, compared with shell-model [2,7] (SM) and Quasi-particle Random Phase Approximation [8] (QRPA) calculations. The results for the Sn isotopes are preliminary.

Nuclide	This work	SM [2,7]	QRPA [8]
^{126}Sn	0.10(3)		0.069
^{128}Sn	0.073(6)		0.034
^{130}Sn	0.023(5)		0.007
^{132}Te	0.172(17)	0.15	0.131
^{134}Te	0.096(12)	0.08	0.072
^{136}Te	0.103(15)	0.16	0.091

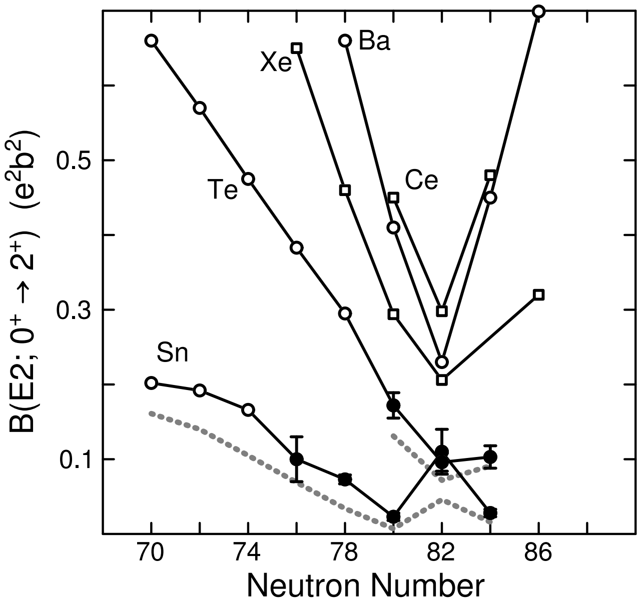

Fig. 2. Values of $B(E2; 0^+ \to 2_1^+)$ for even-even Sn, Te, Xe, Ba and Ce isotopes around neutron number $N = 82$. Open symbols are adopted values from ref. [9] while filled symbols are from the present work ($^{132-136}$Te, $^{126-130}$Sn) or from Varner *et al.* [10] (^{132,134}Sn). The thick shaded dotted lines show the results of QRPA calculations by Terasaki *et al.* [8].

other elements made up less than 1% of these two beams. Since the uncertainties in the measurements made using cocktail beams are dominated by the uncertainty in the beam composition, use of these purified beams results in a significantly higher precision.

Spectra of γ-rays from ^{128,130}Sn, gated by prompt coincidence with carbon recoils and Doppler-shift corrected, are shown in fig. 1. Also shown for comparison is a corresponding spectrum from an earlier experiment on the isobar "cocktail" $A = 128$ beam, ~ 14% of which was ^{128}Sn. Absolute γ-ray efficiencies were measured using ^{60}Co and ^{152}Eu sources, and corrected for Doppler shifts and for the modified solid angle of the Ge detectors in the frame of the γ-emitting recoils. Using these efficiencies and the ratios of coincidence to singles yields, we can extract a ratio of Coulomb-excitation to Rutherford-scattering cross-sections. These same cross-section ratios

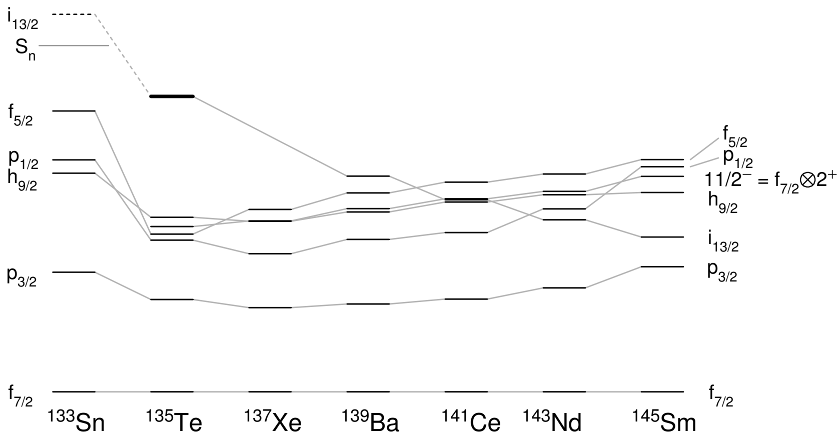

Fig. 3. Systematics of single-neutron level energies in $N = 83$ nuclei.

were then calculated using the Winther-DeBoer code to extract the $B(E2)$ values. Final values for the $B(E2)$ of Te isotopes, and preliminary values for Sn isotopes, are listed in table 1. They are also displayed together with the $B(E2)$ systematics for this mass region in fig. 2. Also shown in fig. 2 are the results from Varner *et al.* [10] for the Coulomb excitation of ^{132}Sn and ^{134}Sn, using the ORNL-MSU-TAMU BaF$_2$ array at the HRIBF.

It was expected from shell-model calculations [7] and systematics that the $B(E2)$ value for ^{136}Te would conform to the symmetry about neutron number $N = 82$ exhibited by Ba, Ce and other heavier nuclei, and be similar to the value for ^{132}Te. Instead, the ^{136}Te value is significantly smaller, close to that of ^{134}Te. We also point out the different excitation energies of 2_1^+ states in Sn and Te isotopes across $N = 82$. There is a significant drop in the 2_1^+ energy for both ^{134}Sn (725 keV) and ^{136}Te (606 keV) as compared to their $N = 80$ isotopes (1221 and 974 keV, respectively.)

Recently, a series of Quasiparticle Random Phase Approximation (QRPA) calculations have been performed by J. Terasaki *et al.* [8]. The excitation energy asymmetry in Sn and Te and the $B(E2)$ asymmetry in Te are both well reproduced in these calculations, as is the $B(E2)$ symmetry in heavier elements. The reduced $N = 84$ Sn and Te 2^+ energies arise in the calculation primarily as a result of the small neutron monopole pairing gap extracted from observed odd-even mass differences. This reduces the energy required to break the neutron pair to form a 2^+ state, relative to that required for the proton pair. Thus, the mixed 2_1^+ state is calculated to be of predominately 2ν character, with a low $B(E2)$ value. Results from these calculations are shown as the thick shaded dotted lines in fig. 2.

3 Single-neutron transfer reactions

Energies of single-particle states in odd-mass, near-magic nuclei are vital quantities for nuclear models, either as tests of large-scale shell model calculations or as input to more empirical models. This is especially true close to doubly magic nuclei, such as ^{132}Sn.

Until recently, the $i_{13/2}$ level in the $N = 83$ isotones was known only for ^{139}Ba and heavier; it had not been identified in ^{137}Xe or ^{135}Te, and is believed to lie above the neutron-separation threshold in ^{133}Sn [11]. All these nuclei have $f_{7/2}$ ground states, and all have levels previously assigned as $p_{3/2}$, $p_{1/2}$, $h_{9/2}$ and $f_{5/2}$ single-neutron excited states. The systematics of these levels are shown in fig. 3.

We have investigated the inverse-kinematics neutron transfer reactions ^{9}Be(^{134}Te,^{8}Be) and ^{13}C(^{134}Te,^{12}C) leading to ^{135}Te, using a ^{134}Te beam on $^{\rm nat}$Be and ^{13}C targets, at energies just above the Coulomb barrier. The Be-target data are strikingly clean; the immediate disintegration of the unstable ^{8}Be produces correlated α-particle pairs, which are detected in single elements of the HyBall array. This in turn provides a very clean trigger for coincident γ-rays. The C spectrum is significantly less clean than that from the Be target, due to the lack of isotopic sensitivity in the particle detectors. Inelastic excitation to the 2^+ and neutron stripping to ^{133}Te are the dominant contaminants. Spectra from a preliminary investigation of these reactions have been reported in ref. [6].

More recently, we have performed a second, higher-statistics experiment at the HRIBF, with these same two reactions, in an attempt to identify the $\nu i_{13/2}$ level in ^{135}Te. The ^{134}Te beam had an intensity of about 2×10^6 ions per second, and an energy of 4.3 MeV per nucleon. Light charged ions from the reaction were detected in the new ORNL "Bare HyBall" array of CsI detectors, and coincident gamma rays were detected in the CLARION array. From systematics, the $\nu i_{13/2}$ level was expected at a little above 2 MeV in excitation. It was also expected to γ-decay to the known $11/2^-$ state at 1180 keV; we therefore searched for γ-γ coincidences between the 1180 keV transition and a new transition at around 800–1000 keV.

The resulting γ-ray spectra are shown in fig. 4; the lowest part shows the spectrum from the Be target, gated by pairs of α-particles, and the upper parts show data gated by carbon ions from the ^{13}C target. Transitions from previously assigned states [12] are clearly visible, and are labeled by γ-ray energy and level assignment. Also visible in the ^{13}C spectrum is a new transition at 929 keV. The top two spectra in fig. 4 show γ-γ coincidence spectra from

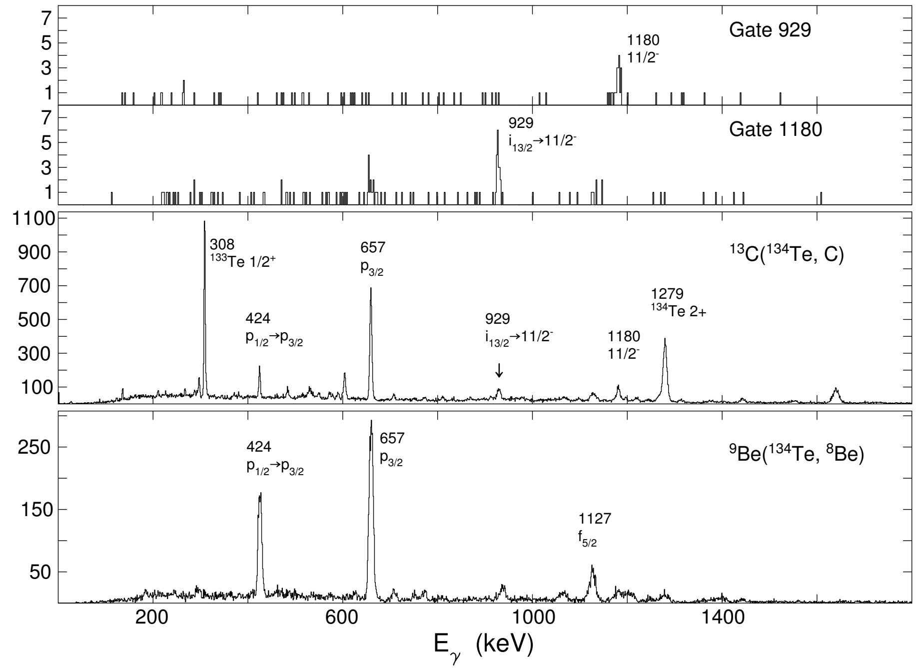

Fig. 4. Gamma-ray spectra from the neutron transfer experiment with ^{134}Te on $^{\rm nat}$Be and ^{13}C targets. The spectra are gated by coincidence with α-particle pairs (Be target, lowest part) or carbon ions (^{13}C target, upper parts) detected in the "Bare HyBall" array. The two top panels show the gated γ-γ coincidence spectra from the carbon target that were used to determine the feeding of the $11/2^-$ state (1180 keV) by the new 929 keV transition.

the ^{13}C target, gated on this new transition, and on the 1180 keV transition depopulating the $11/2^-$ state. Clearly these two lines are in coincidence, leading us to assign a new level at 2109 keV in ^{135}Te. Gamma-carbon angular-correlation measurements confirm that the 929 keV transition is of stretched dipole or unstretched quadrupole character, and is emitted from a state with angular momentum strongly aligned perpendicular to the reaction plane. The alignment of the $i_{13/2}$ should indeed be large, due to the large transferred angular momentum ($L = 7$) required to populate it from the $p_{1/2}$ initial state in ^{13}C.

The new level, at an excitation energy of 2109 keV, is therefore assigned as the $\nu i_{13/2}$ state in ^{135}Te, and is included as the heavy line in fig. 3.

There is no simple way to extract absolute cross-sections for the the population of observed levels in this experiment. It is however possible to determine the *relative* cross-sections for the various excited states, from an analysis of the γ-ray intensities. The results of such an analysis, normalized to the cross-section for the $p_{3/2}$ level at 659 keV, are presented in table 2. Feeding of low-lying levels by transitions from higher-lying levels, when known, was subtracted; such feeding was also searched for using the γ-γ coincidence data. The errors quoted in table 2 allow for estimates of the systematic uncertainty in this procedure.

Also shown in table 2 are the ratios of calculated cross-sections, obtained using the finite-range DWBA code PTOLEMY [13]. With the exception of the 1180 keV $\frac{11}{2}^-$ level, the calculations show good agreement with experiment, both in terms of the overall trends and in the relative strengths for the two reactions. The $\frac{11}{2}^-$ level is known to arise from a fully aligned coupling of the 2^+ quadrupole phonon with the $\frac{7}{2}^-$ ground state. Since such a configuration cannot easily be accomodated in the DWBA code, calculation for the $\frac{11}{2}^-$ level was done assuming an $h_{11/2}$ configuration instead. This is not expected to produce realistic results, but the calculated ratios are listed in table 2 for the sake of completeness.

Table 2. Relative cross-sections observed and calculated for the ^{13}C(^{134}Te,^{12}C) and ^{9}Be(^{134}Te,^{8}Be) single-neutron transfer reactions leading to levels in ^{135}Te. See text for details.

Level	Energy (keV)	^{13}C(^{134}Te,^{12}C) Expt	DWBA	^{9}Be(^{134}Te,^{8}Be) Expt	DWBA
$p_{3/2}$	659	≡1.00(8)	≡1.00	≡1.00(7)	≡1.00
$p_{1/2}$	1083	0.22(2)	0.193	0.92(4)	0.452
$f_{5/2}$	1126	0.17(3)	0.181	0.59(4)	0.603
$\frac{11}{2}^-$	1180	0.13(5)	[0.536]	0.22(2)	[0.089]
$(h_{9/2})$	1246	0.042(12)	0.023	0.054(13)	0.086
$i_{13/2}$	2109	0.22(2)	0.335	0.04(3)	0.056

4 Plans for future measurements

The variety and high intensity of these neutron-rich beams holds the potential for a large variety of new experiments. Some of the approved experiments planned for the near future include a measurement of the static quadrupole moment of the first 2^+ state in ^{126}Sn through the Coulomb-excitation reorientation effect.

In single-particle transfer reaction studies, we plan to investigate sub-Coulomb transfer of single neutrons on a doubly magic ^{132}Sn beam, and attempt to extract quantitative spectroscopic information from asymptotic normalization coefficients. Targets of $^{\rm nat}$Be and ^{13}C would again be used for these studies. In addition, using the possible (^{7}Li,^{8}Be) proton-pickup reaction, and/or other similar reactions, we hope to search for the unobserved $\pi s_{1/2}$ state in ^{133}Sb and $\pi p_{3/2}$, $\pi f_{5/2}$ hole states in ^{131}In. We will also identify the $\nu i_{13/2}$ single-neutron level in ^{137}Xe, using the ^{13}C(^{136}Xe,^{12}C)^{137}Xe reaction at the Argonne National Laboratory's ATLAS facility, with Gammasphere and the Microball as detector systems.

A longer-term goal is the measurement of spectroscopic factors in light-ion transfer reactions such as (d, p) and (^{3}He, d), but again measured in inverse kinematics. The major difficulty for these studies is the low beam energy available at the HRIBF for beams close to ^{132}Sn, in practice limited to less than 5 MeV per nucleon. The low energy results in rather featureless angular distributions. Furthermore, drastic kinematic broadening results in a poor Q-value resolution that makes it difficult or impossible to identify the populated state based on the detected light-ion energy alone. We are exploring possible avenues to alleviate these difficulties, including use of the Spin Spectrometer to identify final states using particle-gamma coincidences and gamma calorimetry.

5 Conclusion

$B(E2; 0^+ \rightarrow 2^+)$ values for neutron-rich ^{132,134,136}Te and ^{126,128,130}Sn isotopes have been measured by Coulomb excitation of radioactive ion beams in inverse kinematics. The results for ^{132}Te and ^{134}Te ($N = 80, 82$) show excellent agreement with systematics of lighter Te isotopes, but the $B(E2)$ value for ^{136}Te ($N = 84$) is unexpectedly small. QRPA calculations [8] suggest that this anomaly is linked to weak neutron pairing in ^{136}Te. The value for ^{130}Sn is very small, around 1.4 single-particle units.

We have also been able to observe neutron transfer to single-particle levels in ^{135}Te through the detection of γ-ray transitions in coincidence with target-like residues. The ^{13}C(^{134}Te, ^{12}C) reaction was used to identify the $\nu i_{13/2}$ state in ^{135}Te, at an energy of 2109 keV, by utilizing γ-γ-particle coincidences and particle-γ angular correlations. In addition, observed cross-section ratios agree well with DWBA calculations. This technique appears to be a promising tool in the search for more new levels, and possibly also for determining quantitative spectroscopic information.

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References

1. D.W. Stracener, Nucl. Instrum. Methods Phys. Res. B **204**, 42 (2003).
2. D.C. Radford *et al.*, Phys. Rev. Lett. **88**, 222501 (2002).
3. A. Galindo-Uribarri *et al.*, to be published in Nucl. Instrum. Methods Phys. Res.
4. C.J. Gross *et al.*, Nucl. Instrum. Methods Phys. Res. A **450**, 12 (2000).
5. C.J. Barton *et al.*, Phys. Lett. B **551**, 269 (2003).
6. D.C. Radford *et al.*, Nucl. Phys. A **746**, 83c (2004).
7. A. Covello, private communication; see also A. Covello *et al.*, in *Challenges of Nuclear Structure*, in *Proceedings of the 7th International Spring Seminar on Nuclear Physics*, edited by A. Covello (World Scientific, Singapore, 2002) p. 139.
8. J. Terasaki, J. Engel, W. Nazarewicz, M. Stoitsov, Phys. Rev. C **66**, 054313 (2002).
9. S. Raman, C.W. Nestor jr., P. Tikkanen, At. Data Nucl. Data Tables **78**, 1 (2001).
10. R.L. Varner *et al.*, these proceedings.
11. See, for example, W. Urban *et al.*, Eur. Phys. J. A **5**, 239 (1999).
12. P. Hoff *et al.*, Z. Phys. A **322**, 407 (1989).
13. M. Rhoades-Brown, S.C. Pieper, M.H. McFarlane, PTOLEMY, unpublished; M.H. McFarlane, S.C. Pieper, ANL-76-11.