Coulomb Excitation of Radioactive ^{132,134,136}Te Beams and the Low $B(E2)$ of ^{136}Te

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The $B(E2; 0^+ \rightarrow 2^+)$ values for the first 2^+ excited states of neutron-rich ^{132,134,136}Te have been measured using Coulomb excitation of radioactive ion beams. The $B(E2)$ values obtained for ^{132,134}Te are in excellent agreement with expectations based on the systematics of heavy stable Te isotopes, while that for ^{136}Te is unexpectedly small. These results are discussed in terms of proton-neutron configuration mixing and shell-model calculations using realistic effective interactions.

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Electromagnetic transition rates provide one of the most sensitive probes of nuclear structure. For collective rotation in deformed nuclei, transition strengths are generally the most accurate available measure of the nuclear deformation. In spherical and transitional nuclei closer to closed shells ("magic nuclei"), they are of great value in probing the details of nuclear many-body wave functions.

While accelerated beams of stable ions have been used to measure transition rates in most stable and proton-rich nuclei, they are of limited use for probing neutron-rich nuclei. Most heavy and medium-mass neutron-rich nuclei that have been studied are populated only through fission. Since this mechanism does not lend itself to measurements of lifetimes in the appropriate range, very few transition rates have been measured for 2^+ states in even-even neutron-rich nuclei. These rates provide crucial tests of theoretical predictions, such as the quenching of shell structures in neutron-rich nuclei [1].

The region around ^{132}Sn, with its closed shells of both protons and neutrons, is one for which transition rates would be especially helpful. Although it is expected to be one of the most rigid doubly magic nuclei [2], $B(E2; 0^+ \rightarrow 2^+)$ values in ^{132}Sn and its neighbors remain unknown. These quantities could provide important clues regarding several unexplained anomalies, such as a very low-lying 2^+ state in ^{134}Sn, and the reported difficulties with some shell-model calculations [3] in reproducing the energy spectra of nearby nuclei with 84 neutrons. Since the usual techniques using stable beams cannot be applied here, new methods for measuring transition rates are required.

The Holifield Radioactive Ion Beam Facility (HRIBF) at the Oak Ridge National Laboratory has recently produced the world's first postaccelerated beams of heavy neutron-rich nuclei. At the HRIBF, fragments from proton-induced fission in a uranium carbide target are extracted, ionized, charge-exchanged, and injected into a 25 MV tandem accelerator. Intensities on target can be 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.

These neutron-rich radioactive ion beams (RIBs) open the possibility of a wide range of new spectroscopic studies around ^{132}Sn, including Coulomb excitation in inverse kinematics. Because of the weak beams, high 2^+ energies, and low $B(E2)$ values, these experiments are challenging; other problems include the impurity of the RIB, and background radiation from stopped beam. We have recently developed a novel method for measuring Coulomb excitation of a RIB, in which scattered target nuclei are detected at forward angles and are used both as a clean trigger for selecting γ rays and to normalize to the integrated beam current through Rutherford scattering. This Letter reports on the first application of this technique, to the measurement of the $B(E2; 0^+ \rightarrow 2_1^+)$ value in ^{132,134,136}Te. Preliminary results have been reported in Ref. [4]. A measurement for ^{132,134}Te using a different method has also been performed by Barton *et al.* [5] using these beams at the HRIBF.

Beams of ^{132}Te at 396 and 350 MeV, and of ^{134,136}Te at 396 MeV, were used to bombard a natural carbon foil of 0.83 mg/cm^2 thickness, located at the target position of the recoil mass spectrometer (RMS) [6]. Energetic carbon nuclei from target-beam collisions were detected at laboratory angles between 7° and 44° in the HyBall array [7] of 95 CsI crystals. Any signal in the HyBall served as a trigger for recording the events. Gamma rays, detected by eight segmented clover Ge detectors of the CLARION

array [6], were recorded along with the HyBall data whenever they were in coincidence. In order to minimize background from decay of the radioactive beam, great care was taken in tuning the beam to optimize transmission through the target region. The excellent beam quality provided by the tandem accelerator was a great asset. Beam intensities varied from about 10^5 s^{-1} ($A = 136$) to 10^7 s^{-1} ($A = 132$). Test and calibration measurements were also performed with stable beams, including 384-MeV ^{128}Te and 396-MeV ^{136}Ba.

At the achromatic focus of the RMS, Mo, Pd, or Au foils of about 4 to 5 mg/cm^2 thickness were placed in the path of the beam. Interactions between the foil and the beam created x rays that were detected in planar Ge detectors, enabling us to monitor the relative isobaric compositions of the beams. Beam assays were also performed for each radioactive beam, by stopping the beam at the target position and measuring the γ rays from β decay.

Spectra of γ rays, gated by prompt coincidence with carbon recoils and Doppler-shift corrected, are shown in Fig. 1. They are remarkably clean, due to the selectivity of the HyBall gate in discriminating against room background and decay of stopped beam. The only identifiable contamination arises from Coulomb excitation of stable barium isobars. While below the observation limit for $A = 132$, this Ba beam contamination increases significantly with mass. From a spectroscopic analysis of the beam assays, components of Sn, Sb, and I isobars could also be measured. No Cs or Xe was observed; Xe does not form a negative ion, and Cs has a low probability of charge exchange in the Cs-vapor charge exchange cell.

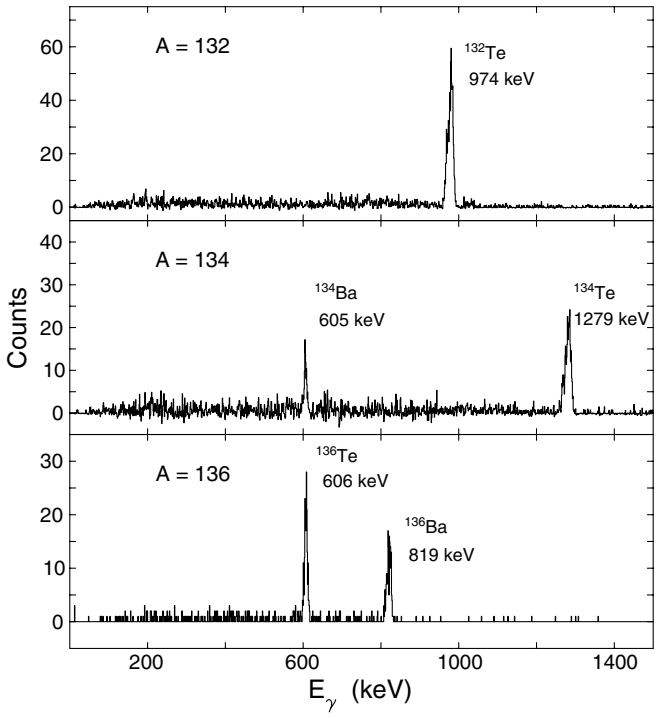

FIG. 1. γ rays from Coulomb excitation of the radioactive ion beams, Doppler-shift corrected and gated by prompt coincidence with carbon recoils in the HyBall detectors. Peaks are all $2_1^+ \rightarrow 0^+$ transitions and are labeled by nuclide and energy.

Observed yields of photopeak γ-C coincidence events and C singles for the C ions detected in the three most forward rings of HyBall are reported in Table I. Also listed are the fractional compositions of the different beams. For the barium isobars, these are determined from the observed Coulomb excitation probability, together with the adopted $B(E2)$ values from Raman *et al.* [8]. The other species were determined from the beam assays, and from the measured x-ray yields, as described above. While the x-ray analysis is constrained by the Ba Coulomb excitation and beam assay results, it is complicated by the Z dependence of both the x-ray production cross section and the beam transmission through the RMS. To allow for this, systematic uncertainties of 20% were assigned to the x-ray results.

Absolute γ-ray efficiencies for the $2_1^+ \rightarrow 0^+$ transitions were measured using ^{60}Co and ^{152}Eu sources and corrected for the γ-ray Doppler shifts and for the different geometrical 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 of Table I, we can extract a ratio of Coulomb-excitation to Rutherford-scattering cross sections. This ratio does not depend on an integrated beam current and is less sensitive to the target thickness uncertainties and other effects than a measurement of the Coulomb-excitation cross section alone. It does, however, need to be corrected for the isobaric composition of the beam. Calculations of differential cross sections were performed using the DeBoer-Winther multiple Coulomb excitation code of Ref. [9] and integrated over the beam

TABLE I. Measured beam compositions, and yields of γ-carbon photopeak coincidences and C singles events.

Beam and energy	Element	Beam fraction (%)	γ-C yield	C yield
$A = 132$	Te	86(4)	80(10)	7.11×10^5
396 MeV	Sb	11(3)		
	Sn	1.3(3)		
	I	1.3(6)		
$A = 132$	Te	86(4)	710(35)	1.63×10^7
350 MeV	Sb	11(3)		
	Sn	1.3(3)		
	I	1.3(6)		
$A = 134$	Te	87(4)	377(22)	1.63×10^7
396 MeV	I	11(3)		
	Ba	1.2(2)[a]	119(15)	
	Sb	0.9(3)		
$A = 136$	Te	59(5)	224(15)	2.99×10^6
396 MeV	Ba	29(3)[a]	189(15)	
	I	12(3)		

[a]Calculated from observed excitation, using adopted [8] values for the $B(E2; 0^+ \rightarrow 2_1^+)$ ($0.66e^2\,b^2$ for ^{134}Ba; $0.41e^2\,b^2$ for ^{136}Ba).

energy through the target and the angles of the applicable HyBall detectors. The Rutherford-scattering value depends on Z for each beam species, so a weighted sum was calculated using the beam fractions listed in Table I. By comparing the calculated and observed ratios, we could then deduce the excitation probability of the relevant beam fractions and hence the $B(E2; 0^+ \rightarrow 2^+)$.

Final values for the $B(E2)$ are listed in Table II and are displayed together with the $B(E2)$ systematics for this mass region in Fig. 2. The quoted errors include contributions for systematic uncertainties in detector angles, γ-ray efficiencies, etc. The measurements for the stable beams of ^{128}Te and ^{136}Ba, also listed in Table II, are in good agreement with the adopted values [8].

In Fig. 2, the present results for ^{132}Te and ^{134}Te agree very well with expectations based on the systematics of lighter Te isotopes. However, it was expected 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 almost a factor of 2 smaller and is close to that of ^{134}Te.

In considering the cause of this anomaly, it is instructive to examine the systematics of the excitation energies of 2_1^+ states in Sn and Te isotopes across $N = 82$. This is displayed in Fig. 3, which shows a significant drop in the 2_1^+ energy for both ^{134}Sn and ^{136}Te, as compared to their $N = 80$ isotopes. The cause of this drop when entering the new neutron shell is not obvious; there is no such effect seen, e.g., around ^{208}Pb, nor can shell-model calculations using semiempirical two-body interactions reproduce the compressed energy spectra for $N = 84$ [3].

To illustrate the possible influence of this asymmetry in 2_1^+ energy on the Te $B(E2)$ values, we invoke a very simplistic seniority-two empirical model for the 2_1^+ states in ^{132,134}Te, where we consider only mixing of π^2, ν^{-2} and ν^2 configurations, and take the observed 2_1^+ levels in ^{134}Te and ^{130,134}Sn as basis states. Then to generate the 974-keV state in ^{132}Te from the mixing of the 1279- and 1221-keV levels requires an interaction of $|V| = 274$ keV. Since the basis states are close in energy, this produces the almost completely mixed configuration

$$|2^+; {}^{132}\mathrm{Te}\rangle = 0.74|\nu^{-2}\rangle \pm 0.67|\pi^2\rangle.$$

For ^{136}Te, the mixing of the 1279- and 725-keV levels requires a very similar interaction strength, $|V| = 283$ keV, but results in a much less mixed 606-keV state,

$$|2^+; {}^{136}\mathrm{Te}\rangle = 0.92|\nu^2\rangle \pm 0.39|\pi^2\rangle.$$

For an attractive force, the lowest 2^+ state has the constructive interference for the transition strength [11]. This means that to reproduce the observed ^{136}Te $B(E2)$ value with the weakly mixed configuration above would require $B(E2) \approx 0.05e^2\,\mathrm{b}^2$ for the ν^2 ^{134}Sn state, which is consistent with extrapolated systematics. Although the ^{132}Te $B(E2)$ value is about twice as large as that for ^{136}Te, the larger interference term for the more mixed configuration means that we require only $B(E2) \approx 0.08e^2\,\mathrm{b}^2$ for ^{130}Sn. This is larger than that deduced for ^{134}Sn, but not unreasonable. In ^{206,210}Pb, the measured $B(E2)$ value [8] also drops, by almost a factor of 2, as the new neutron shell is entered.

This very simplistic model is obviously far from complete. For example, the depression of the 2_1^+ energy in ^{134}Sn, and how it is consistent with any accompanying drop in the transition strength, is not explained. Instead, a more microscopic explanation is needed.

Recently, Blomqvist has demonstrated that shell-model calculations using a set of empirical single-particle energies and two-body matrix elements [12] reproduce the energy spectra of nuclei in this region with remarkable accuracy [13]. A comprehensive comparison of the calculated and experimental $B(E2)$ values for these nuclei, however, is not available. On the other hand, shell-model calculations of the energy spectra and electromagnetic moments of nuclei with $Z = 83$–87, $N = 82$–84 by Sarkar and Sarkar [3] have revealed several shortcomings. [These calculations use interactions obtained from the

TABLE II. $B(E2; 0^+ \rightarrow 2_1^+)$ values ($e^2\,\mathrm{b}^2$) measured in the present work, compared with shell-model calculations (SM) and adopted values from Ref. [8].

Nuclide	This Work	SM	Adopted [8]
^{132}Te	0.172(17)		
^{134}Te	0.096(12)	0.088	
^{136}Te	0.103(15)	0.25	
^{128}Te	0.346(26)		0.383(6)
^{136}Ba	0.46(4)		0.410(8)

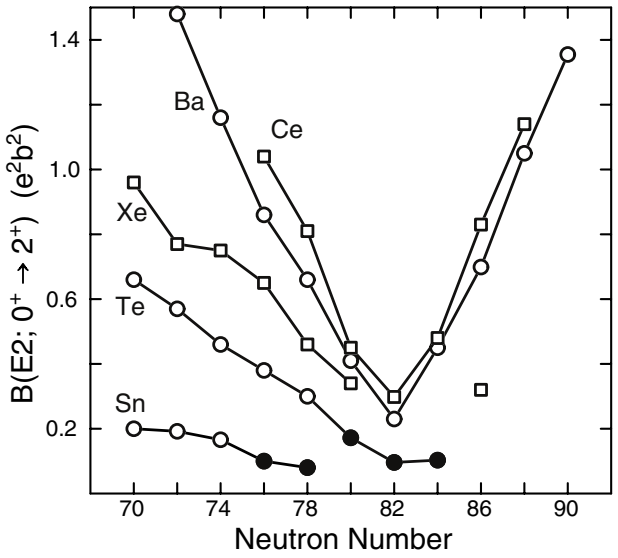

FIG. 2. Values of $B(E2; 0^+ \rightarrow 2_1^+)$ for even-even Sn, Te, Xe, Ba, and Ce isotopes around neutron number $N = 82$. Open symbols are adopted values from Ref. [8], while filled symbols are from the present work (Te) and from Refs. [4,10] (Sn).

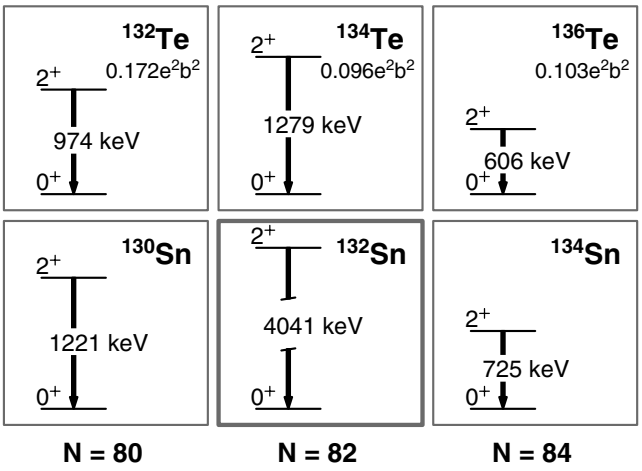

FIG. 3. $2_1^+ \rightarrow 0^+$ transitions in $N = 80$, 82, 84 Sn and Te isotopes, together with $B(E2)$ values from the present work.

well-studied ^{208}Pb region after a radial scaling of $(132/208)^{-1/3}$ and reducing the diagonal neutron-neutron matrix elements by a factor of 0.6 [3].] Although the calculated results agree reasonably well with the experimental data for $N = 82$ and 83, they fail to reproduce the compressed energy spectra for the $N = 84$ isotones.

To further investigate this anomaly, we have performed shell-model calculations for ^{134,135,136}Te, assuming a ^{132}Sn closed core and using a realistic effective interaction derived from the CD-Bonn nucleon-nucleon interaction [14]. Details of these calculations may be found in Ref. [15], which presents results for ^{134}Te and ^{135}I. The calculated energy spectra are in very good accord with the experimental data for ^{134}Te [15], ^{135}Te, and ^{136}Te (597, 997, and 1274 keV for the 2^+, 4^+, and 6^+ levels, versus the experimental values of 606, 1030, and 1382 keV, respectively). The calculated $B(E2)$ values, using effective charges of $1.55e$ for protons and $0.7e$ for neutrons [adjusted to reproduce the observed $B(E2; 6^+ \rightarrow 4^+)$ in ^{134}Sn], are shown in Table II. While the calculation is in very good agreement with the measured $B(E2; 0^+ \rightarrow 2_1^+)$ in ^{134}Te and $B(E2; \frac{19^-}{2} \rightarrow \frac{15^-}{2})$ in ^{135}Te, it exceeds the experimental value for ^{136}Te by more than a factor of 2. In the absence of a more complete set of experimental $B(E2)$ values near ^{132}Sn, it is not clear as to whether this discrepancy is due to the use of a large effective neutron charge, or because of inadequacies in other model parameters. $B(E2)$ measurements in ^{130}Sn and ^{134}Sn would clearly be of great interest.

In summary, $B(E2; 0^+ \rightarrow 2^+)$ values for neutron-rich ^{132,134,136}Te 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. While shell-model calculations using realistic effective interactions are in good agreement with other experimental data near ^{132}Sn, they fail to reproduce the small $B(E2)$ value in ^{136}Te. Future $B(E2)$ measurements in neighboring nuclei may shed some light on the origin of this anomaly.

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