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Coulomb excitation measurements of transition strengths in the isotopes ^{132,134}Sn

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Abstract. We describe an experiment optimized to determine the transition probabilities for excitation of the first excited 2^+ state in ^{132}Sn. The large excitation energy (4.04 MeV) and consequent small excitation cross-section, together with the modest beam intensity available makes this a challenging experiment. The preliminary result is $B(E2; 0^+ \to 2^+) = 0.11 \pm 0.03 e^2b^2$. The high efficiency and generalized nature of the setup enabled us to also measure the first 2^+ state in the two-neutron nucleus ^{134}Sn. We have determined a value of $B(E2; 0^+ \to 2^+) = 0.029 \pm 0.005 e^2b^2$ which shows no sign of the asymmetry with respect to the $N = 82$ shell closure exhibited by the Te isotopes.

PACS. 21.10.Re Collective levels – 25.70.De Coulomb excitation – 27.60.+j $90 \leq A \leq 149$

1 Background

One of the first stops in the *terra incognita* of exotic, neutron-rich nuclei is the region around the shell closures at $Z = 50$ and $N = 82$. In particular, around the double closed shell nucleus ^{132}Sn, we will examine the structure of nuclei to look for new features and to compare with nuclei near the next heavier double-closed-shell nucleus, ^{208}Pb. There have been extensive studies of nuclei around ^{132}Sn using β-decay and spontaneous fission [1]. With the advent of neutron-rich radioactive beams at the Holifield Radioactive Ion Beam Facility (HRIBF) at ORNL, there have for the first time been measurements of the $B(E2; 0^+ \to 2^+)$ for a number of nuclei in the vicinity of the $N = 50$ and $N = 82$ [2,3] shell closures. The results of the $N = 82$ measurements, especially for Te isotopes, provide significant new data on low-lying collective strength in these regions to test theoretical models. They also provided a puzzle, especially the results for ^{136}Te. Across the table of nuclides, the excitation energy of the first 2^+ states are, broadly speaking, inversely related to the strength of the transition or $B(E2; 0^+ \to 2^+)$ [4]. In Te isotopes, across the $N = 82$ shell closure, this relationship does not appear to hold. Both the energy of the first 2^+ and the $B(E2; 0^+ \to 2^+)$ decrease by about 40%. This puzzle was addressed by Terasaki, *et al.* [5] who found that reducing the neutron pairing gap above $N = 82$ could explain this behavior within their QRPA calculations. In addition, the theory made predictions for the adjacent isotopes ^{132,134}Sn.

The recent availability of isotopically-enriched, neutron-rich Sn [6] beams at HRIBF presented us with the opportunity to make the first measurement of excitation matrix elements in the exotic double-closed shell nucleus ^{132}Sn, as well as the two-valence-neutron nucleus ^{134}Sn. The ^{132}Sn measurements can provide an instructive comparison with the unusual properties of low-lying collective states of the next more massive doubly closed shell nucleus ^{208}Pb.

2 Measurement with ^{132}Sn

The high-energy (4.04 MeV) of the 2^+ state in the ^{132}Sn nucleus presented severe challenges for a low-energy

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Coulomb excitation experiment, including small excitation probabilities and the necessity of detecting a 4-MeV photon. The anticipated beam intensity of 10^4 per second compounded the challenges. We developed a setup which was optimized to deal with these issues.

The ^{132}Sn experiment was performed using 470 MeV and 495 MeV ^{132}Sn ions incident on a 1.3 mg/cm^2 ^{48}Ti target. Using a Ti target gave us the largest cross-section for this excitation, eight times more than C and ten times more than Pb. Scattered ^{132}Sn ions and target recoils were detected in a 7 cm diameter annular (CD-style) double-sided Si-strip detector mounted 8 cm downstream of the target. The detector has 48 radial strips and 16 azimuthal sectors, and covered the full range of center-of-mass angles relevant to the Coulex angular distribution (30° to 166°) with a total efficiency of almost 80%. Gamma rays were detected in an array of 150 BaF_2 crystals arranged in six blocks mounted in close proximity to the target. A total trigger efficiency of 55% and a full-energy efficiency of 30% was achieved for 4-MeV gamma-rays. In addition, a carbon-foil-MCP beam counter was employed 57 cm downstream of the target and a Bragg counter was mounted at the beam dump 2 m downstream of the target to monitor beam composition. Beam intensities in excess of 10^5 ^{132}Sn ions per second were achieved, with a purity of 96% [6].

The bombarding energies employed, 3.75 and 3.6 MeV/u, are higher than would be considered safe for Coulomb excitation. A commonly accepted definition of this is a minimum nuclear surface approach of 5 fm [7,8] for 180° scattering. For ^{132}Sn + ^{48}Ti this energy is 2.8 MeV/u at which the excitation cross-section of the 4.04-MeV 2^+ would have been negligibly small, about 30 μb, compared with the 2.5 mb yield at 3.75 MeV/u. At these higher energies, we limit the distance of closest approach by limiting the range of center-of-mass scattering angles included in the analysis (maximum angle is 85° at 3.75 MeV/u and 90° at 3.6 MeV/u). These angles actually correspond to a surface approach of 4 fm at 3.75 MeV/u and 4.4 fm at 3.6 MeV/u. The effect of using these angles is negligible on the value of the $B(E2; 0^+ \to 2^+)$, and only slightly increases the uncertainty of the value. Another feature of the setup resulted from the inverse-kinematics of the reaction. The events in which we are interested are detected as forward scattered projectiles in the Si-strip array. Backward scattering of the projectiles to angles larger than our cut-off also strike the Si array, at the same laboratory angles as good scattering. Fortunately, these overlapping events can be identified by observing the coincidence with knock-on target nuclei (Ti). We can therefore determine the shape of the γ-ray spectrum (background) corresponding to these "unsafe" events very well. This is clear from fig. 1, which shows the reaction kinematics. Backscattered Sn nuclei between 132° and 164° in the center of mass are in coincidence with recoiling Ti nuclei in our particle detector.

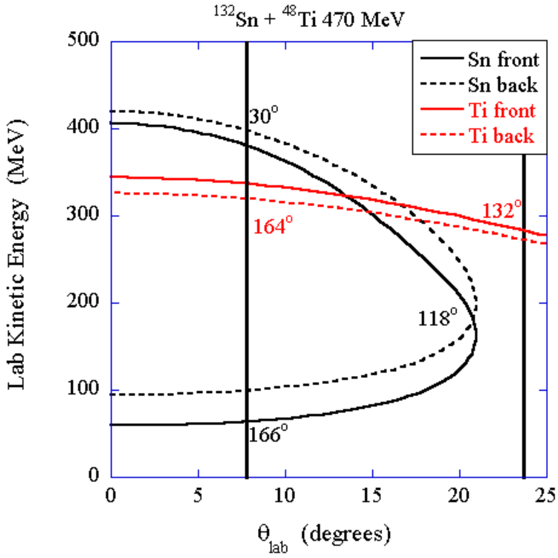

Fig. 1. Kinematics of the ^{132}Sn + ^{48}Ti reaction. "Front" and "Back" refer to the sides of the target. The angles shown in the figure are center-of-mass angles for the scattering.

In fig. 2, we show the separation which allows us to distinguish the part of the angular distribution most interesting to us and exclude the background from forward-scattered target ions. The spectrum on the bottom shows the effects of non-Coulomb scattering in the large concentration of yield around 118°. The yield from this part of the spectrum contributes a surprisingly large background of photon events near 4 MeV. A spectrum of photon yield subject to our "safe" center-of-mass angles, $\theta \leq 90°$, energy greater than that corresponding to about channel 175 on the vertical axis of fig. 2, and the one-particle requirement is shown in fig. 3. From this result we extract our total yield.

Using the yield shown in fig. 3, we have determined the $B(E2; 0^+ \to 2^+) = 0.11(3)\ e^2b^2$, which amounts to almost 13% of the isoscalar quadrupole energy weighted sum rule. Our measured $B(E2; 0^+ \to 2^+)$ is shown in fig. 5, along with results for other Sn isotopes. This is similar to the fraction of the quadrupole sum rule strength exhausted by the ^{208}Pb 2^+ state, which is 14%. This preliminary analysis does not yet include a complete experimental calibration of the photon detector efficiency. This analysis has been done with detailed simulations of the response of the BaF_2.

3 Measurement with ^{134}Sn

The large increase in the intensity of neutron-rich Sn beams available at HRIBF presented us with the opportunity to apply our highly-optimized setup to a measurement on the two-neutron nucleus ^{134}Sn. The beam intensity of the purified [6] $A = 134$ isotopes was 9000 ions per second, which was determined to be 61.6(3)% Te, 25.6(2)% Sn, 12.2(2)% Sb and 0.56(4)% Ba. Without purification the beam is 98.7(7)% Te, 1.1% Sb. In this case, a ^{90}Zr target with a thickness of 1.0 mg/cm^2 was employed along

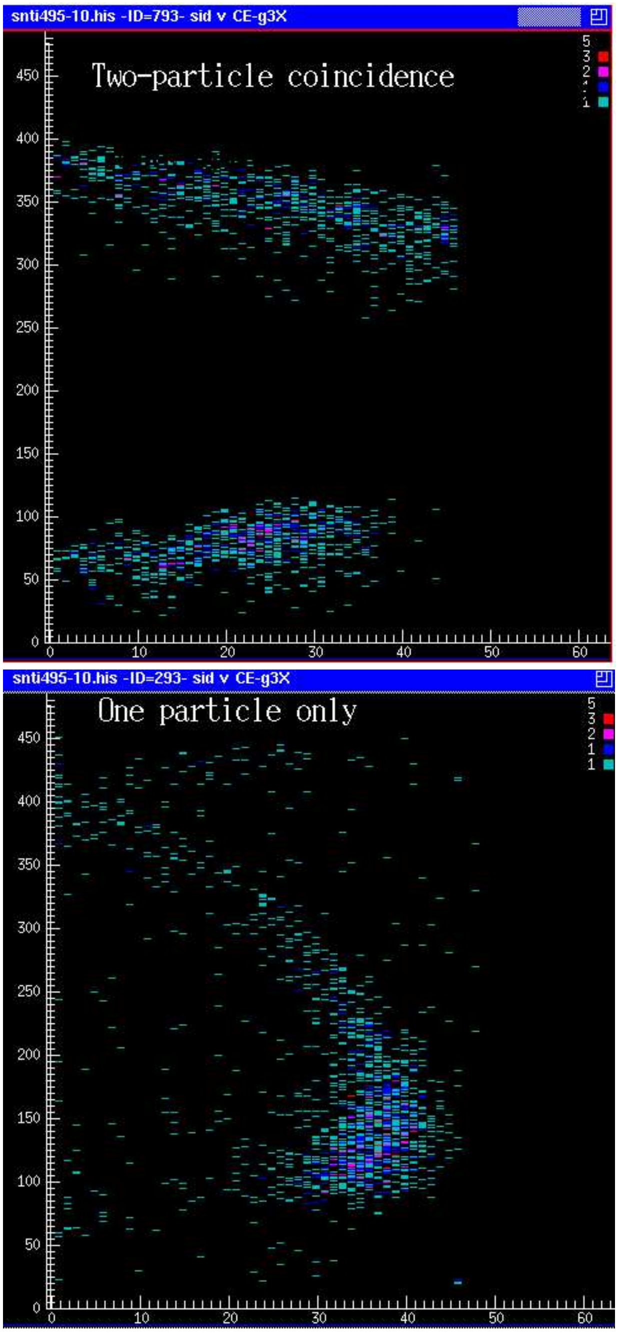

Fig. 2. Measured yield of the ^{132}Sn + ^{48}Ti reaction, sorted by particle multiplicity. The horizontal axis is proportional to the laboratory scattering angle; channel 34 corresponds to 85° in the center of mass. The vertical axis is proportional to the pulse height in the detector. The acceptable data correspond to energy greater than channel 175.

with a beam energy of 400 MeV, which is safe by any measure. The Si detector was moved to 4 cm from the target to accommodate the change in kinematics, but otherwise the setup was identical. In order to better understand the spectra, measurements were made with a pure beam of ^{134}Ba and an unpurified beam of $A = 134$. The resulting spectra can be seen in fig. 4.

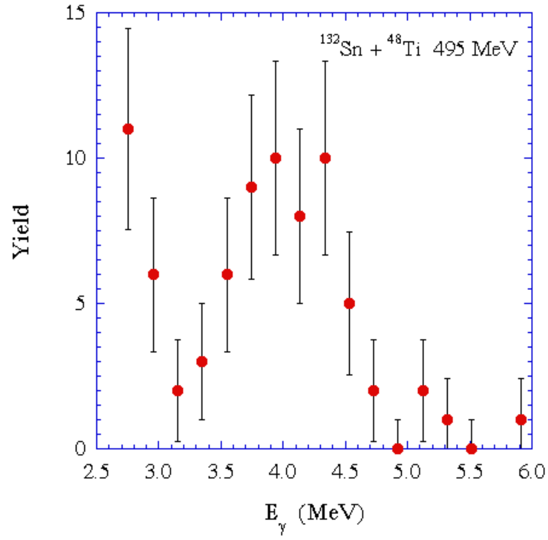

Fig. 3. Yield of photons around 4 MeV in ^{132}Sn Coulomb excitation.

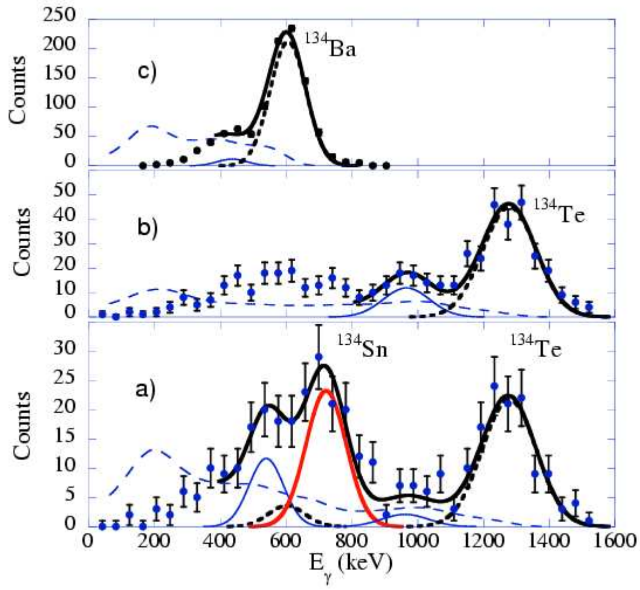

Fig. 4. Results of the ^{134}Sn measurement. The black curve is the sum of the background and individual peak curves shown. The region where the background exceeds the data indicates the detection threshold of the array.

In panel (a), the short dashed curves are fits to the known peaks in Te and Ba and the thick solid-line Gaussian is the fit to the Sn 2^+, fixed to the known γ-energy of 725 keV. The thin solid-line Gaussians are unexplained peaks, one at 539 keV and the other at 961 keV; these contribute only trivially to the uncertainty of the ^{134}Sn yield. The thick solid curve is the sum of the continuum response and the fitted peaks. There is no arbitrary background included in these fits. The continuum underlying the peaks, both shape and intensity, is obtained from

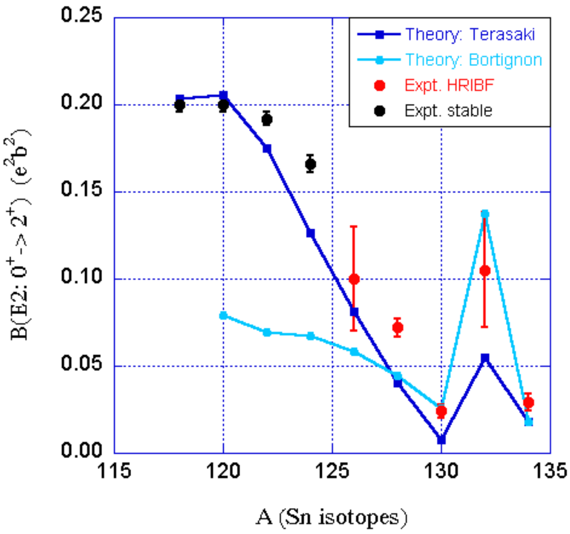

Fig. 5. Dependence of $B(E2; 0^+ \rightarrow 2^+)$ on A for Sn isotopes. The dark curve is the calculation of Terasaki [5], discussed in the text. The light curve is from Colo [9].

simulations of the detector response, normalized to the peak areas. Panel (b) is the spectrum for the 98% ^{134}Te beam. Panel (c) is the result for a stable beam of ^{134}Ba. The yields in spectrum (a) for Te and Ba are consistent with the measurements shown in panels (b) and (c), accounting for the Bragg detector measurements of the mixed beam composition. In all panels, the long-dashed curve is the self-consistent Monte Carlo simulation of the detector response discussed above. The γ-threshold is $\sim$ 300 keV. The preliminary experimental result obtained was $B(E2; 0^+ \rightarrow 2^+) = 0.029(5)\ e^2b^2$, which, as can be seen from fig. 5, is very close to the value for the two-hole nucleus ^{130}Sn.

The behavior of the $B(E2; 0^+ \rightarrow 2^+)$ in the Sn isotopes as a function of neutron pairing has been investigated by Terasaki *et al.* [5,10]. They find that the ^{134}Sn $B(E2; 0^+ \rightarrow 2^+)$ is insensitive to the pairing gap, as one would expect. The energy of the ^{134}Sn 2^+ state is much more sensitive; the low experimental value (725 keV) is better reproduced with weaker pairing. However it is worthy of note that shell model calculations of Brown *et al.* [11,12] agree very well with both the energy of the 2^+ state in ^{134}Sn and the $B(E2; 0^+ \rightarrow 2^+)$, as do relativistic RPA calculations of the Munich group [13].

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