COLLECTIVE MODES STUDIED BY COULOMB EXCITATION*

Douglas Cline

Nuclear Structure Research Laboratory, University of Rochester
Rochester, NY 14627, USA

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The large gain in sensitivity provided by powerful new γ-ray detector arrays, such as Gammasphere, coupled with other advances in the field of heavy-ion induced Coulomb excitation, open exciting new research opportunities for exploiting Coulomb excitation to probe nuclear structure. Three recent examples are given that exploit this unprecedented sensitivity. The actinide nuclei ^{248}Cm and ^{240,242,244}Pu have been Coulomb excited using ^{208}Pb ions at the barrier. The positive and negative-parity yrast bands have been extended to high spin, $\leq 34\hbar$, and the evolution of alignments probed. Heavy-ion induced Coulomb excitation of a ^{162}Dy beam is providing significant new information on states to high spin in the ground, S and γ bands, as well as a double γ-phonon band. Collective octupole correlations are especially strong in ^{208}Pb and ^{96}Zr implying the possible existence of localized octupole double-phonon states in these nuclei. Heavy-ion Coulomb excitation has been used to locate octupole double-phonon strength in these nuclei; the results for ^{208}Pb show large fragmentation of the octupole double-phonon strength whereas a major fraction of the strength may have been located for ^{96}Zr.

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1. Introduction

Collective shape degrees of freedom play a key role in nuclear structure physics. The $E\lambda$ properties are the most direct and unambiguous measure of λ-multipole shape degrees of freedom. Coulomb excitation is the preeminent probe of collective $E\lambda$ matrix elements in that it selectively excites collective bands in the yrast domain, with cross sections that are directly related to the $E\lambda$ matrix elements involved in the excitation.

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Three major developments have opened exciting new research opportunities for exploiting Coulomb excitation as a probe of nuclear structure [1]. The first is the availability of $\approx$4.5 MeV/u high-Z projectiles, such as ^{208}Pb, which makes it feasible to Coulomb excite the yrast sequence up to spin 34 in strongly deformed actinide nuclei. The second major advance is the development of powerful detector systems for high-resolution γ-ray spectroscopy, which is the only viable experimental technique for resolving the many states Coulomb excited when heavy ions are utilized. In particular, new γ-ray detector arrays such as Gammasphere and Euroball, plus associated heavy-ion detector arrays like CHICO [2], have sufficiently high detection efficiency to collect good-statistics multi-fold γ-ray events providing orders of magnitude improvement in sensitivity. The third important advance is the development of the Coulomb-excitation least-squares search code GOSIA [3]. This code, developed by Thomas Czosnyka makes it feasible to extract essentially complete sets of $E\lambda$ matrix elements for low-lying states of nuclei from heavy-ion induced Coulomb excitation data.

Following brief comments on the Coulomb excitation technique, this paper will present results of three Gammasphere Coulomb excitation experiments, performed mostly during the past year, that address both quadrupole and octupole collective modes in nuclear structure.

2. Experimental techniques

Heavy ions have considerable advantages for Coulomb excitation studies, but unfortunately they also introduce a major technical problem in that the concomitant large recoil velocities lead to considerable degradation of the deexcitation γ-ray spectra due to Doppler effects. There are two ways to reduce the influence of Doppler broadening, both of which have been used in the Gammasphere research described here.

2.1. Particle-γ coincidence technique

The primary way of correcting for Doppler effects is by use of thin targets so that the excited nuclei recoil in vacuum, allowing detection of the recoiling nuclei at known scattering angles in coincidence with the deexcitation γ-rays. Knowing the recoil direction and velocity of the deexciting nucleus allows the individual γ-ray signals to be corrected for the Doppler shift on an event by event basis. For the past two decades our Coulomb excitation experiments have employed large solid-angle position-sensitive, parallel-plate, avalanche detector arrays [1] to detect the scattered projectile and ejectile in kinematic coincidence plus an array of Ge detectors to observe the cooincident deexcitation γ-rays. Recently we have developed the Rochester

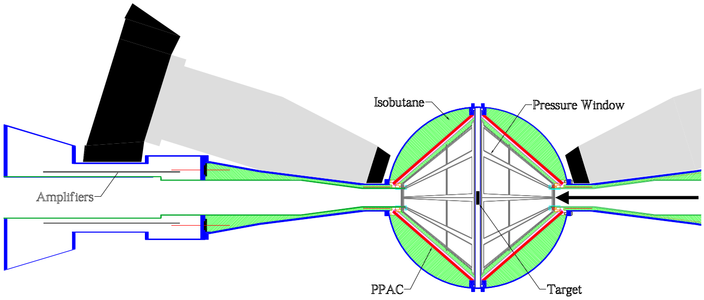

Fig. 1. Schematic of the PPAC array CHICO and two representative Gammasphere Ge detectors.

compact heavy-ion detector, CHICO, [2] specifically for use with Gammasphere. CHICO comprises two identical 35.6 cm diameter hemispherical, minimum-mass, target chambers, one at forward angles and the other at backward angles, as shown schematically in figure 1. Each of these hemispheres contains ten trapezoidal position-sensitive, parallel-plate, avalanche detectors mounted conically around the beam. The target is sandwiched between the two hemispheres. The array of PPAC modules detect scattered nuclei in kinematic coincidence over an angular range of $12^\circ < \theta < 85^\circ$, $95^\circ < \theta < 168^\circ$ and 280° in ϕ. CHICO was designed to have the largest size that fits within the cavity inside Gammasphere to optimize the angle and mass resolution. For binary collisions, the angular resolution $\Delta\theta = 1^\circ$, coupled with a time-of-flight resolution of 500ps, results in a mass resolution of 5% and Q-value resolution of 18MeV. CHICO can handle high count rates and has a useful solid angle of 68% of 4π. The Gammasphere/CHICO combination has several advantages for Coulomb excitation work, the γ-ray spectra are clean, and absolute γ-ray yields can be measured simultaneously over a wide range of scattering angles, the latter are needed to determine absolute $E\lambda$ matrix elements. A disadvantage of this technique is that, although the γ-ray spectra are corrected for the gross Doppler shift, there remains a residual Doppler broadening due to the finite size of the Ge detectors for γ rays emitted by moving nuclei. Typically a γ-ray energy resolution of 0.6% is obtained for recoiling nuclei in heavy-ion Coulomb excitation measurements using Gammasphere plus CHICO. They have been used for Coulomb excitation studies of collectivity in nuclei, pair transfer reactions, and the spectroscopy of neutron-rich spontaneous fission products.

The thin-target technique allows measurement of rather complete sets of $E\lambda$ matrix elements for states up to high spin. The completeness and extent of these large sets of measured electromagnetic matrix elements add a new dimension to the study of nuclear shapes. In particular, it is feasible to project the intrinsic-frame E2 properties directly from the data using rotationally-invariant zero-coupled products [1] of E2 operators to directly relate properties in the principal axis frame to those in the laboratory frame. This is a powerful and model-independent method for interpreting the wealth of data produced by Coulomb excitation providing considerable insight into the underlying collective degrees of freedom.

2.2. Thick-target technique

Coulomb excitation measurements employing thick targets lead to Doppler-broadened γ-ray line shapes due to γ-ray emission while the excited nucleus is slowing down in a thick target. The resultant Doppler-broadened line shapes are much too broad to resolve the individual transitions. However, the excellent intrinsic energy resolution of Ge detector can be obtained, resulting in about a 50-fold improvement in energy resolution, if the γ-rays are emitted after the excited nucleus has come to rest. Unfortunately, most deexcitation transitions of interest have lifetimes that are comparable to the stopping time for recoiling nuclei in a thick target and thus are subject to Doppler-broadening. Ward *et al.* [4] have developed a novel method that exploits the high detection efficiency for high-fold γ-ray cascades, available with γ-ray detector arrays like Gammasphere, to select the longest rotational cascades. For these longest rotational cascades, the cummulative decay time for the sequential decays greatly enhances the fraction of the γ rays emitted after the excited nucleus has come to rest, resulting in detection of these stopped peaks with the intrinsic resolution of the Ge detector. This thick target technique is a remarkably successful technique for determining γ-ray decay schemes. Experiments are technically simple to perform, and the energy resolution is sufficient to observe the minute stopped component even for fast transitions. States in actinide nuclei up to spin 34 have been located using this technique which is comparable in spin to what can be attained by the powerful, but more complicated, $p-\gamma$ coincidence technique. The major disadvantage of the thick-target technique is that the γ-ray yields cannot be used to measure reliable absolute transition matrix elements directly since, for the fast transitions, only the minute stopped component is detected.

3. High-spin properties of ^{240,242,244}Pu and ^{248}Cm

Recently the thick-target Coulomb excitation method has been used at Argonne to study the high-spin states in actinide nuclei [5, 6]. Beams of 1300 MeV ^{208}Pb ions from the ATLAS accelerator bombarded targets consisting of ^{240,244}Pu and ^{248}Cm electroplated onto Au or Pb thick backings. The Argonne-Notre Dame Ge array was used to study ^{248}Cm extending the

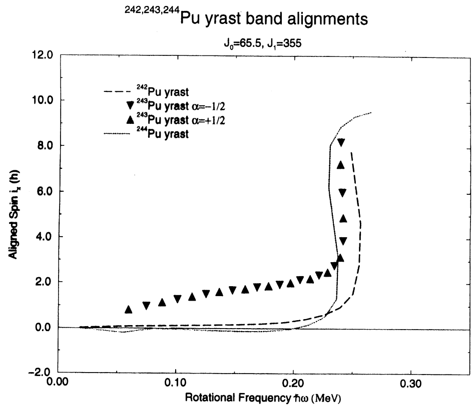

Fig. 2. Aligned angular momenta calculated for the yrast bands of ^{242,243,244}Pu.

ground band to spin 28^+ and the $K = 1^-$ band to spin 23^- [5]. These results are in agreement with those from a separate CHICO/Gammasphere experiment that used 888 MeV ^{144}Sm ions to Coulomb excite ^{248}Cm and extended the ground band to spin 30^+ and and the $K = 1^-$ band to spin 29^- [7]. The ^{240,242,244}Pu nuclei, studied using the thick-target technique with Gammasphere [6], extended the ground bands to spins of $32\hbar$, $30\hbar$ and $34\hbar$ respectively. The nuclei ^{242,243}Pu were populated by neutron transfer at the high bombarding energy used for the Coulomb excitation study of ^{244}Pu. Both signatures of the $K = \frac{7}{2}^+$ ground band in ^{243}Pu were populated up to spin $\frac{59}{2}^+$ via neutron transfer. The yrast-band alignments for ^{242,243,244}Pu, illustrated in figure 2, indicate $10\hbar$ units of alignment and similar frequency at the alignment in ^{243}Pu; which is convincing evidence that the backbend is due to alignment of $i_{\frac{13}{2}}$ protons not $j_{\frac{15}{2}}$ neutrons.

Actinide nuclei exhibit an interplay between collective quadrupole and octupole degrees of freedom[4]. The aligned angular momenta for the ground and octupole bands of ^{240,244}Pu are illustrated in figure 3. The octupole-band alignment shown for the $K = 2^-$ band in ^{244}Pu is similar to that for the $K = 1^-$ bands in ^{248}Cm [6, 7] and $K = 1^-$ band in ^{238}U [4] That is, the alignment increases gradually to an aligned spin of $\sim 3\hbar$, as expected if the octupole phonon decouples from the symmetry axis and aligns with the rotation axis, followed by a rapid increase in alignment at frequencies above 200 keV. These experimental alignments are in agreement with RPA predictions [5]. However, both the ground band and the $K = 0^-$ bands in ^{240}Pu exhibit quite different behaviour in that these two bands exhibit no sign of particle alignment at frequencies as high as 300 keV, which is the highest rotational frequency observed in actinide nuclei. In fact, the $K = 0^-$

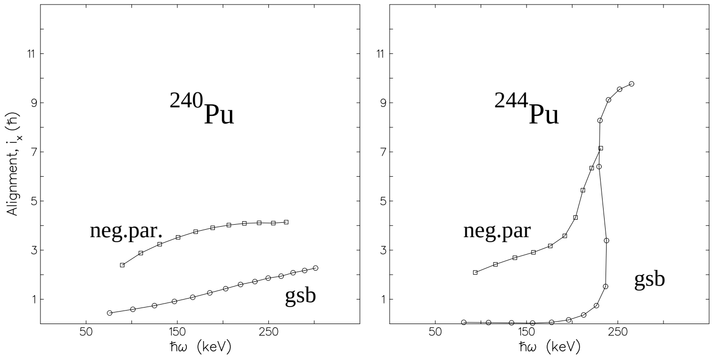

Fig. 3. Aligned angular momenta for the yrast positive and negative (octupole) bands in ^{240,244}Pu.

band in ^{240}Pu exhibits a plateau in alignment of $3\hbar$. This unusual behaviour in ^{240}Pu is not understood; the ground-aligned band interaction strength at the band crossing could be sufficiently weak such that the Coulomb excitation not only follows the ground band but even the moment of inertia is unperturbed, or the onset of strong octupole correlations changes the single-particle structure sufficiently to suppress the proton alignment.

These results illustrate the power of using heavy-ion induced Coulomb excitation plus Gammasphere for studying collective rotational bands in actinide nuclei.

4. Rotational bands in ^{162}Dy

A study of multi-pair nucleon transfer reactions between 780 MeV ^{162,164}Dy beams on a 0.25mg/cm^2 ^{118}Sn target was performed at Gammasphere using CHICO to detect the scattered ions in kinematic coincidence with the coincident γ-rays [8]. An advantage of using CHICO to detect the scattered ions is that it is possible to select scattering angles and corresponding distance of closest approach. This allows selection of grazing collisions, for study of transfer reactions, or selection of peripheral collisions where inelastic scattering dominates. The primary goal of this experiment was to search for manifestations of Josephson-like effects in multi-neutron transfer due to pairing correlations in nuclei. Four-neutron transfer was observed but not with the enhancement predicted by Sorensen and Winther [9]. Two important by-products of this work were; a) observation of significant population of high-spin states in neutron-rich nuclei following neutron transfer in grazing collisions [10], and b) detailed information on the ground, S, γ, octupole and double γ-phonon bands following inelastic scattering of ^{162}Dy as described below.

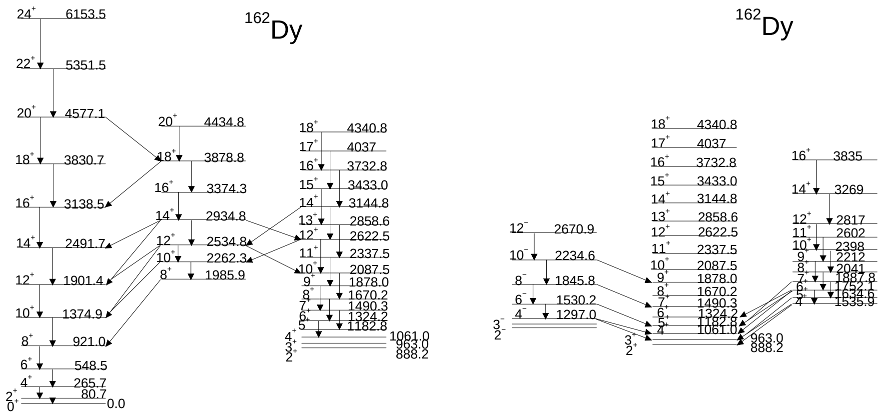

Fig. 4. a) States in the ground, S and γ bands, and b) states and observed transitions connecting the $K = 2^-$, γ, and $K = 4^+$ double γ−phonon bands in ^{162}Dy.

Fragmentation of double γ-phonon 4^+ strength

Nucleus	E_4 MeV	$B(E2{:}4_{\gamma\gamma}\text{-}2_\gamma)$ WU	$(2_\gamma x 2_\gamma)^4$ Strength %	Reference	
^{156}Gd	1.511 1.861	1.8 ± 0.3	22±5*	A. Backlin et al	Nucl. Phys. A380 (82) 189
^{160}Dy	1.694 2.097	0.17 ± 0.04	1.6±0.5*	C.W. Reich,	Nucl.Data Sheets, 68 (93) 189
^{162}Dy	1.536	1.3	~11	C.Y. Wu et al	Unpublished, 1998
^{166}Er	1.978	0.9 ± 5	6±3	C. Fahlander et al	Phy. Lett. B388 (96) 475
	1.986	0.5 ± 5	3±3	C. Fahlander et al	APH N.S., Heavy Ion Physics **5** (97)
	2.029	4.9 ±1.8	35±13	"	"
		7.4 ±2.5	50±17	P.E. Garrett et al	Phys. Rev. Lett. **78** (97) 4545
^{168}Er	2.055	5.1±2.5	43±18*	H.G. Borner et al	Phys. Rev. Letts. **66** (91) 691
^{186}Os	1.352	25 ±5	95±20*	C.Y. Wu et al	Int. Bose-Fermi Systems in Nuclei,
^{188}Os	1.279	12 ±3	94±70*		Iachello, Plenum Press, 1980 p241
^{190}Os	1.163	10 ± 1	90±24*		Nucl. Phys. A607 (96) 178
^{192}Os	1.070	10 ± 1	68±6*		
^{232}Th	1.414	5.1±1.3	125±55*	W. Korten et al	Phy. Lett B317 (95) 19 Z. Phys. A351 (95) 143

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Figure 4a shows that inelastic scattering populates the ground band up to spin $24\hbar$, the γ band up to spin $18\hbar$, while the 8^+ through 20^+ states in the S band were observed. The S band intersects with the γ band near spin 12 and with the ground band near spin 18. The band interaction between the ground and S bands is about 10keV at the band crossing and the band mixing is sufficiently small that the Coulomb excitation follows the ground band rather than the yrast sequence. The interaction between S and γ bands is about 40 keV and there is strong mixing between the S and γ band at spin $12\hbar$ due to a near degeneracy. The decay of the S band suggests strong M1 transitions connecting the S and γ bands. The complete particle-γ angular correlation information, provided by Gammasphere plus CHICO, is being used to extract these M1 strengths. The strong population of the S band provides an excellent opportunity to study its collectivity. GOSIA is being used to extract the complete set of E2 matrix elements between these three interacting bands to elucidate the mixing and properties of these three bands.

Figure 4b shows the decays connecting the γ band to the $K = 2^-$ and $K = 4^+$ bands. The odd-spin negative parity states are not shown because they decay directly to the ground band states rather than the γ band.

The $K^\pi = 4^+$ band has the characteristics of a two-phonon γ-vibration band. A preliminary GOSIA analysis, assuming rotational-band behaviour of the E2 matrix elements, gives that the in-band intrinsic E2 moment for the $K^\pi = 4^+$ band is the same as for the ground band even though the $K^\pi = 4^+$ band has a 35% larger moment of inertia. There are two mechanisms that lead to E2 matrix elements between the $\Delta K = \pm 2$ bands. The first is mixing of the $\Delta K = \pm 2$ due to coupling between the rotational and intrinsic motion. The second contribution is the intrinsic-frame interband E2 matrix elements connecting the $\Delta K = 2$ bands. There are two ways of extracting the double γ-phonon strength. One is to compare measured $B(\mathrm{E2})$ values with model predictions. The second is to extract the intrinsic-frame E2 matrix elements using the Mikhailov plot approach. The latter approach was used to extract the double γ-phonon distribution in several nuclei [11]. Table 1 lists the level energies, experimental $B(\mathrm{E2}; 4^+_{\gamma\gamma} \to 2^+_\gamma)$ strength in Weisskopf units, while the fourth column lists the fraction of the double-phonon strength derived from the intrinsic-frame E2 matrix elements. For ^{162}Dy the $K^\pi = 4^+$ to $K^\pi = 2^+$ intrinsic-frame E2 matrix elements correspond to 11% harmonic double γ-phonon strength in the $K^\pi = 4^+$ band. This strength is consistent with the behaviour observed for the lowest $K = 4^+$ bands in neighboring nuclei. The greatest fragmentation of the double $\gamma-$ phonon strength occurs when the double-phonon states lie at higher excitation energies where mixing with 2 quasiparticle states is probable.

5. Octupole double-phonon states in ^{208}Pb and ^{96}Zr

Considerable evidence exists supporting the interpretation of octupole vibrational collective motion [12]. For example, recent Coulomb excitation work [17,18] shows that measured E3 matrix elements between the ground and negative-parity bands in ^{148}Nd exhibit an odd-even stagger with increasing spin, characteristic of octupole vibrations of a quadrupole-deformed rotor. The unexpectedly large E3 matrix elements connecting the so-called β band to the negative-parity band in ^{148}Nd also could be a manifestation of considerable mixing of double-octupole 0^+ strength in the β band [17,18].

The E3 properties of octupole double-phonon states provide the best measure of the harmonicity or softness of the octupole mode. For a pure harmonic vibration, the multiplet of double-phonon states will lie at twice the excitation energy of the one-phonon state and the $B(\mathrm{E3};[3^- \times 3^-]^I \to 3^-) = 2 \times B(\mathrm{E3};3^- \to 0^+)$. Evidence for double-phonon octupole collective vibrational modes is tenuous. Double-phonon octupole configurations have been attributed to the structure of states in ^{147}Gd [13], ^{144}Nd [14], ^{146}Sm [14] and ^{148}Gd [15,16] but the interpretation is complicated due to the coupling of double-phonon E3 strength to particle-hole components in the wave function in these nuclei.

Octupole collectivity is especially strong in ^{208}Pb and ^{96}Zr leading to a long-standing interest in locating octupole double-phonon strength in these nuclei. Double-phonon octupole vibrational states should be most easily identified in these closed shell nuclei since the level density is lowest and the $B(\mathrm{E3})$ values are the most enhanced. Level energies and γ-ray decay patterns have been used to infer possible double-phonon states in ^{208}Pb and ^{96}Zr, but the $E3$ matrix elements connecting the double-phonon states to the 3^-one-phonon state provide the only unambiguous way of identifying octupole double-phonon strength. Unfortunately, the E3 decay branch in γ-ray deexcitation is negligible compared with competing fast E1-E2 decay paths, and thus, in most cases, E3 matrix elements cannot be inferred from lifetimes or branching ratios.

Heavy-ion induced Coulomb excitation provides a viable way of measuring the double to single phonon E3 strength. The 6^+ member of the $0^+, 2^+, 4^+, 6^+$ octupole double-phonon multiplet is the most favourable for study via Coulomb excitation. The $(2I+1)$ spin factor favours population of the highest spin state, and the three-step E2 excitation is weaker than the two-step E3 excitation for the 6^+ state, whereas two-step E2 excitation can overwhelm the two-step E3 excitation for population of the lower spin members of the multiplet. The high excitation energy of the double-phonon states makes it necessary to maximize the bombarding energy to enhance their population. However, at such high bombarding energies, nuclear excitation can greatly perturb the inelastic excitation cross sections. The great increase in sensitivity provided by Gammasphere plus CHICO has made it possible, for the first time, to use safe Coulomb excitation to locate the octupole double-phonon strength in both ^{96}Zr [19] and ^{208}Pb [20].

5.1. Coulomb excitation of ^{208}Pb

The 2.6145 MeV first excited 3^- state in ^{208}Pb is connected to the ground state by an enhanced $B(\mathrm{E3}; 3^- \to 0^+) = 34$ WU. This state has been interpreted to be an octupole vibration leading to many searches for the $0^+, 2^+, 4^+, 6^+$ octupole double-phonon multiplet that is expected to lie at an excitation energy of about 5.2 MeV. Calculations predict that the $0^+, 2^+, 4^+, 6^+$ octupole double-phonon multiplet will be split by 200 keV due to coupling of octupole vibrations to quadrupole phonons [21], to particle-hole excitations [22–24] and due to the interaction with pairing vibrations [25, 26]. The (p, t) reaction data suggest that the 5.241 MeV could be the 0^+ member of the two-phonon multiplet [27]. Recently it was shown that the 5.241 MeV state, populated via the $(n, n'\gamma)$ reaction, decays directly to the 3^- state consistent with the expected signature of the 0^+ member of the octupole double-phonon multiplet [28]. Unfortunately the crucial $B(\mathrm{E3}; 0^+_2 \to 3^-_1)$ was not measured. The $(n, n'\gamma)$ reaction also contains evidence for candidates of the 2^+ and 4^+ double-phonon strength at 5.286 MeV and 5.216 MeV respectively [29] in that the level energies and measured E1 decay rates are consistent with the expected decay of double-phonon states, but the interpretation is not unambiguous. Previous Coulomb excitation attempts to populate the octupole double-phonon states in ^{208}Pb were unsuccessful, in spite of using above Coulomb-barrier bombarding energies to enhance the population, and sensitivity limits were unreliable because of the dominant nuclear interaction [30, 31, 33, 34].

The latest Coulomb excitation measurement, was performed below the Coulomb barrier so that the Coulomb interaction dominates [20]. A thin (0.9 mg·cm^2) ^{208}Pb target (99.86% enriched)was bombarded by a 650 MeV beam of ^{136}Xe and Gammasphere plus CHICO were used to provide the sensitivity needed to locate the double-phonon 6^+ strength. Five 6^+ states have been identified in prior work at excitation energies of 4.424 MeV, 5.213 MeV, 5.738 MeV, 5.993 MeV and 6.332 MeV [32]. Figure 5 shows a partial level scheme including all states taken into account in the Coulomb excitation analysis and the observed transitions. Deexcitation transitions were seen depopulating the 4^+_1 state at 4.323 MeV and 6^+_1 state at 4.424 MeV. Figure 6 shows the angular distribution of the measured and calculated Coulomb excitation yields, normalized to the $3^-_1 \to 0^+_1$ 2.614 MeV transition.

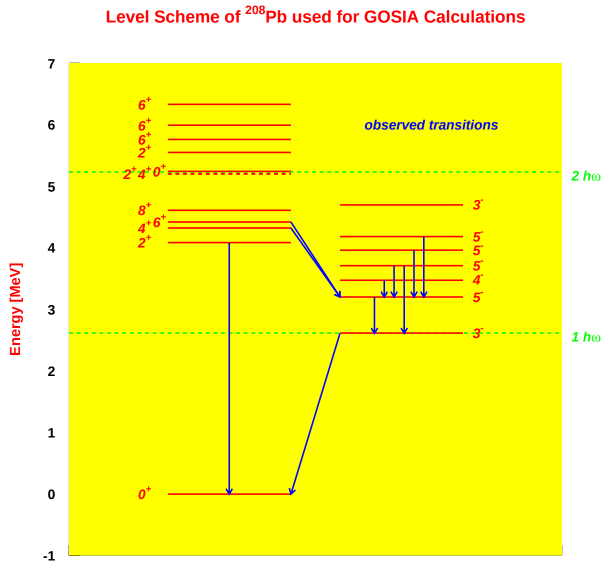

Fig. 5. Partial level scheme of ^{208}Pb and the observed transitions in the Coulomb excitation work.

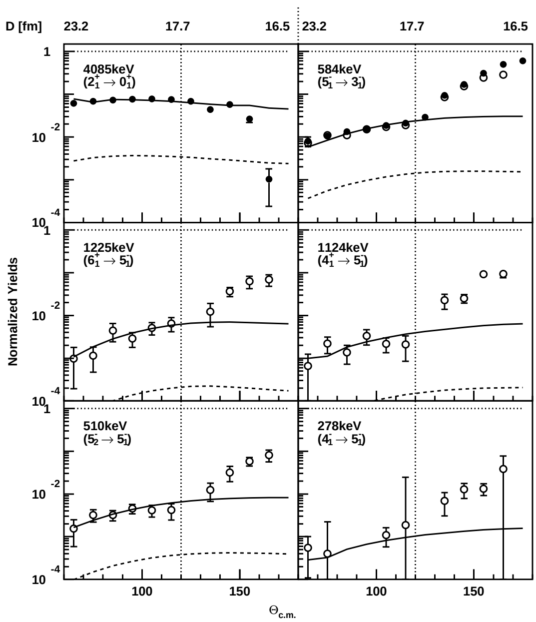

Fig. 6. Angular distribution of the measured and calculated Coulomb excitation yields normalized to the $3_1^- \rightarrow 0_1^+$ transition.

The solid line shows the Gosia predictions at a bombarding energy of 650 MeV. Note that the measured yields agree with the pure Coulomb excitation theory forward of $\theta_{\rm cm} = 120°$, which corresponds to a classical separation distance of 17.7 fm. The nuclear interaction causes the experimental yields to differ from Coulomb excitation theory by up to an order of magnitude at slightly smaller distances of closest approach, illustrating the crucial importance of ensuring that the interaction is pure Coulomb excitation. The much reduced yields predicted using a "safe" bombarding energy of 550 MeV, shown as dashed lines, illustrate the importance of using the highest possible bombarding energy.

It is not possible to extract unique E2 and E3 matrix elements connecting to the 4.323 MeV 4_1^+ state because both double E2 and double E3 excitation paths are comparable and interfere. The upper limit for the E3 matrix element to this state corresponds to 77% of the expected strength for a pure octupole double-phonon 4^+ state. Three-step E2 excitation paths leading to the 6^+ states are much weaker than two-step E3 excitation, and thus it is possible to extract the $B(\mathrm{E3}; 6_1^+ \to 3_1^-)$ strength for the 4.424 MeV state, it ranges from 16% to 28% of the harmonic octupole double-phonon strength depending on assumptions as to possible feeding from higher-lying 6^+ states. Figure 7 shows the measured $B(\mathrm{E3}; 6_1^+ \to 3_1^-)$ strength, normalized to the pure harmonic double-phonon strength. The solid line corresponds to the

Fig. 7. The measured $B(\mathrm{E3}; 6_1^+ \to 3_1^-)$ and limits for population of higher 6^+ states in ^{208}Pb , all normalized to the harmonic octupole double-phonon limit.

2σ strength limits for higher-lying known 6^+ states. The sensitivity limit translates into a maximum E3 strength of 15% at the expected location of the double-phonon vibration of 5.2 MeV.

In summary this experiment has provided the first reliable measure of the distribution of octupole double-phonon 6^+ strength in ^{208}Pb, the results point to large fragmention of this strength.

5.2. Coulomb excitation of ^{96}Zr

The nucleus ^{96}Zr exhibits a nearly magic character due to the partial closures of the $Z = 40$ and $N = 56$ subshells as illustrated by the partial level scheme [35, 36] shown in Figure 8. Strong octupole correlations are

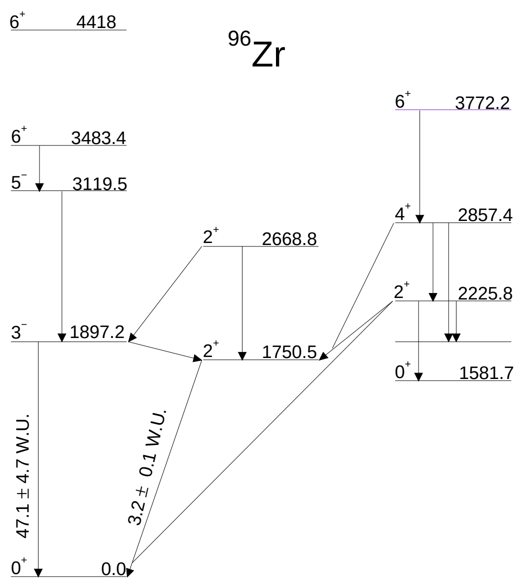

Fig. 8. Partial level scheme and observed transitions in Coulomb excitation study of ^{96}Zr.

expected to occur in ^{96}Zr because of the coherent superposition of proton $2p_{\frac{3}{2}} \rightarrow 1g_{\frac{9}{2}}$ and neutron $2d_{\frac{5}{2}} \rightarrow 1h_{\frac{11}{2}}$ particle-hole excitations [37]. The lifetime of the 1.8972 MeV 3_1^- state was measured at Rochester using the recoil-distance technique [38]. The measured half life of $67.8 \pm 4.3ps$ for this 3_1^- state corresponds to a $B(\mathrm{E3}; 3^- \rightarrow 0^+)$ enhancement of (47.1 ± 4.7) WU which is significantly smaller than implied by earlier centroid-shift measurements [39,40]. The remeasured $B(\mathrm{E3})$ implies a centroid for the distribution of the octupole deformation parameter $\beta_3^{rms} = 0.27$, which is the largest equivalent octupole deformation for any known $B(\mathrm{E3}; 3^- \rightarrow 0^+)$ in nuclei.

The absence of a well-defined octupole rotational band suggests that this octupole collectivity is dynamic, not static, consistent with octupole vibrational modes. The measured $B(\mathrm{E1}: 3_1^- \to 2_1^+) = (1.27 \pm 0.08) \times 10^{-3}$ WU is similar to the E1 strength in other regions of strong octupole collectivity [12]. The $B(\mathrm{E2}{:}0^+ \to 2^+) = (3.2 \pm 0.1)$ WU is an order of magnitude weaker than the E3 collectivity in ^{96}Zr implying that octupole collectivity is significantly more important than quadrupole collectivity, which is a consequence of the closure of the $2\mathrm{p}_{\frac{1}{2}}$ proton and $2\mathrm{d}_{\frac{5}{2}}$ neutron subshells. However, an intruder quadrupole rotational band based on the 1.582 MeV 0^+ state has been identified previously [43]. The strong E3 collectivity, low E2 collectivity, and low excitation energies of the presumed octupole states, makes ^{96}Zr the best case for investigation of double-phonon octupole structure in nuclei. The 3.4834 MeV 6_1^+ state has been suggested to be the octupole double-phonon 6^+ state. [35, 41, 42]

A 400 MeV ^{96}Zr beam was Coulomb excited by a ^{208}Pb 0.385mg/cm^2 self-supporting target enriched to 99.86%. CHICO was used to record the scattered ions in kinematic coincidence and in coincidence with Gammasphere [19]. Figure 8 shows the levels populated and transitions observed. The analysis is only partially complete, but some results are unambiguous.

Figure 9 shows the measured angular distribution for Coulomb excitation of the supposed octupole double-phonon 3.483 MeV 6_1^+ state. This state was

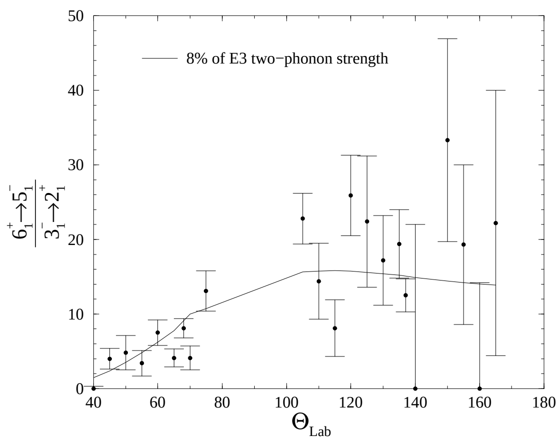

Fig. 9. Angular distribution of the measured and calculated Coulomb excitation yields for the $6_1^+ \to 3_1^-$ transition in ^{96}Zr.

seen clearly in even the p-γ spectra and the measured yields are consistent with a $B(\mathrm{E3}; 6_1^+ \to 3_1^-)$ of at most about 8% of the harmonic double-phonon strength. Note that the data obey Coulomb excitation predictions at all scattering angles for the safe bombarding energy used in this experiment.

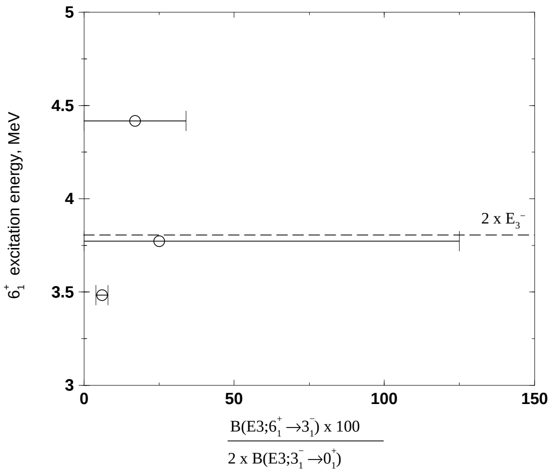

Fig. 10. Measured limits for the $B(\mathrm{E3}; 6_i^+ \to 3_1^-)$ values, normalized to the harmonic octupole double-phonon limit for ^{96}Zr.

Figure 10 shows the ratio of the extracted $B(\mathrm{E3}; 6_i^+ \to 3_1^-)$ to the harmonic vibrator limit. The preliminary analysis gives a best fit of $6 \pm 2\%$ of double-phonon strength for the 6_1^+ state. The deexcitation transition from the 3.7722 MeV 6_2^+ state to the 2.8574 MeV 4_1^+ state was observed. Unfortunately, because of the appreciable enhancement of the $B(\mathrm{E2}; 6_2^+ \to 4_1^+)$, the three-step E2 excitation can compete with two-step E3 excitation leading to a large uncertainty in the $B(\mathrm{E3}; 6_2^+ \to 3_1^-)$ derived from the preliminary analysis. That is, the best value is about 25% of the harmonic strength but the measured strength could range between 0 and 125%. The preliminary analysis gives that the 4.418 MeV 6_3^+ state has a $[\mathrm{E3}\times\mathrm{E3}]^6$ strength of about $17 \pm 17\%$.

These preliminary results show unambiguously that the 3.4834 MeV 6_1^+ state has a small component of the octupole double-phonon strength, in contradiction with earlier claims [35,41,42]. The 3.7722 MeV 6_2^+ state, which has been described to be a member of the intruder quadrupole collective band, in fact, may contain an appreciable fraction of the octupole double-phonon strength. The more complete analysis of the higher-fold γ-ray data, now in progress, may lead to a more precise measure of the octupole double-phonon strength distribution. A comparison [44] of microscopic QRPA calculations with inelastic scattering data suggests that the 6_1^+ is predominantly a $\lambda = 6$ one-phonon excitation with an octupole double-phonon strength in this state of around 20%; whereas the one-phonon strength in the 6_2^+ is predicted to be weak implying a larger octupole double-phonon strength in the 6_2^+ state. These predictions are consistent with the experimental results.

These studies of ^{208}Pb and ^{96}Zr illustrate that Coulomb excitation measurements are a powerful probe of octupole double-phonon strength. This work demonstrates that E3 matrix elements are the only reliable measure of octupole double-phonon strength. In contrast to the case of ^{208}Pb, where large fragmentation of the octupole double-phonon strength is indicated, the preliminary results for ^{96}Zr imply that a major fraction of the octupole double-phonon strength may have been located at about twice the excitation energy of the octupole one-phonon state.

6. Conclusions

Gammasphere, and associated particle detector array CHICO, have been used in heavy-ion induced Coulomb excitation experiments to probe nuclear structure. Three examples of experiments performed during the past year, have been presented.

The positive and negative parity yrast bands in ^{248}Cm and ^{240,242,243,244}Pu have been Coulomb excited up to spin $34\hbar$. The ground-band data provide convincing evidence that the backband is due to alignment of $i_{\frac{13}{2}}$ protons not $j_{\frac{15}{2}}$ neutrons. Both the ground band and $K = 0^-$ band in ^{240}Pu show no evidence for band crossing in contrast to that seen in the other nuclei and in contrast to theoretical predictions.

Inelastic scattering of ^{162}Dy populated the ground, γ, S, and $K = 4^+$ bands to high spin. Rather detailed electromagnetic properties can be extracted for the S, ground and γ bands through two band crossings. The lowest $K = 4^+$ double γ-phonon band has been studied up to spin $16\hbar$ and a 11% double γ-phonon strength measured for this band.

Gammasphere coupled to CHICO achieved a excitation probability sensitivity of about 5×10^{-7} to provide the first reliable measure of the octupole double-phonon 6^+ strength in ^{208}Pb and ^{96}Zr. For ^{208}Pb, about a 20% of the strength was observed in the lowest 6^+ state and none, within the sensitivity limits, for the higher lying states implying considerable fragmentation of the octupole double-phonon strength in this nucleus. For ^{96}Zr only $6 \pm 2\%$ of the octupole strength was located in the 6_1^+ state previously presumed to be the octupole double-phonon state, whereas the 6_2^+, presumed to be the quadrupole intruder band 6^+ state, appears to contain an appreciable fraction of the octupole double-phonon strength.

These results illustrate that the unprecedented sensitivity available using Gammasphere, and the associated particle detector array CHICO, is providing considerable new insights and opening exciting new research opportunities for exploiting multiple Coulomb excitation to probe nuclear structure.

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