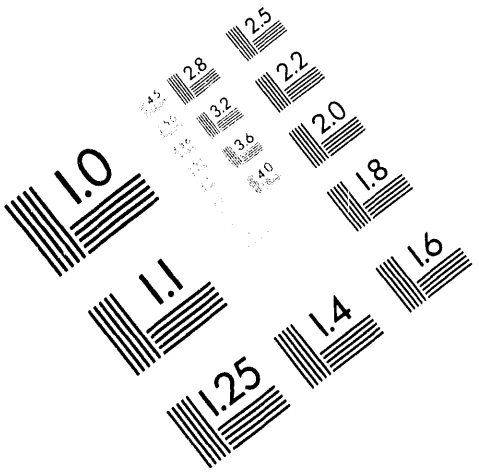

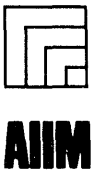

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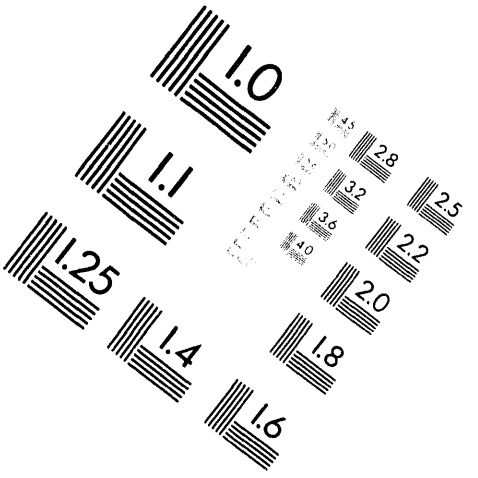

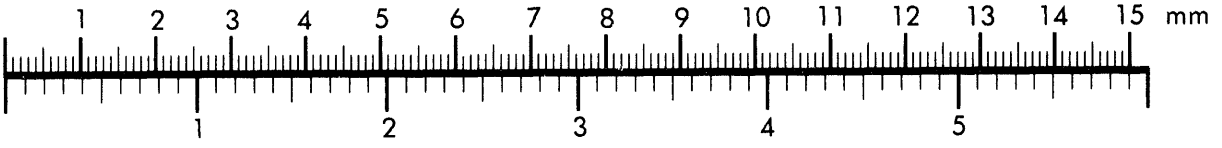

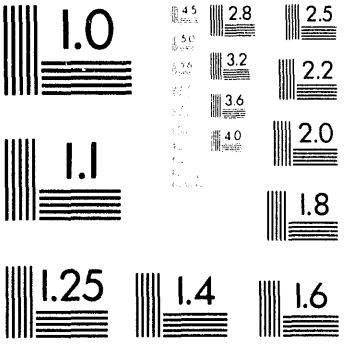

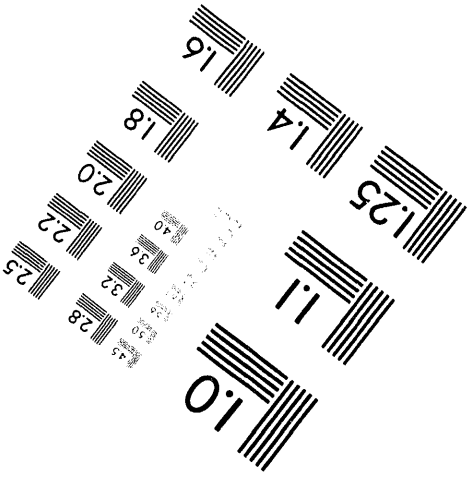

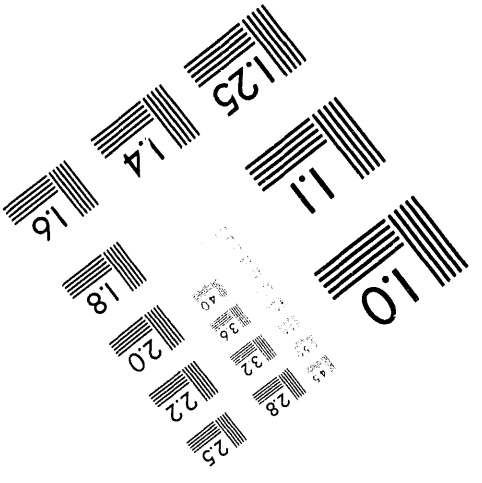

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Evidence for Octupole Vibration in the Superdeformed Well of ^{190}Hg

B. Crowell, R.V.F. Janssens, M.P. Carpenter, I. Ahmad, S. Harfenist,*
R.G. Henry, T.L. Khoo, T. Lauritsen and D. Nisius†
Argonne National Laboratory, Argonne, Illinois 60439

A.N. Wilson and J.F. Sharpey-Schafer
Oliver Lodge Laboratory, University of Liverpool,
P O Box 147, Liverpool L69 3BX, United Kingdom

J. Skalski
Soltan Institute for Nuclear Studies, Hoza 69, 00-681 Warsaw, Poland

An excited superdeformed (SD) band has been observed in ^{190}Hg which decays to the lowest-energy (yrast) SD band rather than to the less deformed states as observed in most known SD bands in the A~150 and A~190 regions. The band exhibits properties which are in good agreement with predictions of collective octupole vibrations in the SD well of ^{190}Hg.

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* Student Research Participant, Georgia Tech, Atlanta, GA 30332
† graduate student from Purdue Univ., West Lafayette, IN 47907

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The presence of superdeformed (SD) nuclear states, i.e., states with very elongated shapes, in several regions of the periodic table is now well documented.[1-3] Besides the lowest-energy SD rotational sequence (hereafter referred to as the yrast SD band), excited SD bands have also been found in many nuclei and can be understood in terms of excitations of particles across the Fermi surface in the deformed mean field. However, no excited SD bands have been observed based on collectively vibrating band-heads. The existence of such bands should be expected, since rotational bands associated with quadrupole and octupole vibrations are commonplace features of nuclei at normal prolate deformation. The corresponding excitation energies represent a measure of the stiffness of the nucleus with respect to the deformations involved.

Among the collective vibrational excitations, those associated with the octupole degree of freedom have been predicted to play a significant role in the SD wells of the A~150 and A~190 nuclei.[4-7] Octupole collectivity is enhanced at these large deformations by the presence near the Fermi surface of many pairs of orbitals with opposite parity and $\Delta\ell=3$. Calculations using Hartree-Fock and modified harmonic oscillator mean fields[4-7] predict that in the A~150 and A~190 regions, the SD minimum in the potential energy surface is far more octupole-soft than the first minimum, and that this softness extends to the non-axially symmetric octupole modes, which are relatively unimportant for shapes with smaller deformations.[8] Cranked Strutinsky calculations with a Woods-Saxon potential[9] even suggest that a reflection-asymmetric, axially non-symmetric minimum corresponding to a banana-like shape may become lowest in energy at high spin in some nuclei near A~190. Attempts to reproduce these calculations within the same cranking approach, but with a differently parametrized Woods-Saxon potential, did not, however, yield the same results.[10]

The calculations of refs. 5 and 7 not only predict the presence at low excitation energy of rotational bands associated with octupole vibrations, but they also suggest a distinct signature for such bands. Very large E1 matrix elements (B(E1) ~ 10×10^{-3} W.u.) should connect the octupole states to the yrast SD levels. Thus, while the in-band transitions with B(E2)~2000 W.u.[11] prevail in most excited SD bands, in the case of octupole-vibrational SD bands, deexcitation to the yrast SD band may be expected. No clear evidence for strong inter-band E1 transitions has been reported thus far. (Transitions between two SD bands in ^{193}Hg[12] initially thought to be of E1 multipolarity, were shown to have M1 character instead.[13])

We report here on the discovery of a new SD band in ^{190}Hg with the properties expected for octupole-vibrational SD states. In particular, transitions linking the new SD states with levels of the previously known SD band[11,14] have been found and, as a result, the excitation energy of the new band relative to the yrast SD band was measured.

The experiment was carried out using the early implementation phase of the GAMMASPHERE spectrometer[15] which consists of 32 Compton-suppressed Ge detectors. Excited states in ^{190}Hg were populated with the reaction ^{160}Gd(^{34}S,4n) at a beam energy of 163 MeV, with a target consisting of a stack of three self-supporting 0.5 mg/cm^2 ^{160}Gd foils. The beam was provided by the 88-Inch Cyclotron at the Lawrence Berkeley Laboratory. Events of interest were selected by requiring that at least three Compton-suppressed detectors fire in prompt coincidence within a time window of 50 ns. A total of 660 million triple and higher-fold coincidence events was recorded. The data were analyzed by sorting all events into a three-dimensional histogram.[16] Double-gated one-dimensional histograms were created using full background-subtraction and proper propagation of errors.[17]

The previously known SD band in ^{190}Hg[11,14] was observed. With the added sensitivity of GAMMASPHERE, it was possible to add a 317.7 keV transition at the bottom of the band (fig. 1a), and the highest transitions were determined more accurately as well (fig. 1b). More importantly, the coincidence spectra gated on the members of this band contain transitions belonging to a second band (fig. 1a), which is populated five times more weakly. This excited band begins an accelerating pattern of de-excitation to the yrast SD band (fig. 1c) at a rotational frequency of $\hbar\omega$=0.30 MeV, and no measurable intensity remains in the band below $\hbar\omega$=0.25 MeV. This pattern of decay is unlike those of almost all previously observed SD bands in the A~150 and A~190 regions, in which the nucleus remains in the SD band until finally decaying to the normally deformed states. The probability of direct decay to the normally deformed states in the present case is measured to be 4±31%, i.e. consistent with zero. Only two other cases exist in which somewhat similar patterns have been observed; one is due to an accidental degeneracy of levels in ^{150}Gd,[18] and the other involves M1 transitions between signature partners in ^{193}Hg.[13]

The above observations come from measurements of coincidence relationships between the two SD bands, but the inter-band transitions themselves have also been tentatively identified in this experiment (figs. 1c,2). All three of these transitions, at 607, 625, and 641 keV, are unfortunately close in energy to other gamma-rays in the spectrum associated with superdeformation in ^{190}Hg (the 608.1 and 641.5 keV in-band transitions in the excited SD band, and the normally deformed 625.6 keV $4^+ \rightarrow 2^+$ transition fed in the decay of the SD states). The following evidence points toward their placement in the level-scheme of fig. 2: (1) the intensity of the coincidence between the 543 keV and 641 keV transitions is larger by a factor of ~3 than it would be if the coincidence were only due to the in-band

E2 transitions in the excited SD band; (2) the energy difference between the two paths leading to the $(27+\pi^-)$ state (i.e., 625(1)+558.4(1)–641(1)–543.3(3) keV) is equal to −0.9(14) keV, consistent with the proposed level-scheme to within 0.6 standard deviations; (3) the centroid of the compound peak near 625 keV peak is shifted downward by approximately 1.4 keV, or 3 standard deviations, in gates on the excited SD band, compared to the energy of the normally deformed $4^+\rightarrow 2^+$ transition; (4) as discussed in more detail below, the coincident intensities between the two SD bands are consistent with the total intensities of the three pairs of overlapping peaks; and (5) a sum of double coincidence gates on the 625 keV transition along with low-lying members of the yrast SD band shows the expected enhancement of the 576 and 608 keV lines, compared to a similar coincidence spectrum gated on the 417 keV $2^+\rightarrow 0^+$ transition.

The surprisingly large branching ratios for decay from the excited SD band to the yrast SD band allow the unambiguous determination of the multipolarity of the inter-band transitions as E1, for the reasons outlined below. Estimates of the partial widths of the inter-band transitions can be obtained by assuming that the quadrupole moment of the states in the excited band is similar to that of the yrast band, i.e. Q_0=18±3 eb.[11] The extracted partial half-lives for the connecting transitions with energies of 641, 625, and 607 keV are then 110±30, 120±30, and 180±80 fs, respectively. These are far too short for M1 or E2 transitions, which would have to have strengths of about 1.0 W.u. or 900 W.u., respectively, to achieve these values. Such strengths would be unprecedentedly large[19] for configuration-changing transitions in a deformed nucleus. (The mechanism described by Semmes et al.[13] for strong M1 branches between signature partners cannot apply here, assuming that the yrast SD band is a K=0, zero-quasiparticle configuration.) All but five of the detectors in this experiment were located at forward and

backward angles, and $\Delta J=1$ dipole transitions were therefore attenuated relative to $\Delta J=2$ quadrupole transitions by a factor of 0.74 due to their angular distributions. This attenuation factor was measured to be 0.7 ± 0.4 for the transitions linking the excited band to the yrast band, a value which marginally favors $\Delta J=1$ dipole assignments. Based on the above evidence, and assuming that the yrast SD band corresponds to a K=0, zero-quasiparticle configuration with even spin and positive parity, we conclude that the excited band has negative parity, and probably odd spin.

With the assignment of E1 multipolarity, the strengths of the inter-band transitions are all consistent with $(8\pm2)\times10^{-3}$ W.u. This E1 rate is three orders of magnitude larger than those typically observed in heavy, deformed nuclei and is similar to those observed in the octupole-unstable normally-deformed states of actinide nuclei.[8] The extracted E1 rate is in good agreement with calculations[5,7] for the neighboring nucleus ^{192}Hg which predict a strength of 11×10^{-3} W.u. for transitions from an octupole-vibrational state in the SD well to the zero-phonon yrast SD band (at zero rotational frequency). Transitions of this strength correspond to an electric dipole moment of 0.48(3) e·fm.

Another unique feature of the excited band is its moment of inertia. The dynamic moments of inertia $\mathfrak{J}^{(2)}$ for the two SD bands are presented as a function of rotational frequency $\hbar\omega$ in fig. 3. The $\mathfrak{J}^{(2)}$ values for the yrast SD band exhibit the same behavior as those of all other SD bands in even-even nuclei of the A~190 region, i.e. a smooth increase of $\mathfrak{J}^{(2)}$ occurs with increasing frequency. At the highest frequencies, a sharp rise is noticeable. Such a rise has been qualitatively reproduced in cranked Strutinsky[14,20] and cranked Hartree-Fock[21] calculations, and is interpreted as being due to a combination of a dynamic reduction in the pairing correlations as a function

of spin and a band crossing between the zero-quasiparticle SD band and a rotation-aligned $(j_{15/2})^2$ neutron band. More important for the present discussion is the observation that the excited SD band is characterized by a constant value of $\mathfrak{J}^{(2)}$=123±1 $\hbar^2$/MeV (with χ^2=3.6 per degree of freedom) which is larger than that of the other SD bands in the region. In fact, it is larger by 6% than the moment of inertia calculated for a rigid body with a prolate deformation corresponding to the ordinary SD minimum[11] with β_2=0.47, β_4=0.07. (The rigid-body moment of inertia was calculated using the experimental value of r_0=1.212 fm for the nearby nucleus ^{194}Pb.[7] A correction for the diffuseness of the surface was included.) Since the superfluidity of a nucleus can only reduce the moment of inertia relative to its rigid-body value, the quadrupole moment of the states in the excited SD band, Q_o, is apparently larger than that of the typical SD minimum.[22] This observation is consistent with the calculations of ref. 7, which predict Q_o=1.13×Q_{yrast} for the octupole vibrational band. An upward revision of the value of Q_0 by this amount does not increase the extracted E1 strengths significantly compared to the statistical errors.

Based on the discussion above, we suggest that the excited SD band observed in this experiment is a rotational band built on a one-phonon octupole vibration in the SD well. Experience with normally deformed states shows that the octupole-vibrational bands with K=0, 1, 2 and 3 are ordinarily significantly split, and that the full multiplet is seldom observed. Thus, the observation of a single band in this experiment is not surprising. The octupole multiplets in the normally deformed well are typically mixed significantly at high spin by the Coriolis force, and a similar effect has been predicted to occur in the SD well.[6] All four values of K can contribute to an odd-spin wave-function, but the strong transitions to the K=0 yrast band observed here imply that the K=0 and K=1 components are dominant. The

excitation energy of the excited band relative to the SD yrast line varies from 0.40 MeV at the bottom of the band to only 0.15 MeV at the top (assuming odd spin for the excited band). Although the generator coordinate calculations of refs. 5, 7 and 10 were carried out at zero rotational frequency, RPA calculations have been performed for states with collective rotation[6] giving, at $\hbar\omega$=0.25 MeV, a predicted excitation energy of 0.7 MeV above the yrast band for the lowest vibrational mode, composed mostly of the K=2 component, and 1.1 MeV for the next vibrational state, which is mainly K=0 and 1. This is in only rough agreement with the observed excitation energy of 0.4 MeV near $\hbar\omega$=0.25 MeV, but the comparison is not as informative as could be hoped for as the calculations were performed at fixed ω, and thus the states being compared have different angular momenta, since the two SD bands have different moments of inertia.

From the study of octupole bands in the normally deformed well of many nuclei it is well known that, at moderate spins, the wave-functions of these negative parity states are dominated by a small number of two-quasiparticle configurations.[8] (An indication of such an effect is present, for example, in the RPA calculations of ref. 6 for the K=2 octupole vibration in the SD well of ^{192}Hg, but not for the K=0,1 states.) It is interesting to note that, if a similar effect were present in the excited SD band discussed here, most of the lowest two-quasiparticle excitations in ^{190}Hg would involve a $j_{15/2}$ quasineutron coupled to a quasineutron occupying one of the positive parity orbitals located near the Fermi surface (see ref. 11 for the relevant quasiparticle spectrum). The occupation of a single $j_{15/2}$ orbital would have the effect of blocking the first rotational alignment of a $j_{15/2}$ neutron pair. Octupole correlations are also predicted to dilute the rotation-aligned character of the quasiparticle orbitals.[11] Both of these effects would influence the $\mathfrak{J}^{(2)}$ moment of inertia of the excited SD band and result in more

constant $\mathfrak{J}^{(2)}$ values as a function of frequency than in the yrast SD band, in agreement with the observations in fig. 3.

In conclusion, we have observed an excited SD band in ^{190}Hg, whose properties agree well with those predicted by generator coordinate calculations for a rotational band built on an octupole-vibrational band-head. This is the first experimental information to become available regarding the susceptibility to octupole deformation of nuclei in the A~150 and A~190 regions of superdeformation. This is also one of the first cases (ref. 13) in these regions in which it has been possible to obtain an experimental measurement of the relative excitation energy, parity, and possibly spin of two SD bands.

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22. Quasiparticle alignments may lead to an increase in the apparent moment of inertia over some range of spins, but cannot account for the large and constant moment of inertia observed here. The rigid-body moment of inertia is also insensitive to octupole deformation,[10] although the actual moment of inertia may show dependence on octupole deformation through a variety of dynamical effects.

Captions for figures:

Fig.1. Double-gated gamma-ray coincidence spectra, showing SD transitions in ^{190}Hg: (a) Sum of double gates on transitions in the yrast SD band with $\hbar\omega$<0.28 MeV; (b) similar to panel a, but with gates at high frequencies to enhance the top of the band; (c) sum of double gates on transitions in the excited SD band. Transitions in the excited SD band are marked with underlining, normally deformed transitions in coincidence with the SD bands are marked with asterisks, and transitions which are doublets with the inter-band E1 transitions are marked with daggers (see text). Areas of peaks do not correspond to actual gamma-ray intensities because some transitions have been used as gates, while others have not because they are unresolved doublets.

Fig. 2. Partial level-scheme of SD states in ^{190}Hg. Where branching ratios are different from 100%, they are shown in brackets, with the error-bars in parentheses. Branching ratios were determined from the coincident intensities between the two bands, not directly from the intensities of the inter-band transitions. The energies of the transitions connecting the two bands are tentative. Transitions at the top and bottom of the yrast SD band have been omitted (cf. fig. 1), as indicated by the dots. The spin next to each level is undetermined up to an over-all even integer constant X, and the brackets on the spins of the excited band indicate that the assignment of odd spin to these states is tentative. The energy of the 607 keV inter-band transition is based on differences of the other gamma-ray energies.

Fig. 3. The dynamic moment of inertia $\mathfrak{J}^{(2)}$ as a function of rotational frequency $\hbar\omega$ for the two SD bands in ^{190}Hg.

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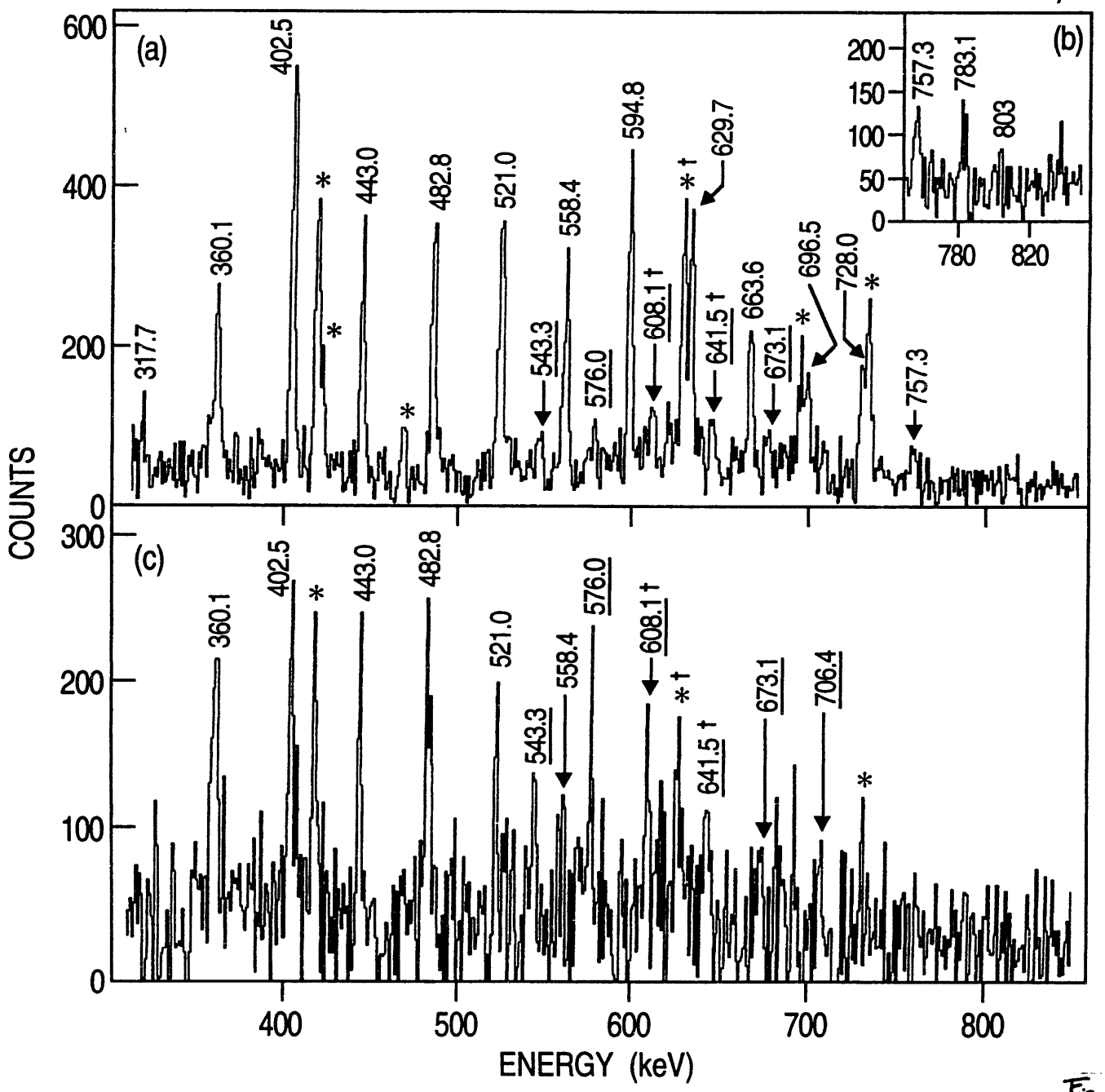

Fig. 1
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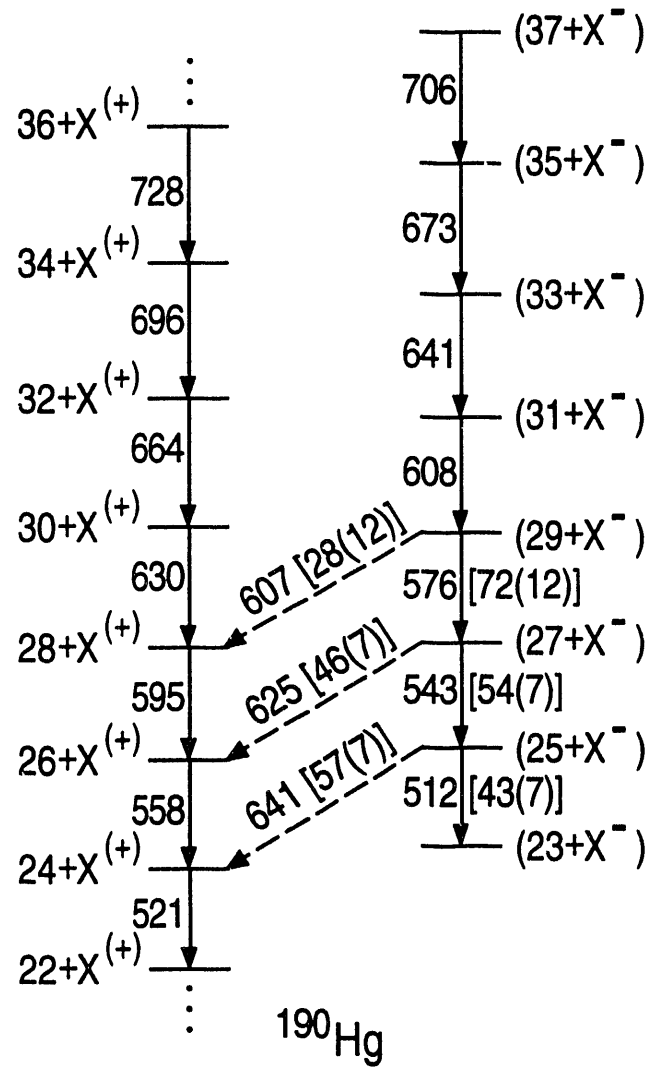

Fig. 2
B. Crowell et al.

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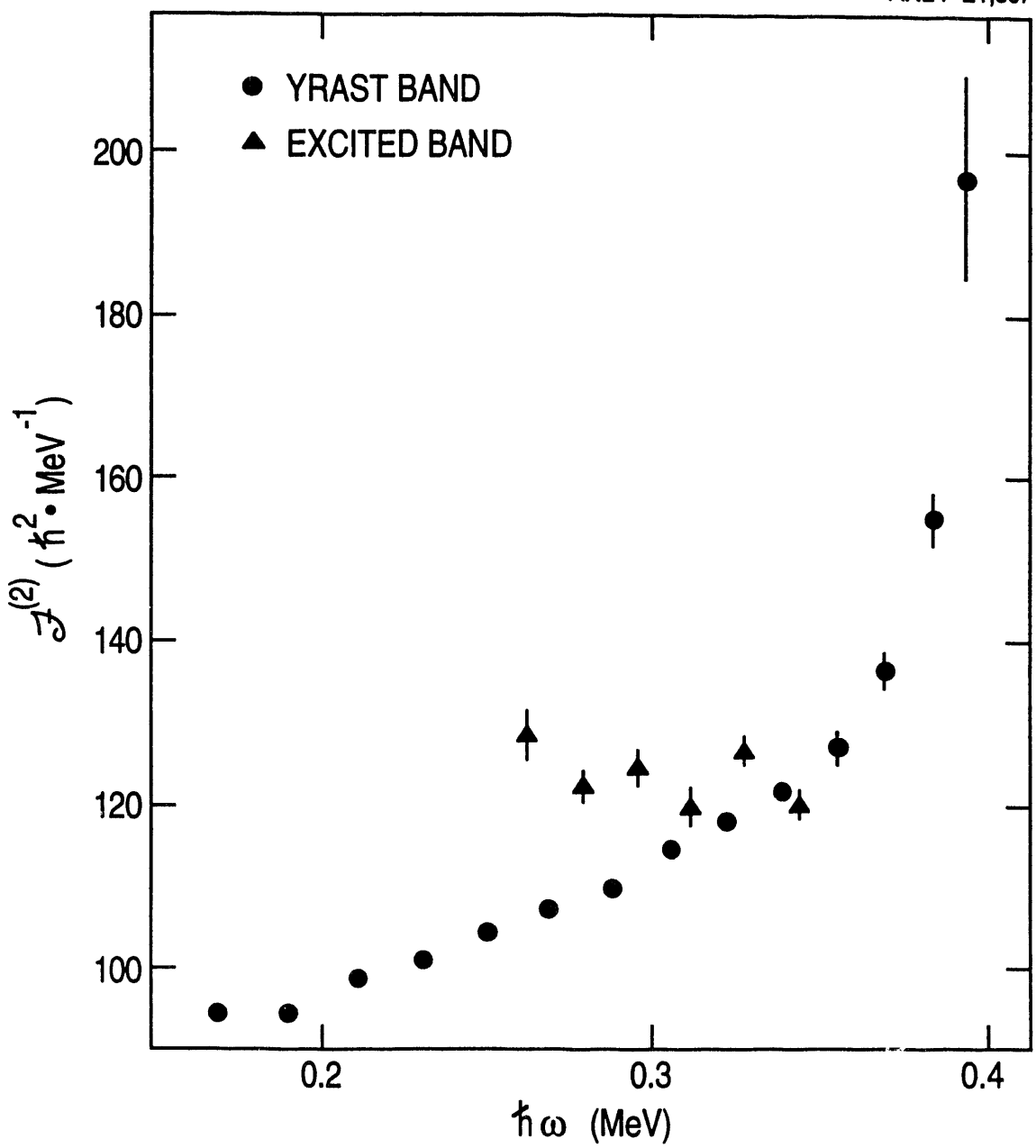

Fig. 3
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