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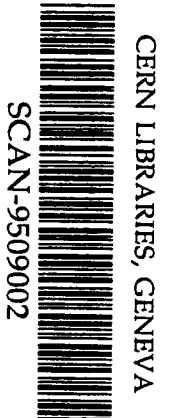
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C. Schuck<sup>3</sup>, and F.S. Stephens<sup>1</sup>

<sup>1</sup> *Nuclear Science Division, Lawrence Berkeley Laboratory  
University of California, Berkeley, CA 94720, USA*

<sup>2</sup> *Argonne National Laboratory, Argonne IL 60439, USA*

<sup>3</sup> *C.S.N.S.M., IN2P3-CNRS bat 104-108, F-91405 Orsay Cedex, France*

<sup>4</sup> *I.P.N., IN2P3-CNRS bat 104, F-91406 Orsay Cedex, France*

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M.A.Deleplanque<sup>1</sup>, R.M.Diamond<sup>1</sup>, B.Gall<sup>3</sup>, F.Hannachi<sup>3</sup>, R.G.Henry<sup>2</sup>, R.V.F.Janssens<sup>2</sup>,  
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<sup>1</sup> *Nuclear Science Division, Lawrence Berkeley Laboratory, Berkeley CA 94720, U.S.A.*

<sup>2</sup> *Argonne National Laboratory, Argonne IL 60439, USA.*

<sup>3</sup> *C.S.N.S.M., IN2P3-CNRS bat 104-108, F-91405 Orsay Cedex, France.*

<sup>4</sup> *I.P.N., IN2P3-CNRS bat 104, F-91406 Orsay Cedex, France.*

## Abstract

For the first time, two excited superdeformed bands have been observed in the double closed shell superdeformed nucleus  $^{192}\text{Hg}$ . One of the SD bands exhibits a pronounced peak in the dynamic moment of inertia which is interpreted as a crossing between two excited SD configurations involving the  $N=7$  intruder and the  $[512]_{\frac{5}{2}}$  orbitals. This is only the second occurrence of such a crossing in a SD nucleus around  $A=190$ . The second excited SD band has near identical transition energies to an excited SD band in  $^{191}\text{Hg}$ .

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Superdeformation in the mass 190 region was first observed in  $^{190}\text{Hg}$  [1]. Soon after, a superdeformed (SD) band was observed in  $^{192}\text{Hg}$  [2,3], and since then approximately 40 SD bands have been reported in this mass region (i.e., in Au, Hg, Tl and Pb nuclei). The  $A=190$  SD bands exhibit a number of striking features. In particular many SD bands show the same smooth rise in the dynamic moment of inertia ( $\mathfrak{S}^{(2)}$ ) as a function of rotational frequency ( $\hbar\omega$ ), which is associated [3,4] with the successive alignment of neutrons and protons in the presence of pair correlations. In addition to the similar moments of inertia, the transition energies of many SD bands are also ‘identical’<sup>1</sup> [5]. Since pair correlations play an important role in  $A=190$  SD nuclei (required to explain the rise in  $\mathfrak{S}^{(2)}$ ), the observation of so many bands in even and odd mass nuclei with similar moments of inertia is surprising. Unpaired nucleons close to the Fermi surface are expected to reduce (block) the pairing strength, and hence increase the moment of inertia. Thus, in addition to similar  $\mathfrak{S}^{(2)}$ 's, the occurrence of identical SD bands with near identical transition energies appears even more surprising.

Besides these more general features of SD bands near  $A=190$ , the observation in  $^{193}\text{Hg}$  [6] of a band-crossing involving  $N=7$  and  $N=5$  quasiparticle orbitals has raised several questions regarding (i) the spectrum of quasiparticle states in the vicinity of the Fermi surface and (ii) the role of collective excitations (octupole vibrations) in SD nuclei. To date such a band-crossing has only been observed in  $^{193}\text{Hg}$ , although similar crossings are expected to occur in neighboring nuclei as well.

In this letter we present new data which provide important experimental information on the above mentioned properties of  $A=190$  SD bands. Two excited SD bands in the doubly closed shell nucleus  $^{192}\text{Hg}$  are reported for the first time. At low frequencies one of the new bands is identical to a SD band in  $^{194}\text{Hg}$  [4,7], while at higher frequencies one observes a

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<sup>1</sup>In general, identical bands are those which have either integer or half-integer alignments relative to each other. The alignment is the difference in the total angular momenta at a given rotational frequency.



clear band-crossing, similar to that observed in  $^{193}\text{Hg}$ . It is shown that the properties of this band may be used to place constraints on (i) the relative position of neutron orbitals around the  $N=112$  SD shell gap, and (ii) the influence of pair correlations on the valence quasiparticle routhians. The second new SD band displays a sharp increase in  $\mathfrak{S}^{(2)}$  at the highest frequencies and, in addition, is identical to a SD band in  $^{191}\text{Hg}$  [8] over a large frequency range.

SD states of  $^{192}\text{Hg}$  were studied using the Gammasphere spectrometer [9] and the reaction  $^{160}\text{Gd}(^{36}\text{S},4n)^{192}\text{Hg}$  at a beam energy of 159 MeV. In this phase of operation Gammasphere consisted of 30 escape-suppressed, large volume (75%) Ge detectors. The beam of 2 – 3 pA was supplied by the Lawrence Berkeley Laboratory 88" cyclotron and the target consisted of two  $500\mu\text{gcm}^{-2}$  self-supporting foils. A total of approximately  $5 \times 10^8$  events were collected in which three or more suppressed Ge detectors registered an event.

Three SD bands were observed in this data set, one of which (band 1) has been reported [2,3] previously and is associated with the  $^{192}\text{Hg}$  yrast SD configuration. The new SD bands (bands 2 and 3 – shown in Fig. 1) are in coincidence with low-lying transitions in  $^{192}\text{Hg}$  and are therefore also assigned to  $^{192}\text{Hg}$ . The SD rotational nature of the bands was inferred from the regular transition energy spacing ( $\sim 40$  keV). The intensities for bands 2 and 3 are approximately 10% and 5% relative to band 1 which has  $\sim 2\%$  of the  $^{192}\text{Hg}$  channel intensity. Therefore we associate these new bands with excited SD configurations. The low intensities for bands 2 and 3, relative to band 1, are consistent with the expected large SD shell gaps at  $N=112$  and  $Z=80$ . The energies for bands 1-3, together with their relative in-band intensities are given in table 1. Band 2 was also observed independently in an experiment performed with the Eurogam spectrometer [10] at Daresbury using a gold-backed target [11].

The dynamic moment of inertia ( $\mathfrak{S}^{(2)}$ ) for each of the SD bands in  $^{192}\text{Hg}$  is shown (Fig. 2) as a function of rotational frequency ( $\hbar\omega$ ). Except at high frequencies the three SD bands exhibit the same gradual increase in  $\mathfrak{S}^{(2)}$  as one observes for almost all SD bands in this region. This smooth increase is attributed [3,4] mainly to the successive alignment of both  $N=7$  neutrons and  $N=6$  protons in the presence of pairing, and as a consequence, one

expects the  $\mathfrak{S}^{(2)}$  to decrease after the alignment process is complete. This decrease in  $\mathfrak{S}^{(2)}$  (at  $\hbar\omega \approx 0.4$  MeV) was recently observed for the first time in  $^{194}\text{Hg}$  [12]. Both previous work [13] and the present data (Fig. 2) show that the  $\mathfrak{S}^{(2)}$  for  $^{192}\text{Hg}$  band 1 flattens at  $\hbar\omega \approx 0.4$  MeV, further supporting this interpretation.

In  $^{192}\text{Hg}$  band 2 there occurs a clear irregularity or ‘peak’ in the  $\mathfrak{S}^{(2)}$  which suggests the band is undergoing a change in configuration (band-crossing). Since the contribution to  $\mathfrak{S}^{(2)}$  from the single- or quasiparticle alignment ( $i$ ) is  $di/d(\hbar\omega)$ , then a peak in  $\mathfrak{S}^{(2)}$  (relative to a smooth reference) implies a gain in alignment with increasing frequency. In  $^{193}\text{Hg}$ , Cullen et al. [6] observed a peak and a dip in the  $\mathfrak{S}^{(2)}$  of bands 1 and 4 respectively. It was proposed [6] that at low frequencies bands 1 and 4 in  $^{193}\text{Hg}$  correspond to structures where the odd quasineutron occupies the  $[512]_{\frac{5}{2}}$  and the  $N=7$  intruder orbital respectively. At  $\hbar\omega \approx 0.25$  MeV these bands interact, exchange character (quantum numbers) and at high frequencies the structure of  $^{193}\text{Hg}$  band 1 can be associated with the  $N=7$  intruder while that of  $^{193}\text{Hg}$  band 4 is associated with the  $[512]_{\frac{5}{2}}$  orbital. We suggest that the interaction in  $^{192}\text{Hg}$  band 2 also involves a crossing between the  $N=7$  intruder and the  $[512]_{\frac{5}{2}}$  orbital. The crossing frequencies ( $\hbar\omega$ ) and alignment gains ( $i$ ) associated with this interaction are  $\hbar\omega \approx 0.3$  MeV,  $i \approx 2.6\hbar$  for  $^{192}\text{Hg}$  band 2, and  $\hbar\omega \approx 0.25$  MeV,  $i \approx 1.0\hbar$  for  $^{193}\text{Hg}$  band 1. Why the properties of the band-crossing are different in  $^{192}\text{Hg}$  and  $^{193}\text{Hg}$  is indeed a puzzle, it may reflect differences in the Fermi levels, however, one would have expected that the crossing frequency in  $^{193}\text{Hg}$  is pushed to higher values since the separation between the  $[512]_{\frac{5}{2}}$  orbital and the  $N=7$   $\frac{3}{2}$  orbital is larger in  $^{193}\text{Hg}$  compared with  $^{192}\text{Hg}$ . To date,  $^{192}\text{Hg}$  and  $^{193}\text{Hg}$  are the only SD nuclei which exhibit such a crossing. Why similar SD bands are not observed in neighboring nuclei, with similar neutron Fermi levels (e.g.,  $^{194}\text{Hg}$ ,  $^{194}\text{Tl}$ ,  $^{194,195}\text{Pb}$ ), remains an important unanswered question.

Since  $^{192}\text{Hg}$  has an even number of neutrons, band 2 is most likely associated with a 2-quasiparticle configuration. For an interaction of the type suggested above one quasineutron should occupy the favored signature of the  $N=7$  intruder at high rotational frequency which

then crosses (interacts with) the  $[512]_{\frac{5}{2}}$  orbital as the frequency decreases. Fig. 3 shows a quasineutron diagram for  $^{192}\text{Hg}$  taken from the Hartree-Fock (HF) cranking calculations of Gall et al. [14] illustrating the crossing between the  $N=7$  and the  $[512]_{\frac{5}{2}}$  orbitals at  $\hbar\omega \approx 200$  keV. The second quasineutron most likely occupies either the  $[642]_{\frac{3}{2}}$  or  $[624]_{\frac{9}{2}}$  orbital (for the sake of simplicity and since we are not able to distinguish between the two candidates, we will only refer to the  $N=6$  orbital in the following discussion). In  $^{192}\text{Hg}$  we do not observe a SD band which exhibits a dip in  $\mathfrak{F}^{(2)}$  (cf.  $^{193}\text{Hg}$  band 4 [6]). However, in the frequency range ( $\hbar\omega \geq 0.3$ ) where SD bands are mainly populated, the  $[512]_{\frac{5}{2}}$  orbital (Fig. 3), which is occupied in that band is expected to lie higher in excitation energy than the favored signature of the  $N=7$  orbital. Therefore a SD band (e.g. similar to  $^{193}\text{Hg}$  band 4) based on a configuration in which the  $[512]_{\frac{5}{2}}$  is occupied at high frequency may be too weak to observe in these data.

It is important to note that while HF calculations predict a crossing between the  $N=7$  and the  $[512]_{\frac{5}{2}}$  orbitals, cranked shell model (CSM) calculations using a Woods-Saxon potential do not predict this band-crossing in the  $^{192}\text{Hg}$  excited SD structures. This is due to the fact that the two models predict different energies for the  $N=7$  intruder orbitals relative to the Fermi level, and hence these data on  $^{193}\text{Hg}$  place constraints on the position of the  $N=7$  quasineutron intruder orbitals relative to the  $[512]_{\frac{5}{2}}$  orbital and the Fermi level.

Below the band-crossing,  $^{192}\text{Hg}$  band 2 has transition energies which are very close to those of  $^{194}\text{Hg}$  band 2 [4,7] (see Fig. 4a). In  $^{194}\text{Hg}$ , Riley et al. proposed that band 2 is based on a  $[512]_{\frac{5}{2}} \otimes [624]_{\frac{9}{2}}$  configuration, and in addition they observe another SD band (band 3) which has transition energies at the half-way points to  $^{194}\text{Hg}$  band 2. As a result,  $^{194}\text{Hg}$  bands 2 and 3 are considered to be signature partners based on a strongly coupled configuration. Although the orbitals involved in the  $^{194}\text{Hg}$  excited SD bands are similar to those proposed for  $^{192}\text{Hg}$ , it was not possible to identify a band in  $^{192}\text{Hg}$  which would correspond to a strongly coupled signature partner to band 2. However, the transition energies for band 2 occur close to the half-way points relative to band 1, and therefore if such a signature partner to band 2 exists, it would most likely be masked by the much

stronger band 1.

The band-crossing in  $^{192}\text{Hg}$  band 2 provides evidence for the importance of pair correlations in  $A=190$  SD bands. Calculations which do not include pairing are not able to predict any band-crossing (except at very high rotational frequencies,  $\hbar\omega \geq 0.8$  MeV). By including pair correlations, the  $N=7$  intruder becomes a mixture of the  $K = \frac{3}{2}$  and  $K = \frac{5}{2}$  components, causing this orbital to align (i.e., become lower in energy with increasing frequency) and interact with the  $[512]_{\frac{5}{2}}$  orbital [14]. It is also important to recognize that the presence of pair correlations also affects the alignments of other orbitals (see Fig. 3). In fact, those valence quasineutron routhians which one would like to assign as ‘spectators’ exhibit too much alignment. Thus these data provide a crucial test for current calculations, since they must first reproduce the band-crossing in  $^{192}\text{Hg}$ , while at the same time yield at least one ‘spectator’ orbital with near zero alignment. Moreover, since there are now two examples of SD bands in the  $A=190$  region which undergo a quasineutron crossing, it is necessary for theory to also explain why the properties of the band-crossing are different in  $^{192}\text{Hg}$  and  $^{193}\text{Hg}$ . As a final comment on the properties of band 2 we note that below  $\hbar\omega = 0.2$  MeV, this band has  $\mathfrak{S}^{(2)}$  values which are higher than those of  $^{192}\text{Hg}$  band 1. This difference in  $\mathfrak{S}^{(2)}$  at low frequencies between 0-quasiparticle and neighboring excited (or odd) quasiparticle configurations is seen consistently throughout the  $A=190$  SD region and may be due to either pair blocking [15] in the excited (or odd quasiparticle) SD bands and/or the alignment of valence particles.

The second new SD band (band 3) is also likely to be associated with a 2-quasiparticle structure and exhibits a number of interesting features which enable us to draw the following conclusions.

- (i) The  $\mathfrak{S}^{(2)}$  moment of inertia for band 3 (Fig. 2) is similar to that of band 1 (except at the very highest frequencies), and therefore band 3 is assigned the same intruder configuration as band 1.
- (ii) The transition energies for band 3 are within 1-2 keV of those in  $^{191}\text{Hg}$  band 2 (Fig. 4b), and although  $^{191}\text{Hg}$  band 2 is known to have a signature partner (i.e.,  $^{191}\text{Hg}$  band 3 [8]) we

do not observe a similar signature partner for  $^{192}\text{Hg}$  band 3. The absence of a signature partner implies that neither of the two quasiparticles are in deformation aligned high- $K$  orbitals.

(iii) The transition energies for  $^{192}\text{Hg}$  band 3 occur close to the  $3/4$  points relative to those in  $^{192}\text{Hg}$  band 1 (Fig. 4c) and since transitions connect states with spins  $I \rightarrow (I - 2)$ ,  $^{192}\text{Hg}$  band 3 has near half-integer alignment with respect to  $^{192}\text{Hg}$  band 1. This is not expected for a 2-quasiparticle band and the observed half-integer alignment may be accidental.

(iv) Band 3 exhibits a sharp increase in  $\mathfrak{S}^{(2)}$  (Fig. 3) at high frequency ( $\hbar\omega \approx 0.33$  MeV) which suggests it is undergoing a band-crossing or a level interaction.

Given the above observations, and assuming that our assignments to  $^{192}\text{Hg}$  band 2 are correct, we are left with a number of problems with the interpretation of band 3. If bands 2 and 3 are undergoing the same level interaction (i.e., the crossing of the favored  $N=7$  intruder orbital with the  $N=5$  orbital), it is very difficult to understand why the two crossing frequencies are different. On the other hand, if the increase in  $\mathfrak{S}^{(2)}$  (band 3) involves the unfavored  $N=7$  intruder orbital, one may expect that bands 2 and 3 would behave like strongly coupled signature partners at low frequency, which is clearly not the case. Although many quasiparticle orbitals are predicted to occur close to the Fermi level (Fig. 3), it was not possible to assign a quasiparticle configuration to band 3 which was consistent with the all above observations.

To summarize, we have observed two excited SD bands in  $^{192}\text{Hg}$ , which are associated with 2-quasiparticle excitations. Band 2 shows evidence for a band-crossing, and corresponds to the occupation of a  $N=7$  intruder at high frequency and the  $[512]_{\frac{5}{2}}$  orbital at low frequency. This is only the second example of such a crossing and provides important experimental information on the quasiparticle spectra around the  $N=112$  SD shell gap and on the role of pairing in SD nuclei. It is a puzzle why similar crossings are not seen in neighboring SD nuclei. Band 3 is seen to exhibit a number of intriguing features, such as near ‘identical’ transition energies compared with  $^{191}\text{Hg}$  band 2 and an abrupt increase in  $\mathfrak{S}^{(2)}$  at high frequency.

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Table 1. Transition energies (keV) and in-band relative intensities for the three SD bands in  $^{192}\text{Hg}$ . 'a' denotes transitions for which intensities could not be obtained due to the presence of close lying known yrast transitions in  $^{192}\text{Hg}$ .

$^{192}\text{Hg}$ SD band 1		$^{192}\text{Hg}$ SD band 2		$^{192}\text{Hg}$ SD band 3	
$E_\gamma$	Intensity	$E_\gamma$	Intensity	$E_\gamma$	Intensity
214.4 (0.3)	8 (2)				
257.8 (0.1)	88 (5)	282.4 (0.2)	71 (8)		
300.1 (0.1)	101 (5)	322.1 (0.2)	103 (8)	333.1 (0.3)	66 (7)
341.4 (0.1)	107 (6)	361.3 (0.2)	100 (7)	372.8 (0.2)	113 (8)
381.6 (0.1)	104 (5)	400.2 (0.2)	99 (6)	412.1 (0.2)	90 (9)
421.1 (0.2)	'a'	438.0 (0.2)	96 (6)	450.6 (0.3)	95 (8)
458.8 (0.2)	108 (6)	475.2 (0.2)	97 (7)	488.3 (0.3)	97 (8)
496.0 (0.2)	94 (6)	511.0 (0.2)	108 (7)	525.5 (0.4)	80 (8)
532.1 (0.2)	88 (5)	546.7 (0.2)	103 (6)	561.7 (0.4)	44 (7)
567.4 (0.2)	69 (4)	578.8 (0.2)	91 (7)	597.3 (0.4)	50 (7)
601.7 (0.2)	71 (4)	604.4 (0.2)	82 (7)	630.1 (0.5)	'a'
634.9 (0.2)	'a'	624.2 (0.3)	55 (8)	659.0 (0.8)	20 (4)
668.1 (0.2)	55 (5)	652.2 (0.3)	65 (8)	681.0 (1.5)	15 (6)
700.1 (0.2)	49 (6)	684.3 (0.3)	50 (8)		
731.5 (0.2)	42 (6)	717.7 (0.3)	30 (7)		
762.3 (0.3)	31 (5)	749.8 (0.4)	19 (4)		
792.7 (0.4)	29 (4)	783.1 (0.5)	12 (3)		
822.9 (0.4)	6 (2)	(819 (1))			
853.1 (0.5)	3 (1)				
(888.7 (0.7))	$\leq 5$				



## FIGURES

FIG. 1. Spectra of SD bands 2 and 3 in  $^{192}\text{Hg}$  obtained from the sums of triple and double gated spectra respectively. The energies (keV) of the transitions associated with the decay of SD states are shown; ‘\*’ corresponds to known normal deformed yrast transitions in  $^{192}\text{Hg}$ . In the spectrum of band 3 some of the peaks marked with ‘\*’ may also correspond to transitions in the  $^{192}\text{Hg}$  dipole band (Y.Le Coz et al., Z. Phys. A **348** (1994) 87), which could arise from contaminants in the gating transitions.

FIG. 2. Dynamic moments of inertia ( $\mathfrak{S}^{(2)} = \frac{4}{\Delta E_\gamma}$ , where  $\Delta E_\gamma$  is the difference in the in-band transition energies) as a function of rotational frequency for the three SD bands assigned to  $^{192}\text{Hg}$ . The dashed and dot-dashed lines correspond to  $^{193}\text{Hg}$  bands 1 and 4 respectively.

FIG. 3. Quasineutron Routhians for  $^{192}\text{Hg}$  taken from ref. [14], illustrating the crossing of the  $N=7$  intruder (most likely a mixture of the  $[752]_{\frac{5}{2}}$  and  $[761]_{\frac{3}{2}}$  components) and the  $[512]_{\frac{5}{2}}$  orbital at  $\hbar\omega \approx 200$  keV.

FIG. 4. Difference in transition energies for (a)  $^{194}\text{Hg}$  band 2 –  $^{192}\text{Hg}$  band 2, (b)  $^{191}\text{Hg}$  band 2 –  $^{192}\text{Hg}$  band 3, and (c)  $^{192}\text{Hg}$  band 1 (3/4 pts.) –  $^{192}\text{Hg}$  band 3. The range is restricted to below the band interaction.

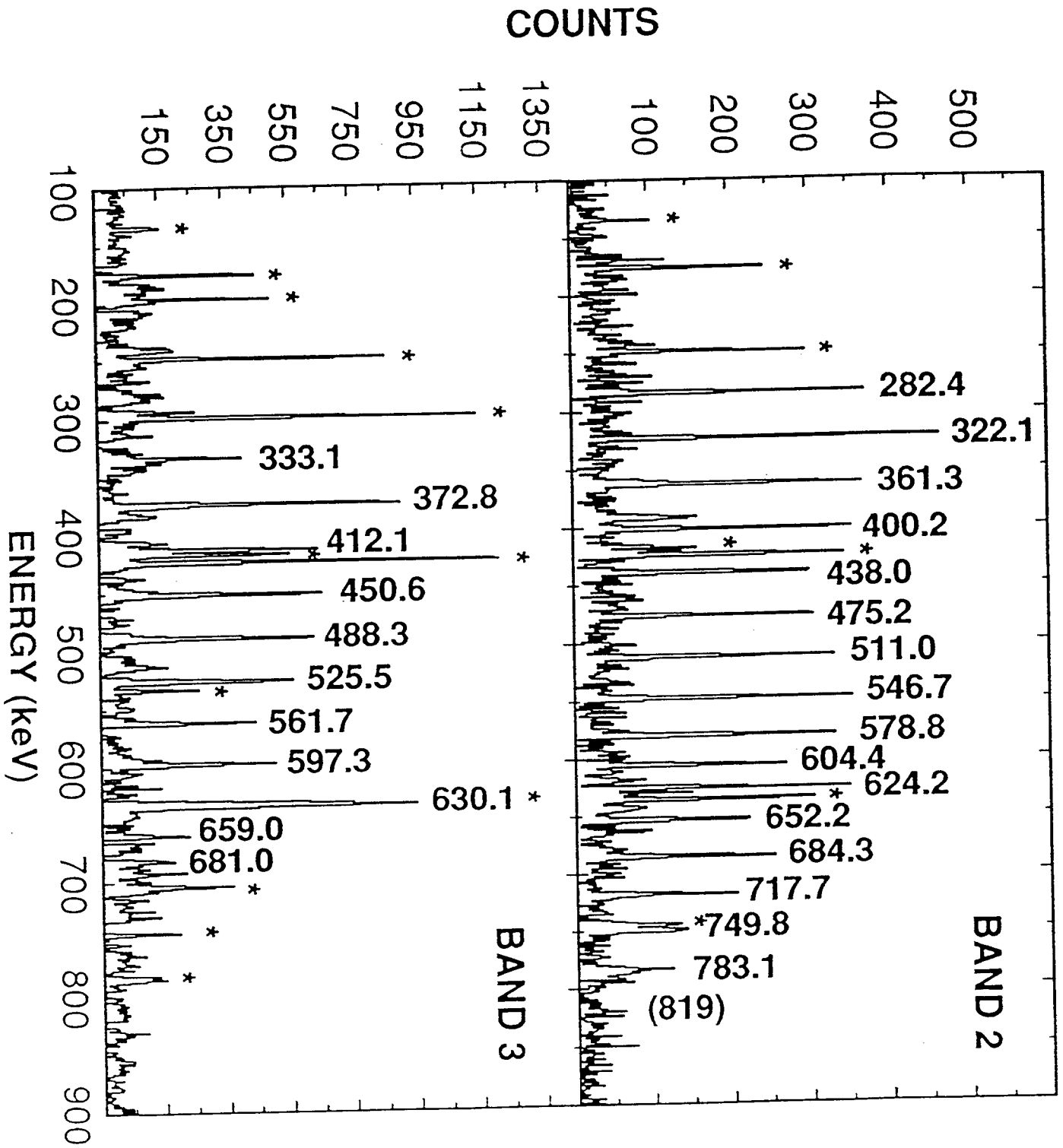


Figure 1

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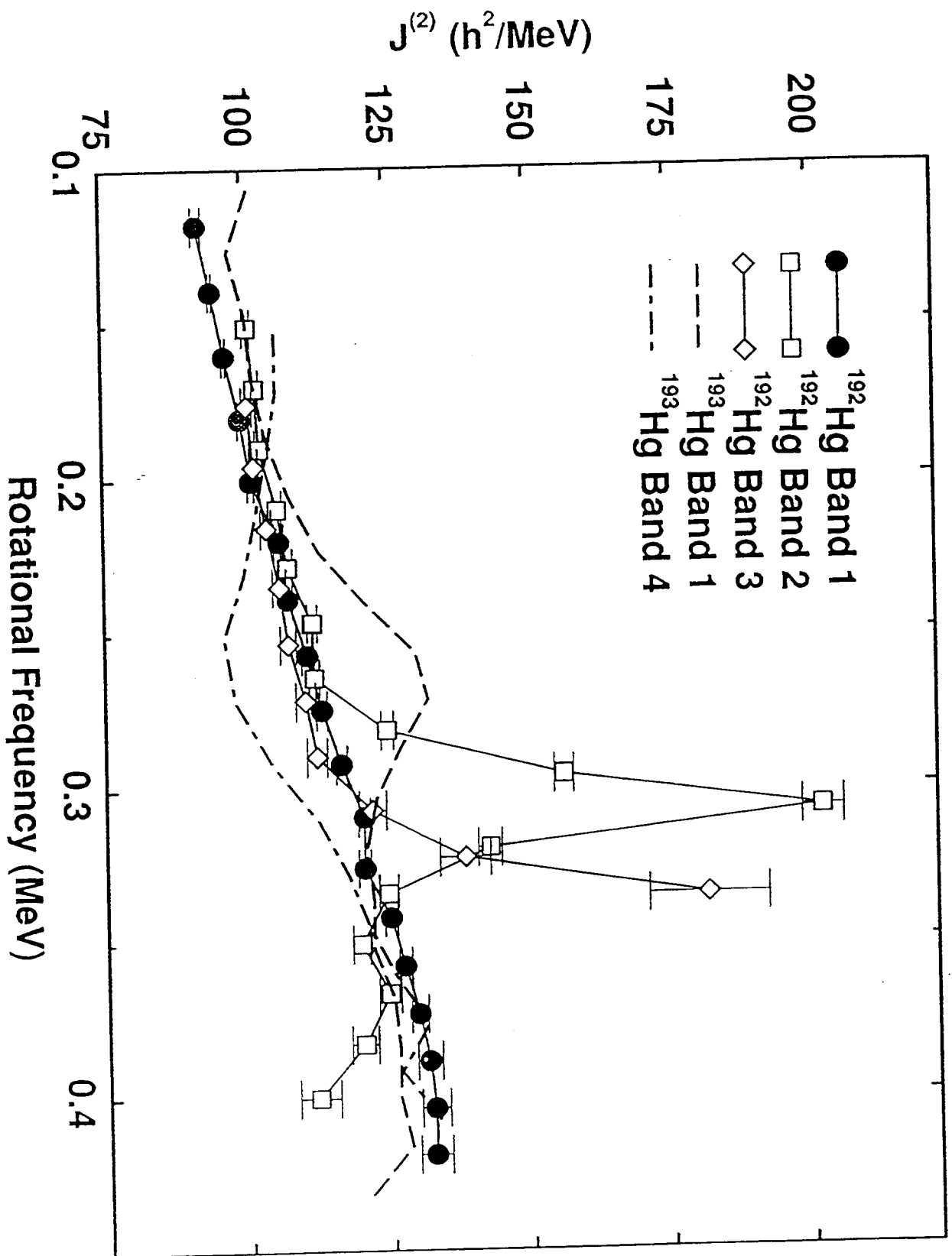


Figure 2  
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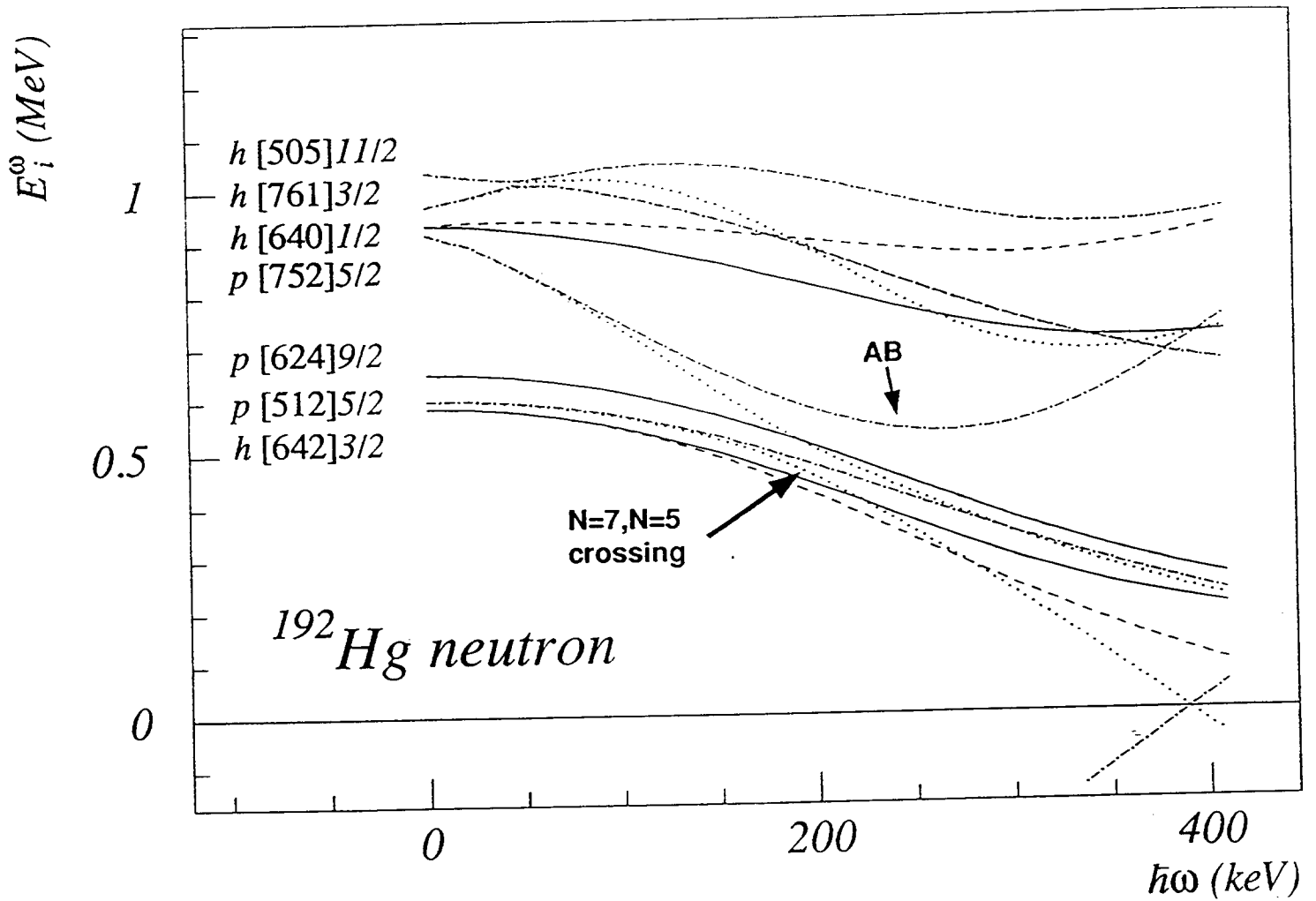


Figure 3  
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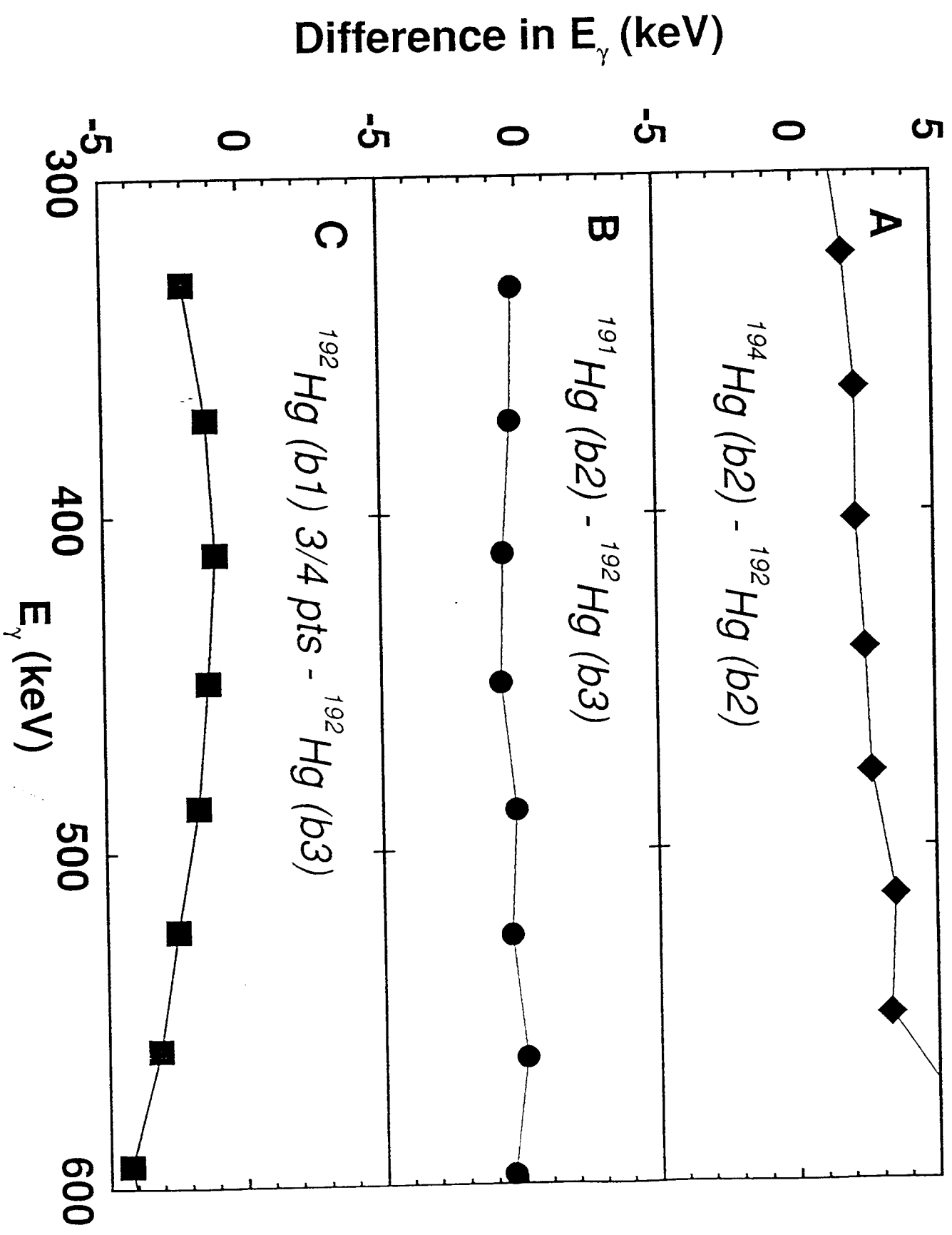


Figure 4  
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