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Conf-921116--12

UCRL-JC-111939
PREPRINT

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This paper was prepared for submittal to
the Twelfth International Conference on the
Application of Accelerators in Research and Industry
Denton, Texas
November 2-5 1992

November 1992

Received by OSTI
NOV 30 1992

Lawrence Livermore National Laboratory

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UCRL-JC--111939

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ABSTRACT: Reports of recent experiments have included observations of regular and irregular bands in neutron deficient Pb isotopes with A=194, 196-201. The bands are populated strongly in HI,xn reactions. The shared characteristics of the bands include: 1) Bandhead energies of few MeV; 2) High bandhead spin; 3) Large alignments; 4) Small dynamic moments of inertia, and 5) Strong $L = 1$ transitions and weaker $L \approx 2$ crossover transitions, with B(M1/B(E2) ≈ 20 μ^2/e^2b^2. Lifetimes of band members in the ^{198}Pb regular band are B(M1) ≈ 1 W.u., and B(E2) ≈ 10 W.u. (with large errors). These observations are consistent with an interpretation of the regular structures as collective oblate bands with both proton and neutron excitations involved; the closed proton shell at

Z = 82 is broken, and coupled to $\nu(i_{13/2})^{-n}$ excitations. The irregular structures may correspond to triaxial shapes, with similar orbits involved. A similar structure has been also found in ^{193}Hg.

I. INTRODUCTION

Nuclear excitations classified by the deformed shell model at energies associated with the promotion of particles across the (sub)shell gap have been found in heavy nuclei with closed (sub)shells. Examples of such states in neutron deficient Pb nuclei include the low-lying 0^+ states in Pb [1], and the 8^+, and 11^- isomeric states in ^{194,196}Pb [2-4]. Theoretical interpretation of these states in terms of promotion of protons across the Z=82 shell gap and oblate deformation was given early by Heyde, et. al. [5], in terms of $\pi\left([400]^{-2}[500]^2\right)_{0^-,8^-}$ and $\pi \left([400]^{-2}[505][606]\right)_{11^-}$ configurations. Cranked shell model calculations [1,6,7] predict oblate minima in the energy surface for these Pb isotopes at $\gamma = -60^0$ and $\beta_2 = 0.17$.

Experimental study of the oblate rotational bands expected to be build on these states is difficult. It requires (i) state of the art spectrometers because of the relatively high bandhead excitation and the complex nuclear level scheme at these excitations, and (ii) heavy-ion accelerators which can produce the energetic beams required to produce these states. Very rich data sets have been obtained at facilities with such capabilities in experiments done with the goal of identification of superdeformation in Pb nuclei. Superdeformed states are produced in these bombardments at the 1 percent level and so large data sets (200 x 10^6 events) are collected. The experimental signature of superdeformation is a γ-ray cascade characteristic of a deformed nucleus, and the band head is predicted to have 4 - 5 MeV excitation. These data sets then include information about the oblate bands. Detailed studies of these data sets have resulted in candidate oblate bands in ^{194}Pb, [4,8] ^{196}Pb [9,10], ^{197}Pb [11,12], ^{198}Pb [13,14], ^{199,200}Pb [15], and ^{201}Pb [16]. A candidate band in ^{193}Hg has also been identified [17]. The next section (Sec. II) describes a typical experiment. A discussion of the properties of these bands is given in Section III, and finally, a summary and future prospects are described in Section IV.

II. EXPERIMENTS

The experiments have been conducted by experimental collaborations from a wide variety of institutions at facilities throughout the world. The experimental arrangement and results from an experiment conducted by the LLNL-LBL-Rutgers collaboration at the LBL 88-Inch Cyclotron Facility will be presented as typical [11]. The nucleus ^{197}Pb was populated in the reaction ^{176}Yb(^{26}Mg, 5n), at E(^{26}Mg) = 135 MeV. The ^{176}Yb targets consisted of two stacked foils, each ~ 0.5mg/cm^2 thick. The target thickness is chosen so that most recoil nuclei decay in flight, rather than slowing down in the target material, and so recoil nuclei have constant velocity in the sensitive volume of the spectrometer. The grazing angular momentum at this bombarding energy $\ell_{gr} \approx 48\ \hbar$. Reaction γ-rays were detected in the Ge detector array HERA, which included 20 Compton suppressed Ge detectors and a 40 element BGO inner ball for multiplicity and sum energy detection. Coincidence data were collected on magnetic tape for detailed analysis after the experimental run. Some 450 x 10^6 events were kept; coincidences between 2 or more Ge detectors defined an event. Event data were sorted with sum energy and multiplicity cuts into matrices after the experiment for analysis. For example, a 2-D matrix, E_γ vs. E_γ (symmetric in γ-ray energy) is useful for extracting coincidence relationships and level scheme construction. Figure 1 illustrates a partial level scheme, emphasizing an irregular band in ^{197}Pb. Multipolarities of the band transitions are established (generally) from directional correlation analysis (DCO), i.e., the γ-ray yields as forward angles compared to the yield at transverse detector angles. [18] The LLNL-LBL-Rutgers collaboration has emphasized the value of asymmetry measurements for multipolarity information. They measure the asymmetry ratio $A = Y_{\parallel}/Y_{\perp}$, where $Y(\Theta_i)$ is the coincident γ-ray yield in 2-fold coincidence with all the array detectors. $Y_{\parallel}$ is obtained with Θ_i = 37, 152, and 154^0, and $Y_{\perp}$ is obtained with Θ_i = 78 and 103^0. A comparison of calculated [19] and measured A suggests γ-ray multipolarity. The DCO ratio and the asymmetry A are illustrated in Fig. 2 for the ^{197}Pb bands. The asymmetry ratio is more sensitive and is determined with better accuracy than the DCO ratio, since more detectors are involved. The results are consistent with stretched dipole for direct transitions in the band, and stretched quadrupole for crossover transitions. Intensity balance arguments suggest that the dipole transitions are M1 transitions.

Partial level schemes have been built up for $^{194,196\text{-}201}$Pb, and ^{193}Hg using similar techniques, and *L = 1* bands with regular and irregular energy spacings have been found. The direct transitions of the band are M1 transitions with some crossover E2 transitions observed. The excitations are not known, because linking transitions connecting the bands with known low-lying states have not been observed, but $E_x \sim 4$ - 6 MeV for the bandhead. The bands are populated with an unusually large cross section, for example, the band in ^{193}Hg is populated with 20% of the cross section. Lifetimes are known in only 1 nucleus, ^{198}Pb [14], where Wang, et al., report that M1 rates are ~ 1 - 2 W.u. and E2 rates, with large errors, are 10 W.u.

III. DISCUSSION

The quantities measured for the *L = 1* bands suggest an interpretation involving proton excitation across the Z = 82 gap. The strong M1 transitions suggest that high K bands involving proton excitations are important elements of the nuclear structure, since g_K is large for protons and the M1 transition rate increases with K^2

$$B(M1) = \frac{3}{4\pi} K^2 (g_K - g_R)^2 \langle I\ K\ 10 | I-1, K\rangle^2$$

where g_K is the orbital g factor and $g_R = Z/A$. High K orbitals are present across the $Z = 82$ shell gap in oblate deformation, based on e.g., $h_{9/2}$, $i_{13/2}$, and $f_{7/2}$ orbitals. The high excitation energy is consistent with promotion of particles across the shell gap. The low dynamic moment of inertia, $J^{(2)}$, is consistent with oblate deformation. The decay of the $L = 1$ bands to the known yrast states has generally not been observed, suggesting that these new bands have a structure and shape different than the yrast states at lower excitation, which have been classified as quasineutron excitations. The spin of these states (I>20) suggests that neutron excitations are involved, presumably low-K $i_{13/2}$ neutron holes which align rapidly. The magnitude of bandhead spin can easily be attained through configurations such as $\pi(h_{11/2})^{-2} (i_{13/2} h_{9/2})^2$ or $\pi(d_{3/2})^{-2} (i_{13/2} h_{9/2})^{-2}$ coupled with $n(i_{13/2})^{-n}$.

More information about the nature of these bands can be gained by assuming the competing L = 1 and L = 2 transitions are M1 and E2, respectively, with multipole mixing $\delta = 0$, and studying the ratio R = B(M1)/B(E2), in units of $[\mu/(eb)]^2$. The ratio is illustrated in Fig. 3. The Pb isotopes with A>196 have values of R between 20 and 40 $[\mu/(eb)]^2$, while for the ^{194}Pb and ^{193}Hg bands the value of R ≈ 2-8 $[\mu/(eb)]^2$. Similar proton configurations have been suggested for these bands: assuming the M1 transition strength is roughly constant, the decrease in R can be attributed to increased B(E2) strength. The measured B(E2) strength in ^{198}Pb is ~10 W.u., consistent with some collectivity. The R values suggest more collectivity in ^{194}Pb, and collectivity ~10 x greater in ^{193}Hg than in the Pb isotopes with A>196.

The bands are strongly populated in the heavy-ion fusion-evaporation reactions, where the bands are usually the strongest spectroscopic features. The production of the band in ^{193}Hg, for example, is 20% of the ^{193}Hg cross section. The strength of the M1 intraband transitions suggests that detailed studies of the quasi-continuum γ-radiation produced in fusion-evaporation reaction needs to include M1 radiation from bands such as these. Finally, it is unlikely that the nuclear spectroscopy is complete, and therefore, conclusions drawn from experiments which rely on knowledge of the complete spectroscopy are suspect· calculation of K x-ray yields, for example.

IV. SUMMARY

Collective bands associated with the promotion of protons across the Z = 82 gap have been observed in ^{193}Hg, and in a number of Pb isotopes: A = 194, 196 - 201. The bands are characterized by strong L = 1 transitions, with observation in some cases of competing L = 2 crossover transitions The bandhead excitation energy and spin are not measured because, in general, γ-ray transitions linking the bands with levels at known excitation have not been observed. Bandhead spins are > typically 20 $\hbar$, and $E_x > 4$ MeV. The E2 transition strength in ^{198}Pb suggests weak collectivity in ^{198}Pb; the ratio B(M1)/B(E2) suggests that the collectivity has increased greatly in ^{194}Pb and ^{193}Hg. The suggested interpretation of the bandhead configurations suggests deformation aligned proton orbitals and rotation aligned neutron orbitals. These bands are, therefore, candidates for analysis in terms of the tilted axis cranking model [20]. More discussion focused on the heavier Pb isotopes has been given by Hubel [21], and discussion of similar bands in the A = 130 region has been given by Fosson [22].

ACKNOWLEDGMENTS

This work is supported in part by the U.S. Department of Energy under Contract No. W-7405-ENG-48 (LLNL), the SDIO/IST (LLNL), in part by the U.S. Department of

Energy under Contract No. DE-AC03-76SF00098 (LBL), and in part by the National Science Foundation (Rutgers).

FIGURE CAPTIONS

FIG. 1 Partial level scheme for the irregular $L = 1$ band in ^{197}Pb.

FIG. 2 Comparison of DCO ratio (a) for bands in ^{197}Pb with the asymmetry ratio $A(b)$ for the regular and irregular band members in ^{197}Pb. Horizontal lines indicate expected ratios stretched $\Delta I = 1$(o) and $\Delta I = 2$(•) transitions.

FIG. 3 The ratio B(M1; I $\rightarrow$ I - 1)/B(E2; I $\rightarrow$ I - 2) for the cascades $L = 1$ bands. This quantity is presented for certain bands in ^{193}Hg(o), ^{194}Pb(◊), ^{197}Pb(□), ^{198}Pb (∇), and ^{199}Pb (Δ). The abscissa is the increase in I measured from the bandhead spin. Certain abscissa values have been displaced for presentation clarity. Details and references are given in the text.

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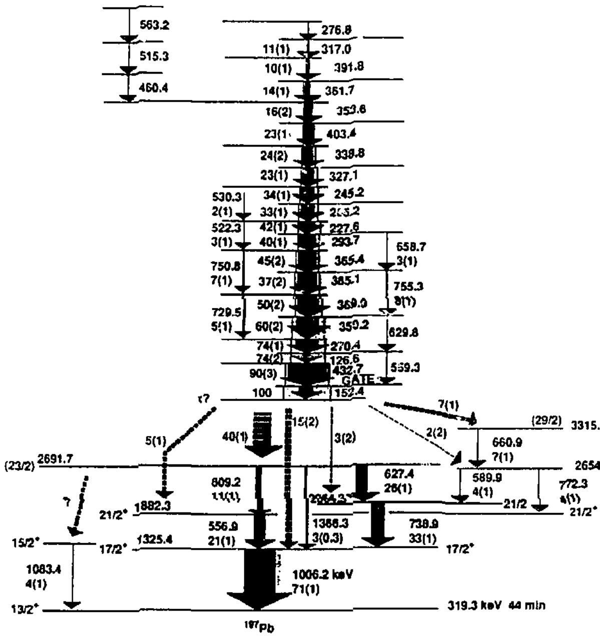

FIG. 1

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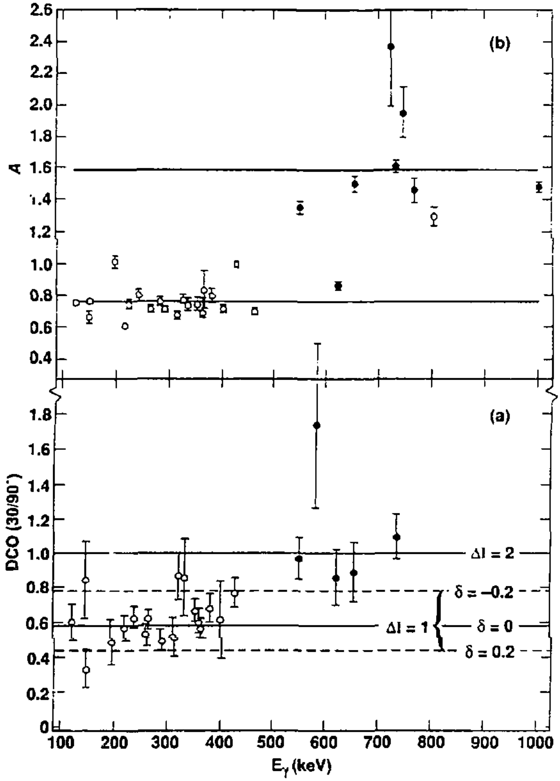

Composite 2

FIG. 2

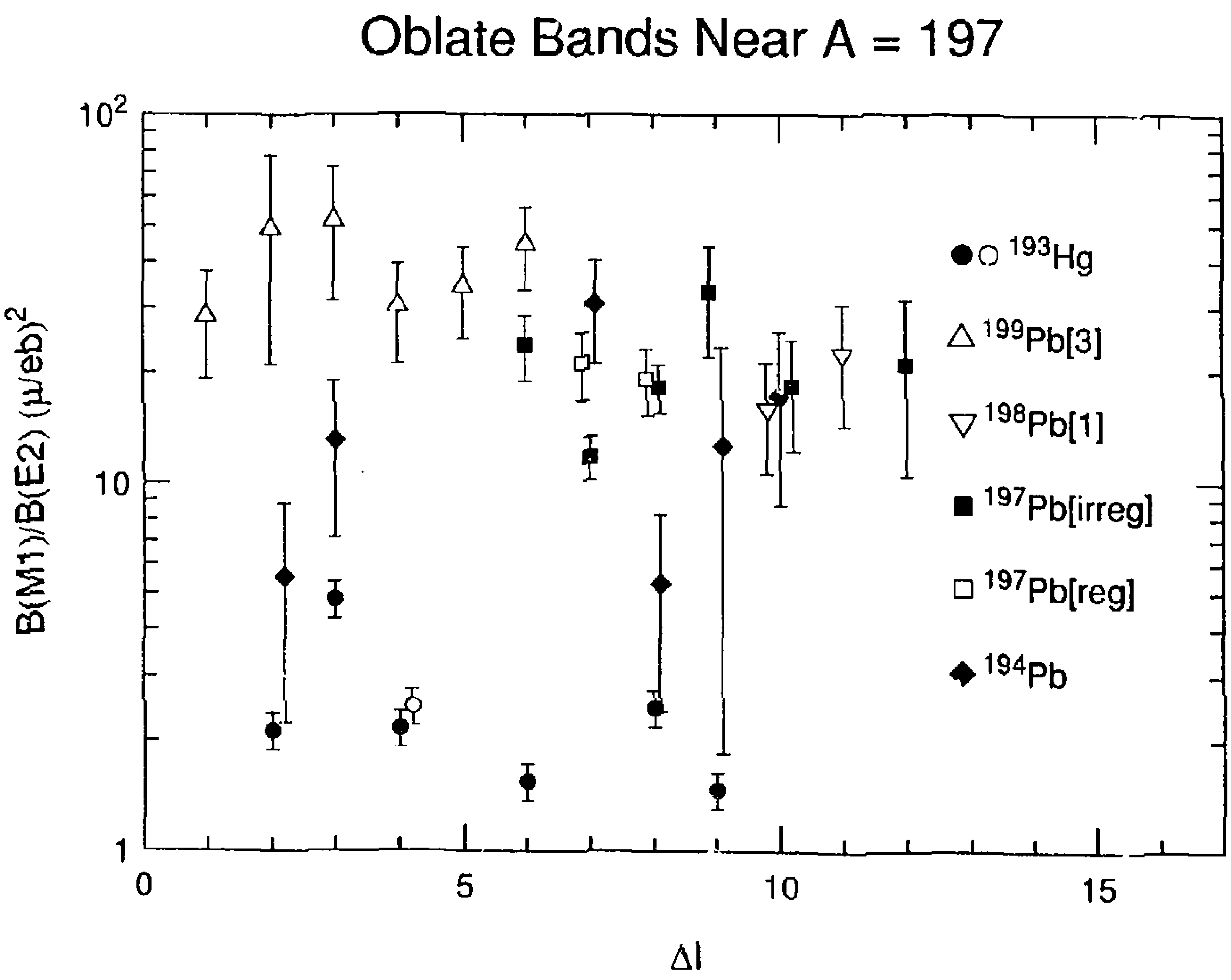
Oblate Bands Near A = 197
B(M1)/B(E2) (μ/eb)^2
10^2
10
1
0
5
10
15
ΔI
193Hg
199Pb[3]
198Pb[1]
197Pb[irreg]
197Pb[reg]
194Pb

FIG. 3