First Lifetime Measurement of Dipole Collective Bands in Neutron-Deficient Lead Nuclei

T. F. Wang, E. A. Henry, J. A. Becker, A. Kuhnert, M. A. Stoyer, and S. W. Yates[(a)]
Lawrence Livermore National Laboratory, Livermore, California 94550

M. J. Brinkman and J. A. Cizewski
Rutgers University, New Brunswick, New Jersey 08903

A. O. Macchiavelli,[(b)] F. S. Stephens, M. A. Deleplanque, R. M. Diamond, J. E. Draper,[(c)]
F. A. Azaiez,[(d)] W. H. Kelly,[(e)] W. Korten,[(f)] and E. Rubel[(c)]
Lawrence Berkeley Laboratory, Berkeley, California 94720

Y. A. Akovali
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830
(Received 5 March 1992)

Lifetimes of states in two $\Delta I=1$ bands in ^{198}Pb have been measured using the Doppler-shift attenuation method. The in-band reduced transition probabilities are $\sim$1–2 Weisskopf units, assuming magnetic dipole transitions. The measured lifetimes in conjunction with the partial level scheme support an oblate collective interpretation for these structures.

PACS numbers: 21.10.Tg, 21.10.Ft, 21.10.Re, 27.80.+w

Neutron-deficient Pb isotopes with a closed proton shell have long been good candidates for studies of excitations involving only a few active particles. In fact, low-lying structures in these isotopes can be described reasonably well in terms of two- and four-quasiparticle excitations [1]. One long-standing question is the possible onset of collective structures at high angular momentum in these isotopes. Collective states in the second minimum in the potential energy surface are known in ^{192,194,196,198}Pb, and they have been identified as prolate superdeformed bands [2–5]. Very recently, bandlike [6–10] $M1$ structures have been observed in ^{194,197,198,199,200}Pb and ^{193}Hg. These structures show similar properties [i.e., $B(M1)/B(E2)\sim 20(\mu_N/e\,\mathrm{b})^2$, little signature splitting, and small dynamic moments of inertia] to the $M1$ bands [11] in the mass-130 region. Three of these papers [7–9] argue that the $M1$ structures in Pb are collective oblate, although no lifetime information was given to confirm this. In this Letter, we report for the first time lifetime measurements on two such high-spin first-well bands in a neutron-deficient Pb isotope. The lifetimes and partial level scheme obtained in this measurement do point to the interpretation of these structures as collective oblate.

Experiments were carried out at the High Energy Resolution Array of the Lawrence Berkeley Laboratory 88-Inch Cyclotron. For the present measurements, 20 Compton-suppressed Ge detectors and a 40-element bismuth germanate central ball were used. The number(angle) of the Ge detectors with respect to the beam direction were the following: 4(37°), 2(51°), 4(79°), 2(103°), 4(123°), 2(152°), and 2(154°). Each detector was 15.5 cm from the target and subtended 82 msr. High-spin states in ^{198}Pb were populated via the reaction ^{154}Sm(^{48}Ca,4n) at $E(^{48}\mathrm{Ca})=205$ MeV. A thin self-supporting target and two backed targets were bombarded. The thin target was a stack of three $\sim$0.5-mg/cm^2-thick ^{154}Sm foils; the backed targets were $\sim$1-mg/cm^2-thick ^{154}Sm, evaporated onto $\sim$12-mg/cm^2 backings of Pb and Au. A total of $\sim 200\times 10^6$ doubly coincident events were collected for each target. The results from the thin-target measurement were used to identify new bands in ^{198}Pb and determine the feeding patterns of these bands. Backed-target results were used to establish the connection between the new levels and the known low-lying isomeric states [1] in ^{198}Pb, to suggest the possible location of previously unobserved isomeric states, and to determine lifetimes using the Doppler-shift-attenuation method (DSAM).

The partial level scheme of ^{198}Pb deduced from the present study is shown in Fig. 1. The transition ordering is based on coincidence relationships, intensity arguments using results from both backed-target and thin-target measurements, and information from a previous study [1]. Two collective [12] bands (labeled I, II) are observed. Band II has the same transition energies as reported in Ref. [8]. The excitation energies of both bands are uncertain. The minimal excitation energy of band II is $\sim$4.34 MeV if the (20^+) state is the band head. Transition multipolarities were determined using the directional correlation method [13]. The results indicate stretched-dipole character for the strong transitions in these two bands, with little or no quadrupole mixing (see below). Assuming $M1$ character for the $\Delta I=1$ transitions, possible spin-parity assignments using these multipolarities and the information from the previous study [1] are also displayed in Fig. 1. For example, the 15^- state, which decays to a 14^+ state via the 630-keV transition, was determined in the previous study [1]. If we assume that $(2\pm 2)\hbar$ are carried by the unobserved transition(s), the state between the 322- and the 764-keV

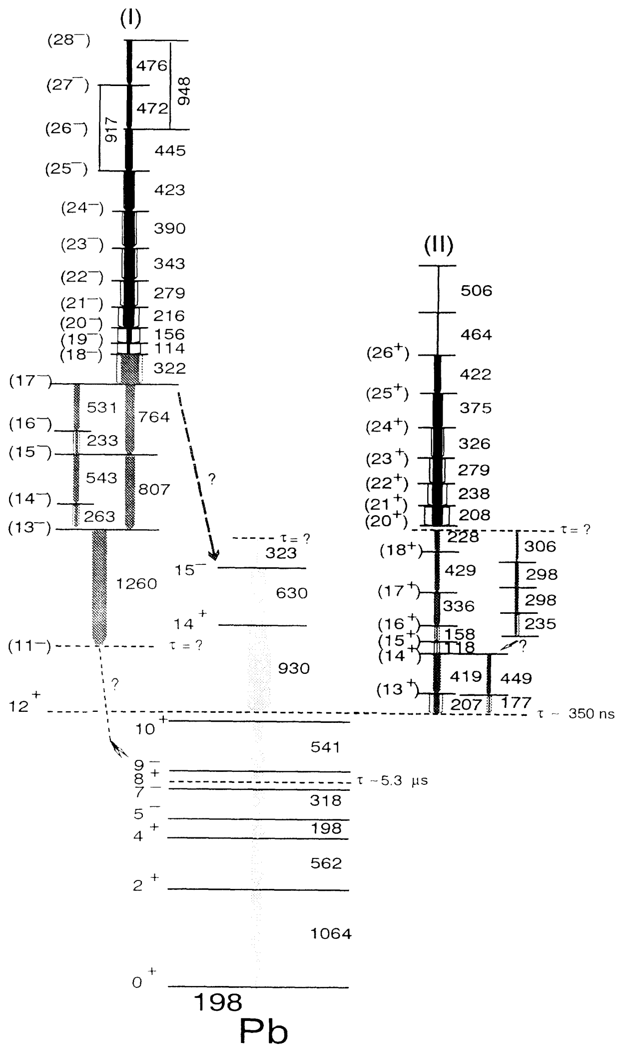

FIG. 1. Partial level scheme of ^{198}Pb. Previously observed states [1] are shaded in light gray, newly established low-lying states are in dark gray, and the proposed collective structures are in black. Dashed lines represent suggested locations of the isomeric states. Intensities of new transitions above the 12^+ ($\tau \sim 350$ ns) isomer are based on γ-ray intensities observed in the thin-target measurement. Outer width of the arrow of the $M1$ transitions represents the transition intensity corrected for internal conversion (assuming they are pure $M1$ transitions). Transition intensities below the 10^+ state cannot be determined from the present study. Isomers with $I^\pi = 11^-$ and $E_x \sim 3.5$ MeV are known in light Pb nuclei. Possibly the 1260-keV transition terminates in such an isomer at $E_x \sim 3.5$ MeV. The identification of the 322-323-keV doublet is based on a channel-by-channel projection of the 2D coincidence matrix, and verified by coincidence gates on other band members. Spin assignments are no better than $\pm 2\hbar$.

transitions could have a spin of 17(2). It is possible that the state populated by the 1260-keV quadrupole transition corresponds to the 11^- isomer known in several other even-even Pb isotopes [14], and so this would suggest a negative parity for band I. Two crossover transitions were observed in band I. The branching ratios obtained from the intensity ratio, $I(L=2)/I(L=1)$, are 0.27(9) for the 917-472-keV pair and 0.22(8) for the 948-476-keV pair. From these ratios and the assumption of a rotational $B(E2)$, absolute values of the mixing amplitude ratio, $|\delta|$, for the two predominately $M1$ transitions are 0.099 and 0.084, respectively. For band II, no crossover transitions were observed, with upper limits of the branching ratios ~ 0.1.

The lifetime analysis was made with coincidence data from the Au- and Pb-backed targets sorted into (a) forward, (b) "90°," and (c) backward matrices. These matrices require a coincidence between (a) a 37° detector with any detector, (b) either a 79° or a 103° detector with any detector, and (c) either a 152° or a 154° detector with any detector. Doppler-shifted line shapes were observed for transitions in both bands for transition energies between ~ 300 and ~ 500 keV. Lifetimes were extracted from these line shapes using the Monte Carlo code DSAMFT_OR [15]. The nuclear and electronic stopping powers were calculated according to the compilation by Ziegler *et al.* [16]. The detailed slowing down history of ^{198}Pb recoils in both Pb and Au backings was simulated (5000 histories with a time step of 0.002 ps), and then sorted according to the geometry of the detectors in each group. The calculated line shapes were obtained taking into account: (1) detector efficiency, (2) the observed transition energies of the band, (3) the sidefeeding intensity for each state in the band (each sidefeeding cascade was modeled with five transitions, a moment of inertia similar to the main band, and independent reduced transition probability [17]), and (4) precursor rotational transitions in the main band. Simultaneous fits to the forward, backward, and "90°" spectra were made. Fits to the "90°" spectra are important for identifying possible contaminant lines in the spectra. Stopped peaks within the fitting region are included in the fit. Examples of the fits at both forward and backward angles are presented in Fig. 2, together with the experimental data. Best fits are obtained with lifetimes of the sidefeedings ranging from 0.4 to 1.4 ps for band I and 0.2 to 0.8 ps for band II. The sidefeeding lifetimes appear to be slower than the transition lifetimes. Lifetimes for bands I and II, summarized in Table I for both Au- and Pb-backed targets, are mutually consistent. Quoted errors include statistical errors, errors from data manipulation (e.g., background subtraction, etc.), and errors from the uncertainty of the sidefeeding intensities and lifetimes. However, systematic errors in the treatment of the slowing-down process, which could be as large as 20%, have been omitted. Reduced transition strengths, $B(\mathcal{ML})$, assuming multipole mixing amplitude $|\delta| = 0$, are also listed.

The relatively large (~ 1–2 W.u.) $B(M1)$ strength among band members suggests that these are high-K bands. The dynamic moment of inertia of both bands ($\mathcal{J}^{(2)} \sim 25\hbar^2$ MeV^{-1}) is about $\frac{1}{3}$ the kinematic moment of inertia, suggesting a large amount of aligned angular

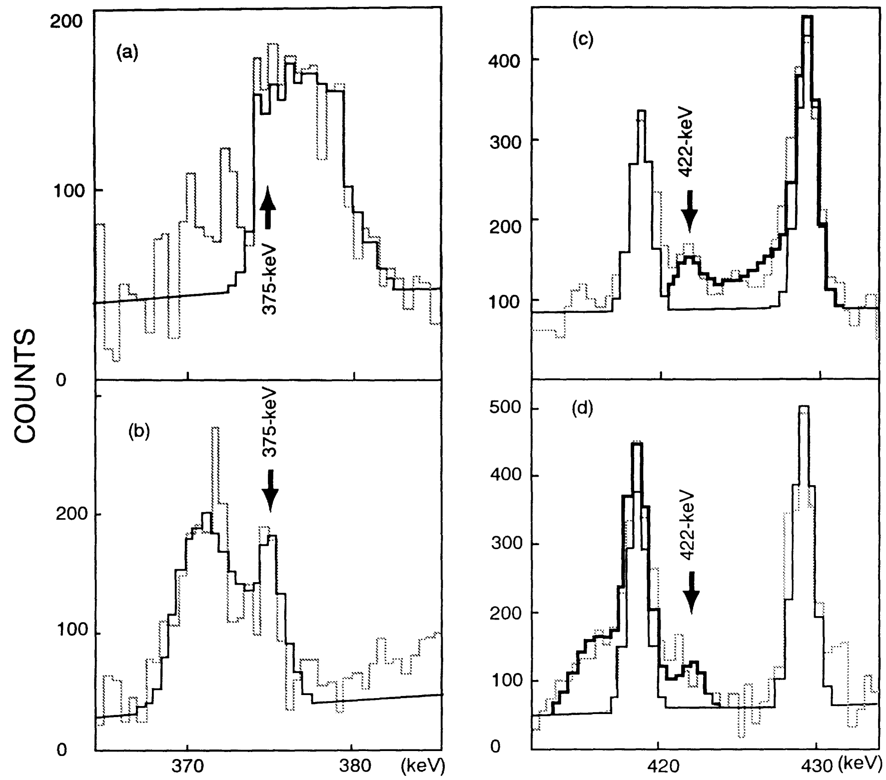

FIG. 2. DSAM fits to selected transitions in band II with the Pb-backed target. Data are shown in gray, and fits in black. Results from the fit to the (a) forward, (b) backward spectrum of the 375-keV transition (stopped position shown by arrow). Examples of fitting a spectral window including additional stopped peaks at 419 and 429 keV: (c) forward, (d) backward spectrum. A fit to these additional peaks is displayed by the thin black line, while the total fit [sum of the 429-keV (forward) or 419-keV (backward) stopped peaks and the shape of the 422-keV transition] is shown by the thick black line.

momentum. This aligned angular momentum is estimated to be $\sim 14(3)\hbar$ from a plot of I vs $\hbar\omega$, and it is presumably from the alignment of $i_{13/2}$ neutrons. For example, Bengtsson and Nazarewicz [18] predict the existence of oblate collective structures built on the $\pi(h_{9/2} \otimes i_{13/2})_{11^-} \otimes \nu(i_{13/2})^{-2}$ configuration in these isotopes. Such a configuration will

TABLE I. Results from the DSAM fits to bands I and II, with data sets from both Pb- and Au-backed targets. τ is the lifetime of the members of the band. (W.u. stands for Weisskopf unit.)

	Pb backing			Au backing		
E_γ (keV)	τ (ps)	$B(M1)$ (W.u.)	$B(E2)$ (W.u.)	τ (ps)	$B(M1)$ (W.u.)	$B(E2)$ (W.u.)
			Band I			
343	1.12(39)	$0.53^{+0.29}_{-0.14}$		1.15(24)	$0.52^{+0.14}_{-0.09}$	
390	0.64(15)	$0.67^{+0.20}_{-0.12}$		0.79(14)	$0.55^{+0.12}_{-0.08}$	
423	0.41(16)	$0.85^{+0.54}_{-0.24}$		0.50(11)	$0.70^{+0.20}_{-0.13}$	
445	0.19(7)	$1.6^{+0.9}_{-0.4}$		0.29(4)	$1.1^{+0.2}_{-0.1}$	
472	0.29(10)	$0.72^{+0.65}_{-0.23}$		0.15(5)	$1.3^{+1.0}_{-0.4}$	
917			$11.3^{+10.3}_{-3.6}$			$20.6^{+15.9}_{-6.3}$
476	0.31(11)	$0.67^{+0.54}_{-0.21}$		0.23(7)	$0.9^{+0.7}_{-0.3}$	
948			$9.7^{+7.9}_{-3.1}$			$13.3^{+10.2}_{-4.4}$
			Band II			
326	0.60(19)	$1.1^{+0.5}_{-0.3}$		0.55(22)	$1.2^{+0.8}_{-0.4}$	
375	0.31(9)	$1.6^{+0.6}_{-0.4}$		0.40(17)	$1.2^{+0.8}_{-0.3}$	
422	0.18(5)	$2.0^{+0.8}_{-0.4}$		0.22(7)	$1.6^{+0.7}_{-0.4}$	
464	0.068(18)	$4.0^{+1.5}_{-0.9}$		0.129(47)	$2.1^{+1.2}_{-0.6}$	
506	0.050(14)	$4.4^{+1.7}_{-1.0}$		0.054(17)	$4.0^{+2.0}_{-1.0}$	

provide the large-K value and the large $B(M1)$ strength. A standard cranked-shell model calculation [19] predicts that the first $\nu i_{13/2}$ alignment occurs at a frequency $\hbar\omega \approx 0.2$ MeV (i.e., a transition energy of 200 keV for dipole transitions). For $K > \frac{1}{2}$ bands, the $M1$ transition rate can be estimated [20] from the relation $B(M1) = (3/4\pi)(K)^2(g_k - g_R)^2 \langle IK10|I-1,K\rangle^2$, where g_R is the collective g factor ($\sim Z/A$). Using [14] $g_K = 0.96$ for the $\pi(h_{9/2} \otimes i_{13/2})_{11^-}$ configuration, the reduced $M1$ transition probability calculated for $I = 26$ is ~ 1.8 W.u., in qualitative agreement with the observed electromagnetic properties of these two bands. An estimate of the lifetime including the contribution of $i_{13/2}$ neutrons can be made using the formula of Dönau and Frauendorf [21]. Assuming two $i_{13/2}$ neutrons with $i = 12$, $g_\nu = -0.2$, $B(M1)$ ~ 4.0 W.u. at $I = 26$. From the measured lifetimes and the branching ratios of the two observed $E2$ transitions, we can calculate the quadrupole moment, Q_0, where $Q_0 = 0.907/[(\tau_{E2} E_\gamma^5)^{1/2} \times \langle IK20|I-2,K\rangle]$, and τ_{E2} is the corresponding $E2$ lifetime. For large I, Q is not very sensitive to K. Assuming $K = 11$, $|Q_0| \sim 2\, e$b for band I. We estimate $|Q_0| \leq 3\, e$b for band II. From the relationship [20] between Q_0 and β_2, the deformation consistent with the properties of these two bands is $|\beta_2| \sim 0.1$. This value is in reasonable agreement with the predicted [18] oblate minimum of $\beta_2 \sim -0.15$.

In summary, we have established a partial level scheme and measured the lifetimes of levels in two new rotation-like bands in ^{198}Pb at relatively high spin and excitation energy. The properties of these bands suggest that they are built on high-K two-proton states with oblate deformation. It is also likely their configurations involve two or more $i_{13/2}$ neutrons to give both observed spin and alignment. Detailed neutron configurations of these structures are beyond the scope of this experimental investigation; further theoretical studies would be of much interest.

We thank Dr. J. C. Wells for the computer routines used in the DSAM analysis. One of us (T.F.W.) would like to thank R. R. Chasman and R. V. F. Janssens for helpful discussions. We thank the LBL 88-Inch Cyclotron crew for flawless operation. This work is supported in part by the Department of Energy, under Contracts No. W-7405-ENG-48 (LLNL), No. DE-AC03-76SF00098 (LBL), No. DE-AC05-84OR21400(ORNL), and by the National Science Foundation (Rutgers).

[a] Permanent address: University of Kentucky, Lexington, KY 40506.

[b] Permanent address: Comision Nacional de Energia Atomica, Buenos Aires, Argentina.

[c] Permanent address: University of California, Davis, CA 95616.

[d] Permanent address: Institut de Physique Nucléaire Orsay, F-91406, Orsay, France.

[e] Permanent address: Iowa State University, Ames, IA 50011.

[f] Present address: Niels Bohr Institute, Copenhagen, Denmark.

[1] K. Honkanen *et al.*, Nucl. Phys. **A451**, 141 (1986).

[2] E. A. Henry *et al.*, Z. Phys. A **338**, 469 (1991).

[3] M. J. Brinkman *et al.*, Z. Phys. A **336**, 115 (1990).

[4] K. Theine *et al.*, Z. Phys. A **336**, 113 (1990).

[5] T. F. Wang *et al.*, Phys. Rev. C **43**, R2465 (1991).

[6] B. Fant *et al.*, J. Phys. G **17**, 319 (1991), report $M1$ bands in ^{194}Pb. For an updated level scheme please refer to M. J. Brinkman, dissertation, Rutgers University, New Brunswick, NJ, 1991 (unpublished).

[7] A. Kuhnert *et al.*, Phys. Rev. C **46**, 133 (1992).

[8] R. M. Clark *et al.*, Phys. Lett. B **275**, 247 (1992).

[9] G. Baldsiefen *et al.*, Phys. Lett. B **275**, 252 (1992).

[10] N. Roy *et al.* (unpublished).

[11] D. Fossan *et al.*, Nucl. Phys. **A520**, 241c (1990).

[12] A preliminary report of this work has been given by T. F. Wang *et al.*, Bull. Am. Phys. Soc. **36**, 1388 (1991).

[13] F. S. Stephens *et al.*, Phys. Rev. Lett. **54**, 2584 (1985).

[14] J. Penninga *et al.*, Nucl. Phys. **A471**, 535 (1987), and references therein.

[15] DSAMFT_OR, a program which fits lifetimes to peak shapes from the original code by J. C. Bacelar, modified by J. Gascon and by J. C. Wells, 1991, and J. C. Wells (private communication).

[16] J. F. Ziegler *et al.*, *The Stopping and Range of Ions in Solids Vol. I* (Pergamon, New York, 1985).

[17] See, for example, H. Emling *et al.*, Nucl. Phys. **A419**, 187 (1984).

[18] R. Bengtsson and W. Nazarewicz, Z. Phys. A **334**, 269 (1989).

[19] See, for example, T. Bengtsson *et al.*, in *Computational Nuclear Physics Vol. I*, edited by K. Langanke *et al.* (Springer-Verlag, New York, 1991).

[20] A. Bohr and B. R. Mottelson, *Nuclear Structure Vol. II* (Benjamin, Reading, MA, 1975).

[21] F. Dönau and S. Frauendorf, in *Proceedings of the International Conference on High Angular Momentum Properties of Nuclei, Oak Ridge* (1983), p. 143.

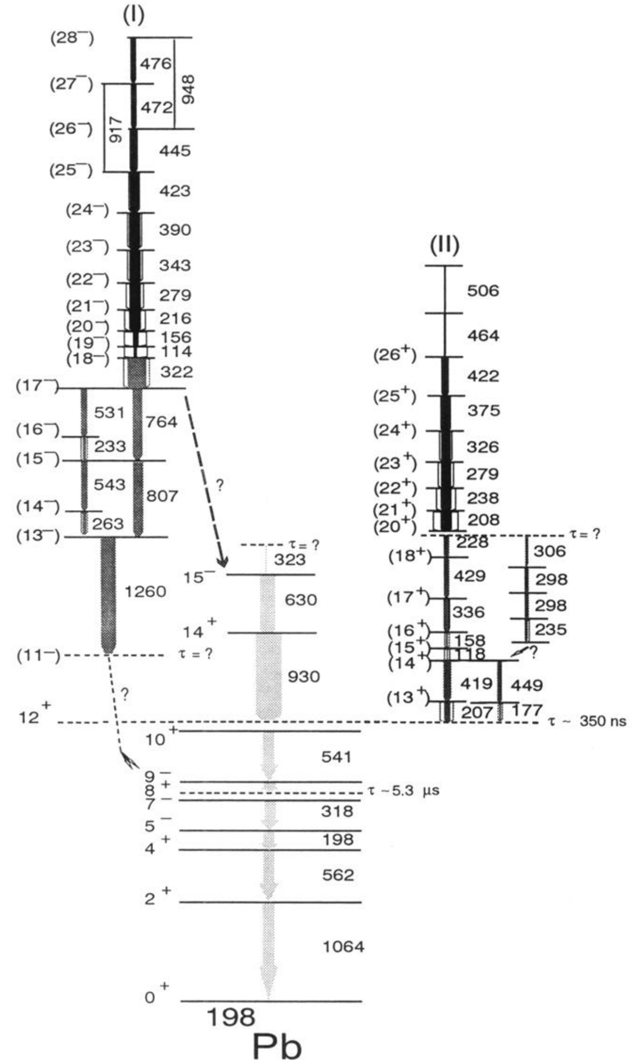

FIG. 1. Partial level scheme of ^{198}Pb. Previously observed states [1] are shaded in light gray, newly established low-lying states are in dark gray, and the proposed collective structures are in black. Dashed lines represent suggested locations of the isomeric states. Intensities of new transitions above the 12^+ ($\tau \sim 350$ ns) isomer are based on γ-ray intensities observed in the thin-target measurement. Outer width of the arrow of the $M1$ transitions represents the transition intensity corrected for internal conversion (assuming they are pure $M1$ transitions). Transition intensities below the 10^+ state cannot be determined from the present study. Isomers with $I^\pi = 11^-$ and $E_x \sim 3.5$ MeV are known in light Pb nuclei. Possibly the 1260-keV transition terminates in such an isomer at $E_x \sim 3.5$ MeV. The identification of the 322-323-keV doublet is based on a channel-by-channel projection of the 2D coincidence matrix, and verified by coincidence gates on other band members. Spin assignments are no better than $\pm 2\hbar$.