Search for hyperdeformation in ^{168}Yb

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The nucleus ^{168}Yb, and its near neighbors, have been studied at the very highest angular momenta using the full Gammasphere array. The experiment was performed in order to search for evidence for the existence of hyperdeformed states, which have predicted nuclear axis ratios of ≈3:1. After exhaustive searching for both discrete and continuum γ rays associated with a hyperdeformed shape, using a wide variety of different analysis techniques, no evidence for the existence of hyperdeformation has been found. This search of unprecedented sensitivity has been carried out with the full Gammasphere, and was performed on arguably the best candidate nucleus. A maximum achievable observational limit of ≈0.02% of the ^{168}Yb channel has been calculated for this particular experiment, using Monte Carlo simulations of the response of Gammasphere. [S0556-2813(97)02410-2]

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INTRODUCTION

The exciting possibility of discovering extremely deformed nuclear shapes with ≈3:1 axis ratios has enthused experimentalists for a number of years. Evidence of hyperdeformation would represent one of the best possible tests of nuclear models at extremes of angular momentum and deformation, and hence experimental searches for states of such an exotic nature are of great importance. The opportunity to undertake searches of unprecedented sensitivity now exists, due to the final completion of the latest generation of γ ray spectrometers, Gammasphere and Euroball.

In this work we report on the results of a search for evidence of hyperdeformation with the full Gammasphere array, the best experimental apparatus available to date. The candidate chosen for study was ^{168}Yb, which is arguably the best possible candidate for observing evidence for the existence of hyperdeformed states.

The first reported experimental data interpreted as evidence for a hyperdeformed nuclear shape was the observation by Galindo-Uribarri *et al.* [1], of a peak at $\Delta E \approx 30$ keV, generated by summing counts near the diagonal of a proton-gated γ-γ coincidence matrix. This existence of this peak was attributed to a ridge structure, and was interpreted as evidence for hyperdeformation, most likely from the ^{153}Dy nucleus. Subsequently, peaks attributed to ridges of $\Delta E_\gamma \approx 30$ keV were confirmed by Lunardon *et al.* [2], in a higher statistics experiment using the same reaction. The results were again interpreted as corresponding to the decay of a hyperdeformed band.

The first discrete-line evidence of hyperdeformation was presented by LaFosse *et al.* [3], where two background subtracted spectra were published. These spectra consisted of sequences of up to 11 peaks with varying spacing between 26 and 33 keV and peak heights between 10 and 30 counts. The spectra were interpreted as corresponding to a spheroid with a major-to-minor axis ratio of about 3:1, and were identified as belonging to the ^{147}Gd nucleus. This result spawned further articles [4,5]. However, a subsequent paper by LaFosse *et al.* [6] was published which changed the interpretation of the sequences. The previous emphasis on the hyperdeformed nature of the sequences was dropped, in favor of a description stressing their unknown origin, due to the lack of increase in peak statistics when two later experiments were performed with almost twice the number of Ge detectors and larger amounts of beam time.

As yet, no firm evidence for the existence of hyperdeformation at high-spin has been discovered in any nucleus, although, evidence for hyperdeformed minima exists at low spin exists in the actinide region [7]. The best way to produce convincing evidence of hyperdeformed states would be to observe a cascade of discrete, mutually coincident, statistically significant, transitions. Since rotation of a hyperdeformed nucleus would be a highly collective phenomenon, the discrete transitions are also expected to be regularly spaced.

Over the past few years, a number of theoretical papers have made predictions of which nuclei are good candidates for observing hyperdeformation. Dudek, Werner, and Riedinger [8] first predicted that deep hyperdeformed minima ($\beta_2 \approx 1.0$) would occur at high spin in nuclei such as ^{166}Er, ^{168}Yb, and ^{170}Hf. Later calculations by Chasman [9], using the cranked Woods-Saxon Strutinsky approach also predicted deep, highly deformed minima in this region of the nuclear chart which become yrast at spins of $70-80\hbar$. Subsequently, calculations by Werner and Dudek [10] confirmed the presence of deep minima for these nuclei at axis ratios close to 3:1.

CHOICE OF CANDIDATE

One of the primary considerations in choosing a candidate for study is the ability of the compound nucleus to survive fission. The rotating liquid drop calculations of Sierk [11]

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show that for neutron-rich isotopes of $Z \approx 70$, the maximum amount of angular momentum that can be sustained before fission is $80-85\hbar$. The fissility parameter of Z^2/A is smallest for neutron rich nuclei. Although hyperdeformed minima are predicted to exist in nuclei in the mass $A \approx 150$ region (e.g., ^{146}Gd [12]), it may well be impossible to populate these states as the minima are predicted to become yrast at spins where the calculated fission barriers vanish [11]. Furthermore, calculations by Chasman [13] predict that hyperdeformed minima in nuclei such as ^{152,153}Dy, which might explain the observed ridge structure, do not exist. For these nuclei, only the well-studied, deep superdeformed minima are present up to the very highest spins. We therefore concluded that a search for hyperdeformation would be most likely to succeed in the $A \approx 170$ region.

In this work we have chosen to study the nucleus ^{168}Yb and its neighbors, since they appear to constitute the best candidate nuclei, due to (a) the presence of minima in potential energy surfaces at axis ratios of 3:1, predicted by cranked Woods-Saxon Strutinsky calculations (which become yrast in ^{168}Yb at $72\hbar$ by Chasman [9], and $76\hbar$ by Dudek and Werner *et al.*) and (b) the ability of these nuclei to survive fission at very high angular momenta. The only feasible high-spin, fusion-evaporation reaction available to study ^{168}Yb uses beams and targets of the highly neutron-rich ^{48}Ca and ^{124}Sn isotopes respectively. This reaction has been studied before using the Eurogam I spectrometer [14] with 45 HPGe detectors, at a beam energy of 210 MeV, and yielded no concrete evidence for hyperdeformation.

EXPERIMENTAL DETAILS

Very high-spin states in ^{168}Yb and its neighbors were populated via the ^{124}Sn(^{48}Ca,xn)$\,^{172-x}$Yb reaction at 215 MeV. This provided a maximum angular momentum of $\ell_{max} \approx 87\hbar$, and excitation energy of 82 MeV in the compound system, according to calculations using the code evapOR [15]. A beam of ^{48}Ca, accelerated by the 88-in cyclotron at the Lawrence Berkeley Laboratory, was incident on a self-supporting target consisting of two stacked foils of ^{124}Sn of thickness 400 μg cm^{-1}. γ rays were detected with the full implementation of the Gammasphere array, consisting at the time of 92 high-efficiency Compton-suppressed Ge detectors. Primary Compton suppression was performed by anticoincidences with the individual seven-element BGO shield for each Ge detector, and secondary Compton suppression was performed by anticoincidences with the six neighboring BGO elements from surrounding Ge detectors, providing that the neighboring Ge detector did not fire. This secondary mode of Compton suppression is known as honeycomb suppression, and results in a further 5% improvement in the peak-to-total ratio for the array.

During 96 h of beam-time, 2.06×10^9 events, with a Compton suppressed Germanium fold $\geqslant 5$, were collected on magnetic tape. After placing off-line gates on the Germanium timing signals to reduce pile-up and detection of random neutrons, the number of events remaining was 1.85×10^9, with a suppressed fold $\geqslant 3$. These events were then compressed into a compact form, in which timing and angular information was removed, leaving only the suppressed Ge fold, the total unsuppressed gamma fold (including both unsuppressed Ge and BGO-only hits) and the Doppler-corrected Ge energies to be written onto a second set of data tapes. The mean fold of the remaining events was particularly high, at 5.23, and the maximum of the unsuppressed fold (K) distribution was also high at 18.2, indicating a large average multiplicity for cascades in the reaction. As the purpose of the experiment was a search for hyperdeformation it was assumed that any γ rays of this type would be emitted with extremely short lifetimes; hence the Doppler correction applied was the fully shifted amount (v/c of 0.027 calculated at midtarget from the kinematics of the reaction).

TABLE I. Observed yields for the ^{124}Sn(^{48}Ca,$xnyp$) reaction at 215 MeV.

Residue	Channel	Yield
^{169}Yb	$3n$	$<$ 0.5%
^{168}Yb	$4n$	21%
^{167}Yb	$5n$	38%
^{166}Yb	$6n$	35%
^{165}Yb	$7n$	5%
^{167}Tm	$p4n$	<0.5%
^{164}Er	$\alpha 4n$	<0.5%
^{163}Er	$\alpha 5n$	<0.5%

The yields of the various residual nuclei observed in this experiment are estimated in Table I. It is difficult to estimate accurately the yields of the charged particle channels due to their very weak intensity. The only way to measure these intensities was by producing triple gated spectra of the yrast bands in these nuclei, and comparing their intensity with those of the stronger channels (see Fig. 1 for an example of a gated spectrum from the ^{168}Yb channel). It is not known what fraction of the intensity flux in the weak channels decays down the yrast bands, so these limits are rough estimates.

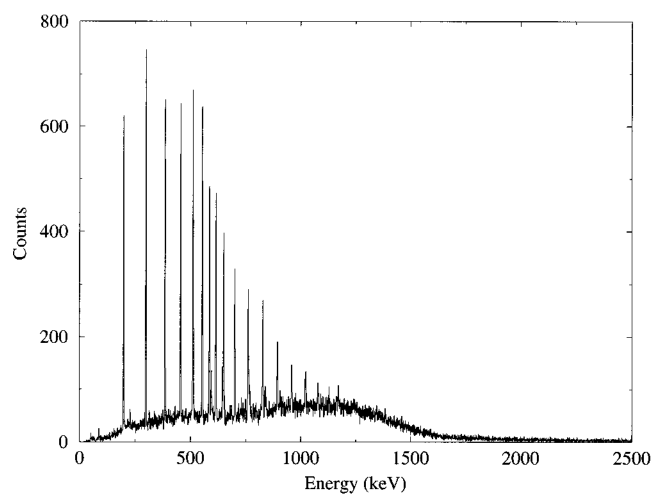

FIG. 1. Sextuply gated spectrum of 20 transitions from the yrast band of ^{168}Yb. This spectrum has deliberately not been background subtracted, in order to show the very large continuum present from (a) Compton scattered γ rays and (b) nonyrast continuum of cascades in coincidence with the yrast band. Approximately 80% of the area of this spectrum is background, which implies that the average number of transitions in cascades must be very large.

ANALYSIS METHODS

Analysis of the data was performed with many different methods. We felt that in the search for evidence of hyperdeformation it was important that analysis did not rely on one method alone. In the search for potential hyperdeformed bands where the average transition number might be very low (<6 transitions), a ridge analysis was performed, involving the use of special γ-γ matrices which will be described shortly. For short bands (6–12 transitions) γ-γ-γ cubes were created using full unpacking of higher-fold events, and for longer bands (10–25 transitions), $4n$-channel-gated and ungated multifold databases were created. Lastly, in order to search not only the strongly populated reaction channels of ^{168}Yb and ^{167}Yb, but also the weaker channels, gated matrices were produced. Triple γ ray gating was employed on the strongest 10 transitions in the yrast sequences of the ^{167}Tm and ^{169}Yb nuclei, and matrices where created by incrementing remaining pairs of γ rays from the events passing the gating condition, thus requiring events to have a fold of at least 5. This was done in an attempt to enhance the proportion of matrix counts from these two nuclei. These matrices were later searched using the genetic algorithm search procedure EVOLVE [16].

The ridge analysis was undertaken by a special method of incrementation to produce γ-γ matrices. When unpacking events into triple coincidences E_1,E_2,E_3, the energies were ordered, and two values for energy differences calculated $\Delta E_1 = E_3 - E_2, \Delta E_2 = E_2 - E_1$. We required that the two differences be the same value to within one full width at half maximum (FWHM) before incrementation of the matrix was performed at the mean spacing value of $(\Delta E_1 + \Delta E_2)/2$ on the y axis, and channel E_1 on the x axis. Gating on the x axis produces a spectrum of average ΔE for triple coincidences with two very similar ΔE values. Any peaks present in this type of spectrum may be attributed to either (a) three discrete transitions in coincidence, with energies E, $E+\Delta E$, and $E+2\Delta E$ or (b) continuum ridge structures. Gating at places on the x axis where there are no photopeaks in the projection increases the probability of only observing counts from ridge structures. This method is preferable to performing the same analysis on a standard γ-γ coincidence matrix, since the problem of misidentifying a peak in the summed spectrum as originating from a continuum ridge is exacerbated by the much greater density of discrete coincidences present. A similar analysis of quadruple coincidences, requiring that three consecutive energy differences in the event be approximately the same value to within one FWHM, was also performed. This type of analysis was very similar to that performed in the hyperdeformed search of Ref. [14].

In order to undertake a grid search for discrete bands, using gating conditions of arbitrary fold, two multifold databases were created, the first without a gating condition, the second singly gated on all lines of the $4n$ channel which had a peak-to-background ratio of greater than 1, namely, the 198, 299, 385, 455 keV transitions. In order to fit the databases on a 9 Gb disk, the energy range was truncated and only events with four or more γ rays between the energies of 600 and 1600 keV were stored. This reduced the storage space to 5.5 Gb for the full database and 1.0 Gb for the $4n$-channel-gated database, with average folds in the region of interest of 4.51 and 3.75, respectively and events taking $\approx$10 bytes each to store. The total numbers of events stored on disk were 500 million, and 109 million for the full and $4n$-channel-gated databases, respectively. The fraction of $4n$ events in the $4n$-channel-gated database was increased by the single gating from 21 to 81%; however, this was achieved at the expense of a loss in statistics of a factor of 5, and a loss in average fold of 0.76.

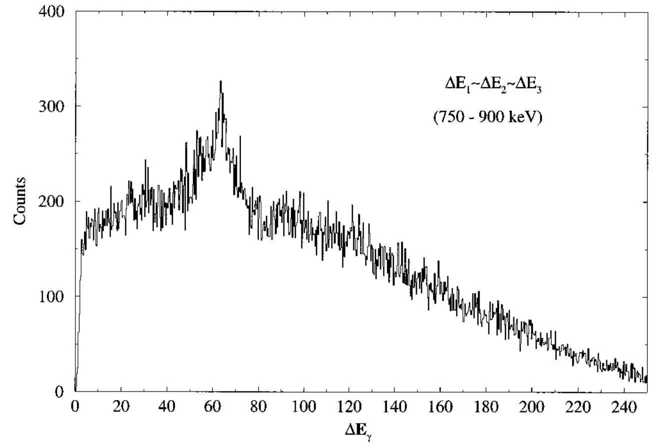

FIG. 2. Spectrum of ΔE, where three similar consecutive energy differences were detected in an unfolded quadruple coincidence. Energy differences are plotted for a cut over a range of γ ray energies between 750 and 900 keV, in places where no photopeaks were observed to be present in the projection.

Any desired sum-of-gates spectrum could be retrieved from the database in a few minutes, the retrieval time being independent of the number of gates to be summed, or the gating fold. The spike-free method of Beausang *et al.* [17] was used to increment spectra. In order to search the data, a grid-search program of the ANDband [18] type was developed, where search speeds up to 10 times faster than ANDband were achieved. These high search speeds were made possible by paying close attention to the incrementation procedure, keeping the number of low-level 32-bit word operations needed per event to an absolute minimum. Approximately 10 000 gated spectra in fold X could be created simultaneously, along with 10 000 background spectra in fold $X-1$. A single search procedure of the full database, for any set of triply gated candidates, took approximately 3 days of CPU time on a Sun SPARC Ultra 1 computer. Many such searches of both databases were performed using varying sets of search parameters for the 10 000 candidates. Parameters varied were (a) band length (10–25 transitions), (b) spacing (22–45 keV), (c) change in spacing per transition (-0.4–$+0.4$ keV), (d) the gating condition (two, three, four, and five gates), (e) gates on the unsuppressed fold distribution ($K>0$–$K>20$), and (f) gate width [1–2 full widths at half maximum (FWHM)] optimum values calculated using methods outlined in [19].

RESULTS

Searching through all the matrices, cubes and databases that were created took many weeks to complete. None of these searches produced any evidence for hyperdeformation.

A typical ridge spectrum is shown in Fig. 2. The broad peak centered at 63 keV corresponds to the decays from a large continuum of nonyrast, normally deformed rotational bands, with spacings in this region between 55 and 70 keV. No evidence exists for any ridges at lower spacings than this in numerous cuts performed at various places over the whole energy range of (600–1600 keV).

As the number of candidates in the search for discrete bands in the databases and cubes was extremely large (>10 000 per search), choosing those candidates with the highest figures of merit will ensure candidate spectra with many more counts than the average at the positions where the gates were set, even if no signal is present. The more candidates in the search, the greater the likelihood that the best spectra will have significant numbers of counts at the peak positions. If we assume that the data set is purely statistical noise, then taking 10 000 independent samples from it will provide, on average, a candidate with a statistical significance of 3.9σ (analogous to picking 10 000 random values from a Gaussian distribution). If the background-subtracted spectrum of this candidate is then transformed, by contracting the number of channels, smoothing, plotting only the portion of it within a certain energy and counts range, the result can look convincing, especially if convenient energy labels are positioned above the places in the spectrum with an excess of counts (see Fig. 3 for an example of a typical candidate with a high figure of merit). This type of spectrum is very easy to create and is not that of a hyperdeformed band. It is comprised of nothing more than peaklike statistical fluctuations. It was possible to create many different spectra such as this with "peaks" at different energies without even attempting additional improvement by allowing the gate positions and widths to be varied individually.

Since no evidence for hyperdeformation was observed in this experiment, the question of interest that now arises is the limit of sensitivity that was achieved in performing the experiment. Providing an accurate measure of this limit is of great importance, as it is certainly possible to make theoretical estimates as to what extent a third minimum may be populated in a hyperdeformed nucleus.

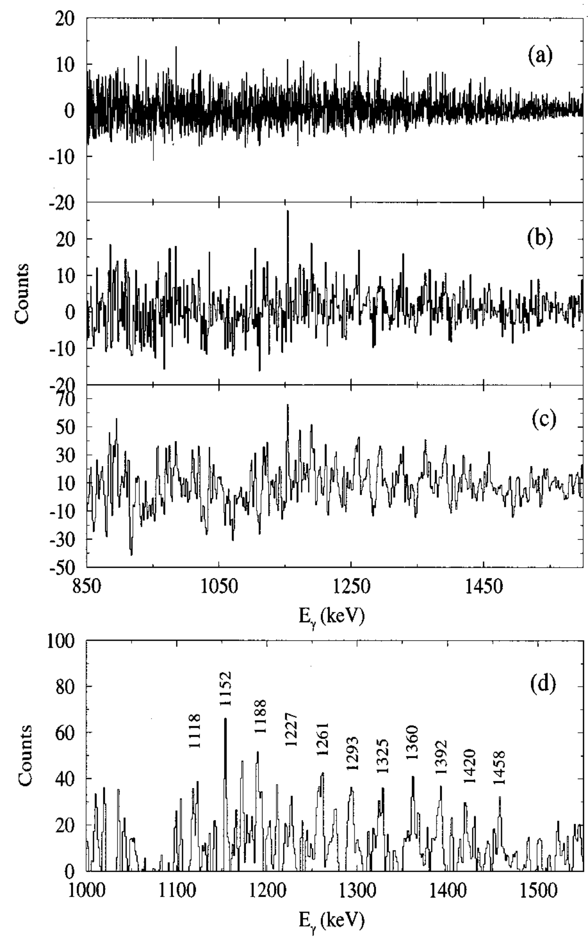

FIG. 3. Spectra of a typical "good" candidate from the search for a discrete hyperdeformed band. The figure consists of (a) the gated spectrum, (b) the effect of a contraction by 4, (c) the effect of smoothing over three channels, and (d) the effect of presenting the spectrum neatly, by setting limits on the energy range, counts range and placing energy labels over the places where the gates were set. The spectrum could be improved further if freedom in the movement of the gate positions by a few channels was allowed. This spectrum is *not* that a hyperdeformed band.

LIMIT OF SENSITIVITY

In order to provide a reliable estimate of the limit of sensitivity, comprehensive Monte Carlo simulations were performed. In order to proceed we have to make an educated guess as to what a hyperdeformed band may look like. The most uncertain quantity in a description of a possible hyperdeformed band, is the length of the sequence of transitions in the cascade. Although it is predicted that the hyperdeformed minimum persists down to the very lowest spins (perhaps as low as 10$\hbar$), it is very unlikely that it will be possible to observe transition energies this low, due to the extremely high rate at which such a band would become nonyrast. After only a few transitions, hyperdeformed states would be surrounded by a sea of normally deformed states with a rapidly increasing level density. Due to the large number of final normal-deformed states available in this scenario, decay out of the band would seem highly probable. As we have no idea what limit is appropriate, Monte Carlo simulations have been performed for bands of length 6 to 20 transitions. First, the hyperdeformed cascade was simulated for each event, and then the response of the Gammasphere array to the γ rays was incorporated. The result of the Monte Carlo simulation is that pure, simulated, hyperdeformed events were generated which were available for addition to the real database.

The assumptions built into our Monte Carlo simulation of hyperdeformed events are that (i) the band starts at spin 80$\hbar$, (ii) it is fed over the top four states between 80 and 72$\hbar$ with equal probability, (iii) the hyperdeformed cascade persists for n transitions, until all flux decays out on the nth transition, (iv) the spacing of the band is 33 keV and the energy of the top transition is 1370 keV, (v) the γ cascades consist of 32–40 γ rays, n of which are hyperdeformed, the remainder being scattered at random across an energy range of 0–2 MeV, (vi) the widths of the peaks are values consistent with γ rays that are fully Doppler shifted, (vii) when gating on the simulated data, the gate positions were exactly central on the photopeaks of the simulated band (an ideal which probably could not be achieved with a search procedure), and (viii) the total photopeak efficiency for Gammasphere to detect a γ ray in the range of the simulated band is 10.0%.

TABLE II. Probability that any given simulated HD event from a cascade of 10 HD transitions will contain n photopeak energies.

0	1	2	3	⩾4
0.349	0.387	0.194	0.057	0.013

The total photopeak efficiency for Gammasphere is calculated at ≈ 1300 keV, given that the total percentage coverage of solid angle by 92 Germanium detectors is 40%, the probability that a detected γ ray will be suppressed by the BGO is 50%, and the probability that if unsuppressed, the full photopeak energy will be detected is 50%. This one factor is by far the most important assumption which governs the limit of sensitivity determined from the Monte Carlo calculation. For example, if the band has ten transitions, then the probability that any given simulated event will contain n photopeak energies is given in Table II (a binomial distribution with $p=0.1, q=0.9$).

If we simulate events for this particular example, and then triple gate on these events, only the 1.3% of them that have four or more detected energies will put counts into the photopeaks of the band. 5.7% of them will put counts into other places/regions, the remainder having too few detected energies to be able to detect them as being of a hyperdeformed nature. Only one quarter of the energies in any particular event will actually be associated with hyperdeformed transitions, the remainder being γ rays from the continuum or normally deformed states.

Simulated data were generated given these assumptions, and the simulated events were then mixed with the real events (see Fig. 4). Two, three, and four gates were applied to every transition in the simulated band. For different length of bands and different gating conditions we determined the number of simulated events that it was necessary to generate so that the significances of peaks in the resultant gated spectrum of the band were equal to 3σ. This significance level was chosen because at this level the gated spectra appear to be of a similar quality to some of the weakest superdeformed bands it has been possible to observe in the $A\approx 150$ mass region (e.g., excited bands in ^{151}Dy [20]). The significance for a given peak can be determined from the following equation, which evaluates the ratio of the total peak counts P to the error on the background:

$$\sigma = \frac{P}{\sqrt{P+2B+(0.02B)^2}}, \quad (1)$$

where B is the total number of counts in the background underneath the peak. The factor of $(0.02B)^2$ is a systematic error included in the estimation of the background error, as there is an uncertainty in how well the Compton background of the spectrum is known. The analysis software RADWARE [21] uses 0.05 as a default value, however, in this case we have assumed that the background spectrum is known to 1 part in 50. The results of the Monte Carlo simulations are shown in Fig. 5. It is clear that a low limit of sensitivity has been achieved in this experiment. The lowest value is for quadruple gating on a band of 18 transitions, corresponding to a limit of 0.004% of the data set, and 0.02% of the ^{168}Yb

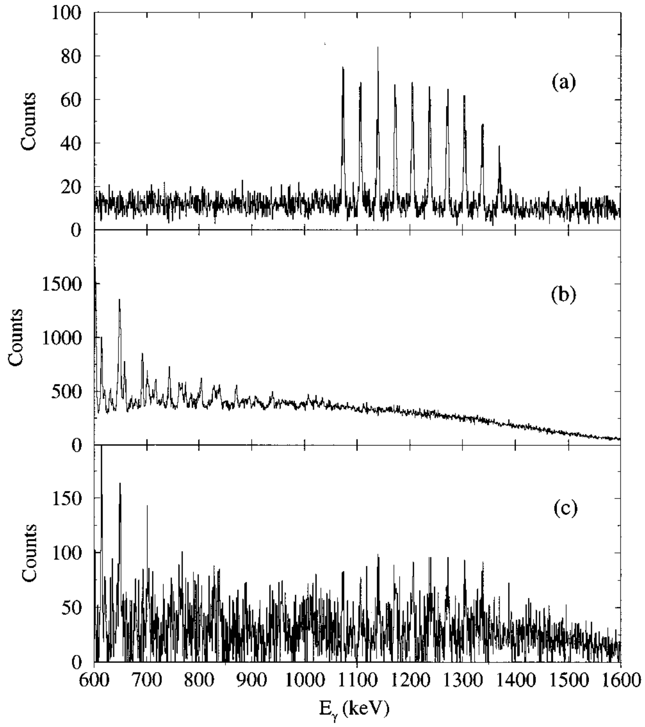

FIG. 4. (a) Triply gated spectrum created from the sum of 10 gates on 70 000 events of simulated hyperdeformed data, where the simulated band had ten transitions and the gates were 1 FWHM wide. (b) Triply gated spectrum created from exactly the same sum of ten gates applied to the real data containing 500 million events in the full database. (c) The sum of the spectra (a) and (b), after a suitable high-statistics background spectrum has been subtracted. The peaks in the simulated band are not particularly prominent in this spectrum, which corresponds to a band of 0.014% intensity. The limit of sensitivity for one data point is calculated from spectra such as (a) and (b).

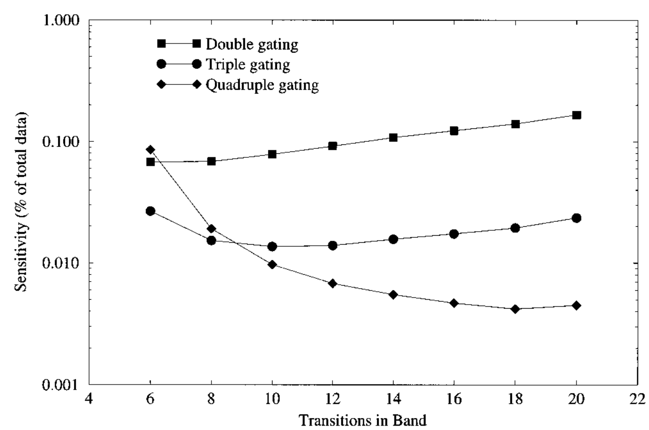

FIG. 5. Plot of the limit of sensitivity of the full Gammasphere for this particular reaction, given the assumptions of the Monte Carlo simulation. This limit will vary from experiment to experiment due to changes in the amount of data collected, and the strength of continuum background, but the major factor in affecting the limit is the total photopeak efficiency for Gammasphere (taken here as 10.0% in the range of the simulated band). Note that the limit of sensitivity for the ^{168}Yb channel is ≈ 5 times higher than these values, as this comprises only 20% of the data set.

channel. The limit of sensitivity would have been even lower had it not been for the large background of correlated cascades of statistical, continuum γ rays emitted in the same energy region as the search range for hyperdeformed bands (see Fig. 1).

SUMMARY AND CONCLUSION

To summarize, no evidence for hyperdeformation has been observed in ^{168}Yb, or its near neighbors. The experiment was performed with the best available apparatus, and the nuclei studied were excellent candidates. The lowest sensitivity limit achievable is 0.02% of the ^{168}Yb channel. Some possible reasons why evidence for hyperdeformation has not been observed in this experiment are (a) hyperdeformed bands were populated at a level lower than the limit of sensitivity, and hence unobservable, (b) the amount of angular momentum brought into the compound system was not sufficient to allow population of hyperdeformed states, (c) fission of the compound nucleus prevented population of hyperdeformed states, and (d) hyperdeformed states do not exist in these nuclei.

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