CANDIDATES FOR NEW TRANSITIONS IN ^{254}No†

by

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Several candidates for transitions in ^{254}No have been observed in an experiment performed at Argonne National Laboratory. The reaction ^{208}Pb(^{48}Ca,2n)^{254}No was used at beam energies of 219 and 223 MeV. The candidates presented were only evident at 223 MeV, which suggests that they come from parent states with high energies that are not populated at the lower 219 MeV beam energy.

1. Introduction

Part of modern nuclear physics is the study of nuclei at the limits of existence. The relative stability of nuclei with more than ~100 protons is generated entirely by the "shell correction energy," a quantum mechanical effect which reflects the shell structure in nuclei [1,2]. This effect is responsible for a theoretical island of stable superheavy nuclei. Different theories disagree about the location of this island. Thus, by studying the quantum states of ^{254}No, one can learn more about the shell correction energy and find out which theories are more likely to be correct.

The aim of this report is to identify higher spin states in the ground state band, which will help determine the maximum spin that the ^{254}No nucleus can sustain, giving us information about the fission barrier as a function of spin.

2. Previous Work

Previous studies of ^{254}No at Argonne National Laboratory (ANL) and at the University of Jyväskylä have tentatively identified the ground state band of ^{254}No up to a spin of 24ħ (see Fig. 1).

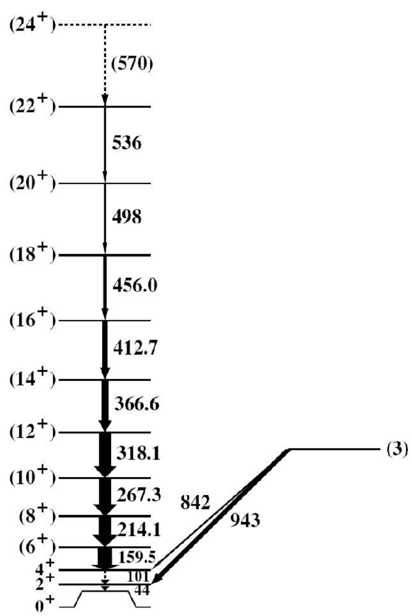

Fig. 1. *Previously published* proposal for partial level scheme of ^{254}No (figure from ref. [1]).

3. Experimental Setup

An experiment (*gsfma116*) to measure the gamma ray coincidences of ^{254}No was performed at Argonne National Laboratory in July 2003 using the Argonne Tandem-Linac Accelerator System (ATLAS). The reaction ^{208}Pb(^{48}Ca,2n) ^{254}No was used to create excited ^{254}No nuclei at beam energies of 219 MeV and 223 MeV. The resulting gamma-rays were detected by Gammasphere, an efficient gamma-ray detector with solid angle nearly 4π, a sum-energy efficiency of 72% (for 898-keV photons) [2], and an energy resolution of approximately 2-3 keV. Most of these nuclei fissioned quickly, but a few remained ^{254}No for longer and cooled down by emitting gamma rays.

The gamma ray energies and other data collected by ATLAS devices were divided in to distinct events, with each event corresponding to one probable nuclear reaction. The ^{254}No events were uniquely identified with the Argonne Fragment Mass Analyzer through measurements of (i) the mass/charge ratio, (ii) the energy lost in the parallel-plate avalanche counter (PPAC), (iii) the time for the particle to fly from the PPAC to a double-sided silicon strip detector (DSSD) ~50 cm away, and (iv) the implant energy in the DSSD [5]. Computed is the *gamma-gamma matrix*, a symmetric two-dimensional histogram where each count represents a *coincidence* between the two gamma ray energies (e.g. a count at (214, 414) indicates that two gamma rays of those respective energies were detected in the same event).

This report also refers to data from two older Argonne experiments with similar setups which had beam energies of 215 MeV (*gsfma23*) and 219 MeV (*gsfma55*) respectively [2]. Referred to also in this report are the data from two ^{254}No experiments from the University of Jyväskylä [1].

4. Results

4-1. Consistency with Previous Work

The numerous gamma-gamma coincidences between gamma-rays with energies in the existing partial level scheme for ^{254}No indicate that the scheme is consistent with the new results at 219 MeV and 223 MeV (*gsfma116*). However, the validity of the scheme's 570 keV transition remains speculative because that energy had no gamma-gamma coincidences with the other energies in the scheme.

4-2. Primary Candidates

Careful examination of the gamma-gamma coincidence matrix at 223 MeV beam energy revealed the possibility of undiscovered transitions at 469, 491, 590, and 1481 keV.

Evidence for these candidates in the form of gamma-gamma matrix projections is shown in Fig. 3. These candidates were not evident in the data taken at 219 MeV beam energy, which suggests that their parent states have a spin and/or energy higher than the states that are populated at 219 MeV.

The strongest candidate from this experiment (*gsfma116*) is 469 keV. This candidate has one coincidence with each of 4 well-established transitions (see Fig. 3). In addition, this candidate has a coincidence with the tentative transition 570 keV, which is hypothesized to be at the top of the currently-known ground state band. This means that there is a good chance that 570 is in the ground state band and 469 keV is the next higher transition in the ground state band, with a parent state spin of 26^+.

The second strongest candidate from this experiment is 491 keV. This candidate has one coincidence with each of 3 well-established transitions, and it also has 3 coincidences that are only 2 keV away.

The other two primary candidates are 590 and 1481 keV, which each have 3 coincidences with well-established transitions.

These primary candidates are good because they have more coincidences with well-established ground state band transitions than the top three transitions already published in ref. [1]; at 223 MeV the published transitions 498, 536, and 570 have only 2, 1, and 0 coincidences with lower published transitions, respectively. However, the published transitions show a somewhat greater intensity in the overall gamma spectra (see Fig. 5).

There are not coincidences between the candidate energies to add supporting evidence.

4-3. The Smooth Extension

The plot of spin versus transition energy is a smooth curve; while the points on the curve are discrete, they appear to follow a predictable pattern. If the next highest state in the ground state band follows that pattern, as predicted by ref. [4], then one would expect its transition energy to be around 600 keV. The previously mentioned candidate at 590 keV is close enough that it could be considered a smooth extension of the curve, but there is actually another smooth extension candidate at 603 keV.

The evidence supporting the 603 keV transition is dubious: There are unusually high counts in the overall gamma spectra in the neighborhood of 603 keV (see Fig. 5). These patterns were seen at all beam energies. However, these patterns are unlikely to come from a single transition, because they have the wrong shape, and they are too wide. Also, the position of these patterns varies noticeably among the different data sets.

In the *gsfma116* data at 219 MeV and 223 MeV beam energies, the only gamma-gamma coincidences between ~603 keV and known transitions are: 601 with 158 keV and 607 with 413 keV. These coincidences are too far apart to be considered to belong to a single transition near 603 keV.

But there is something special about that energy. Perhaps better data would allow the identification of multiple transitions with energies ~603 keV.

4-4. Lesser Candidates

Another four transition candidates came from (probably) a single high-multiplicity event at 223 MeV beam energy where Gammasphere detected seven photons: one K x-ray (143 keV) [2], two gamma rays that are well-established transitions (214 and 414 keV), and four other gamma rays (339, 376, 624, and 1168 keV) which are now called the “lesser candidates.” Fig. 4 shows that each lesser candidate except 376 keV has no interesting coincidences besides the ones resulting from the (probable) seven-photon event (see Fig. 4). These candidates were not evident in the data taken at 219 MeV beam energy.

4-5. No Candidate-Candidate Coincidences

Besides the coincidences coming from the (probable) high multiplicity event described in Section 4-4, there were no coincidences observed between any two of the nine of the candidates mentioned in this report. If a coincidence between two candidates had been observed, it would have been evidence that both candidates were real transitions and one of them fed in to the other.

4-6. Small Peaks

The total ^{254}No gamma ray spectra from this experiment and other ^{254}No experiments are presented in Fig. 5. Some of these spectra show small peaks for some of the candidates reported in this report, which bolsters their candidacies.

4-7. Moment of Inertia

The moment of inertia of a quantum state can be computed from two different equations [5]:

$$J^{(1)} = \hbar^2 \frac{(4I-2)}{(2E_{gamma})}$$

$$J^{(2)} = \hbar^2 \frac{4}{(E_{gamma}(I) - E_{gamma}(I-2))}$$

The plot of transition energy versus moment of inertia for the previously published ground state band transitions is smooth, but if the next transition in the ground state is 469 keV, the star candidate, then the pattern will have a backbend (see Fig. 6). This would imply a structure change in ^{254}No [5].

5. Conclusion

There are several candidates for the next highest ground state band transition in ^{254}No. A smooth extension of the spin-energy curve would be a transition somewhere around 600 keV, but the best candidate for the next ground state transition is actually 469 keV.

However, it is also possible that the next highest ground state band state has not been observed, and that none of the candidates are correct. More data are needed. The next step is to analyze the gamma-gamma coincidences from the University of Jyväskylä to see if the candidates reported here stand out.

The physical significance of a backbend is sufficiently important that a second experiment to confirm it should be considered.

6. References

[1] S. Eeckhaudt, Eur. Phys. J. A 26, 227-232 (2005)

[2] P. Reiter et al., Phys. Rev. Lett. 84, 3542-3545 (2000)

[3] Martin Venhart, private communication via T. L. Khoo (2006)

[4] T. Duguet, Nuclear Physics A 679, 427-440 (2001)

[5] T. L. Khoo, private communication

[6] S. K. Tandel et al., Phys. Rev. Lett., in press (2006)

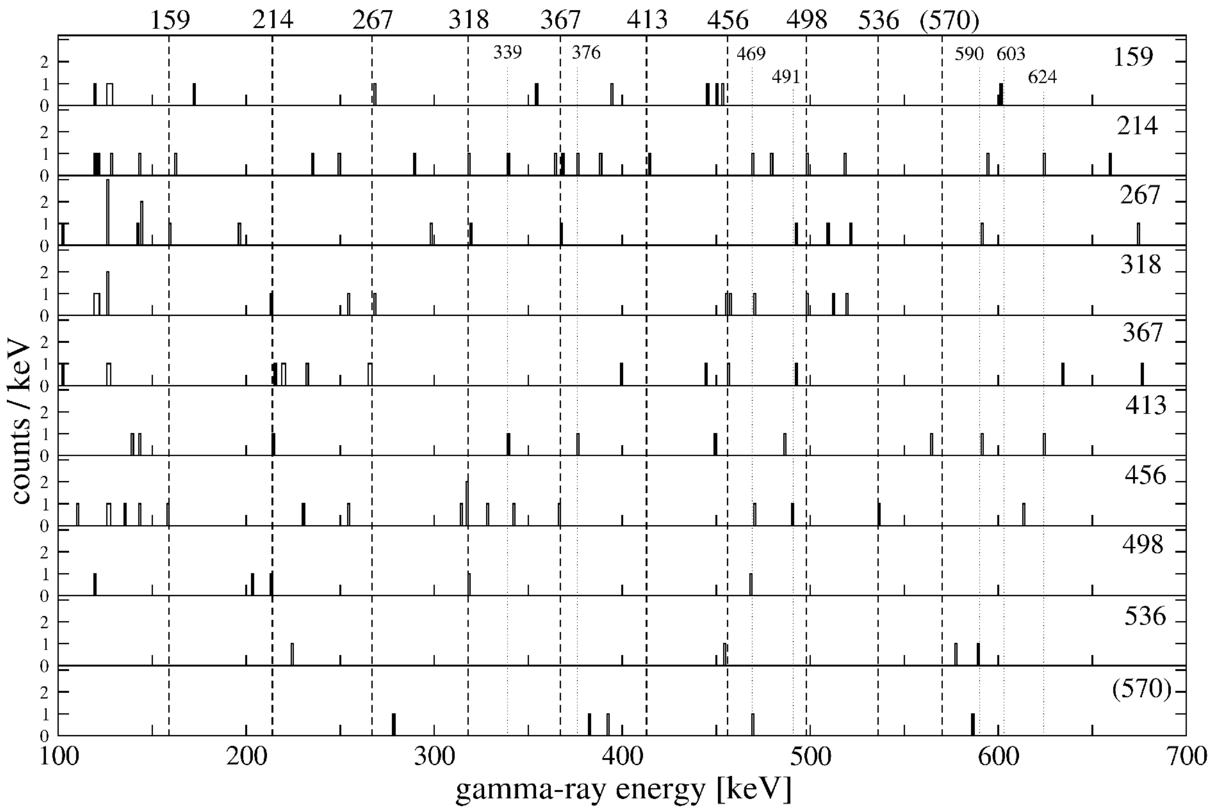

Fig. 2a. Spectra projected from the gamma-gamma matrix at 223 MeV beam energy, gated on all the ground state band transitions from ref. [1]. The numbers in the upper right-hand corner indicate the energy used as a gate. The exact width of the gates and the actual gamma energies are in Fig. 2a Data below.

Gamma energy [keV]	*Coincident gamma energies [keV] between 100 and 700 keV*
158	126, 394, 445, 453, 601
159	**268**, 354, 450
160	119, 127, 128, 172
213	119, **318**, 469, **498**
214	143, 339, 376, **414**, 594, 624
215	121, 128, 162, 235, **368**, 479, 518, 659
216	249, 289, 364, 388
266	102, 142, **367**, 492
267	126, 144, 144, 591
268	126, **159**, 298, **319**, 521
269	126, 196, 509
316	-
317	126, 254, **455**, **457**, 470, 519
318	119, **213**, **498**, 512
319	120, 126, **268**
320	121
365	126, 444
366	127, 265, **456**, 634
367	102, 219, 220, 232, **266**, 492, 676
368	**215**, 399
412	486, 591
413	139
414	143, **214**, 339, 376, 624
415	449, 564
453	**158**, 230, 328, 342
454	**536**
455	254, **317**
456	127, **366**, 490, 613
457	110, 135, 143, 314, **317**, 470
498	119, **213**, **318**
499	203, 468
500	-
534	577
535	224, 589
536	**454**
568	-
569	392, 586
570	278, 382, 469
571	-

Fig. 2a Data. The gamma-gamma coincidences graphed in Fig. 2a. Coincidences with known transitions are **bold**.

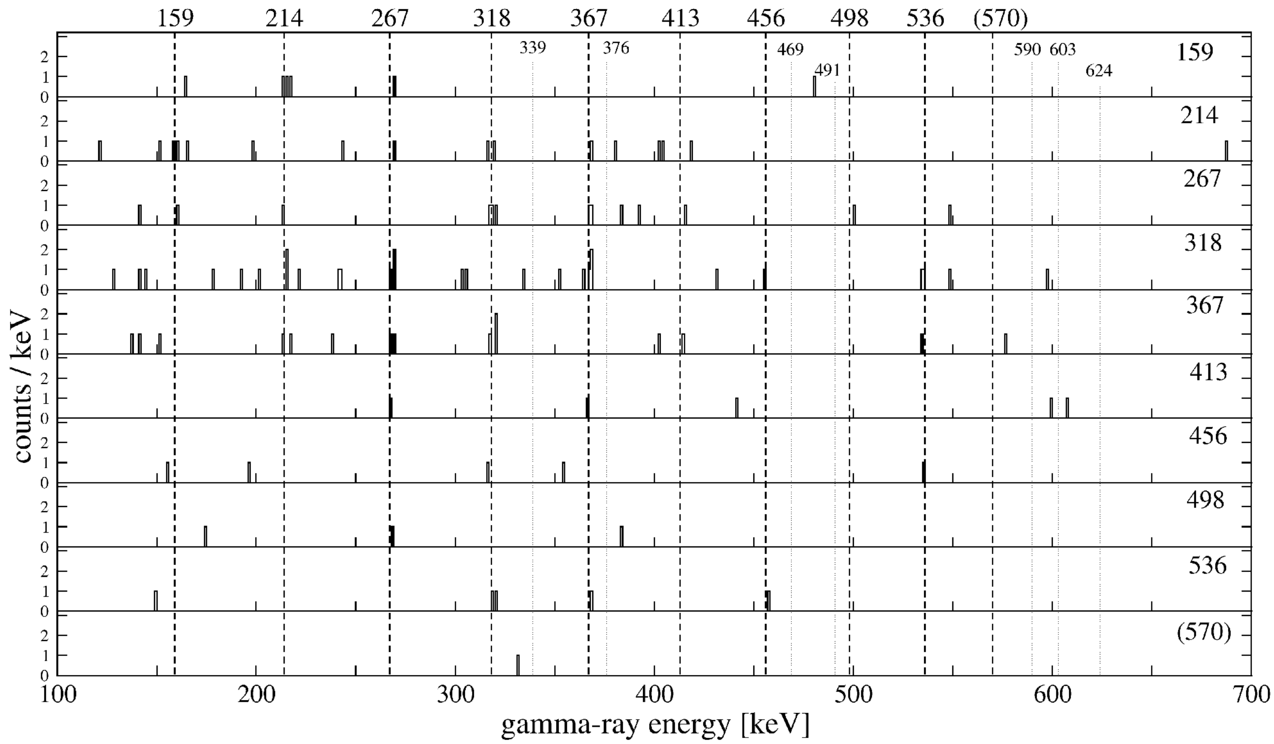

Fig. 2b. Spectra projected from the gamma-gamma matrix at **219 MeV** beam energy, gated on all the ground state band transitions from ref. [1]. The numbers in the upper right-hand corner indicate the energy used as a gate. The exact width of the gates and the actual gamma energies are in Fig. 2b Data below.

Gamma energy [keV]	*Coincident gamma energies [keV] between 100 and 700 keV*
158	**215**
159	164, 217, 480
160	**213**, **269**
213	160, 198, **269**, **368**, 380, 402, 418
214	121, 243, 404, 687
215	**158**, **316, 319**
216	151, 165
266	-
267	141, **317**, **367**, 392, 415
268	383, 500
269	160, **213**, **318**, 320, **368**, 548
316	**215**, 455
317	141, 144, 221, **267**, 305, 364, **367**
318	178, 192, **269**, 303, 334, 352, **535**, 597
319	**215**, 242, 431
320	201, 241, **269**, **368**, **534**, 548
365	217
366	137, 151, 238, **414**
367	**267**, **317**
368	**213**, **269**, 320, 402, 534, 576
412	-
413	441, 607
414	**366**, 599
415	**267**
453	-
454	196, 354
455	155, 316
456	-
457	**535**
498	-
499	-
500	**268**, 383
534	320, **368**
535	**318**, **457**
536	149
568	-
569	331
570	-
571	-

Fig. 2b Data. The gamma-gamma coincidences graphed in Fig. 2b. Coincidences with known transitions are **bold**.

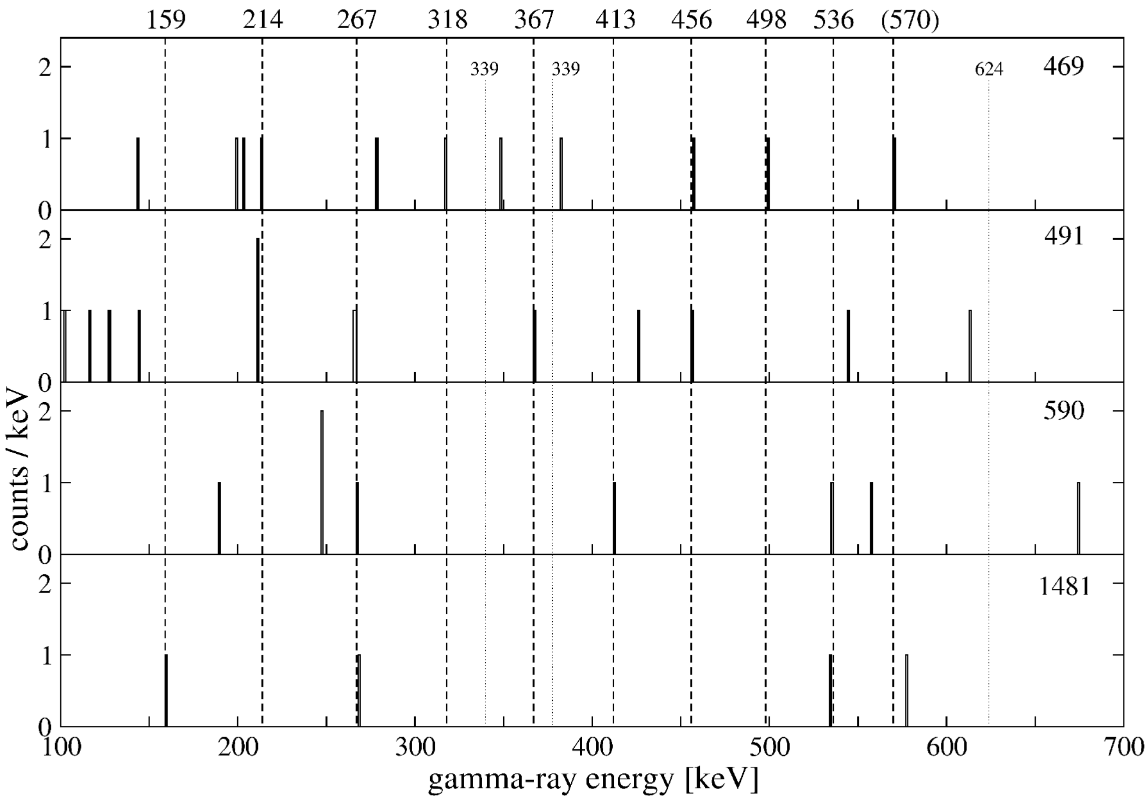

Fig. 3. Spectra projected from the gamma-gamma matrix at 223 MeV beam energy, gated on four candidates for a transition in ^{254}No. The numbers in the upper right-hand corner indicate the energy used as a gate. The exact width of the gates and the actual gamma energies are in Fig. 3 Data below.

Gamma energy [keV]	***Coincident gamma energies [keV] between 100 and 700 keV***
468	143,199, 203, 348, **499**
469	**213**, 278, 382, **570**
470	**317**, **457**
489	116, 127, 265, 544
490	144, 211, 211, 426, **456**, 613
491	-
492	102, **266**, **367**
589	189, 247, 247, **535**, 557
591	**267**, **412**, 674
1479	**159**, **268**
1482	**534**, 577

Fig. 3 Data. The gamma-gamma coincidences graphed in Fig. 3. Coincidences with well-established transitions are **bold**.

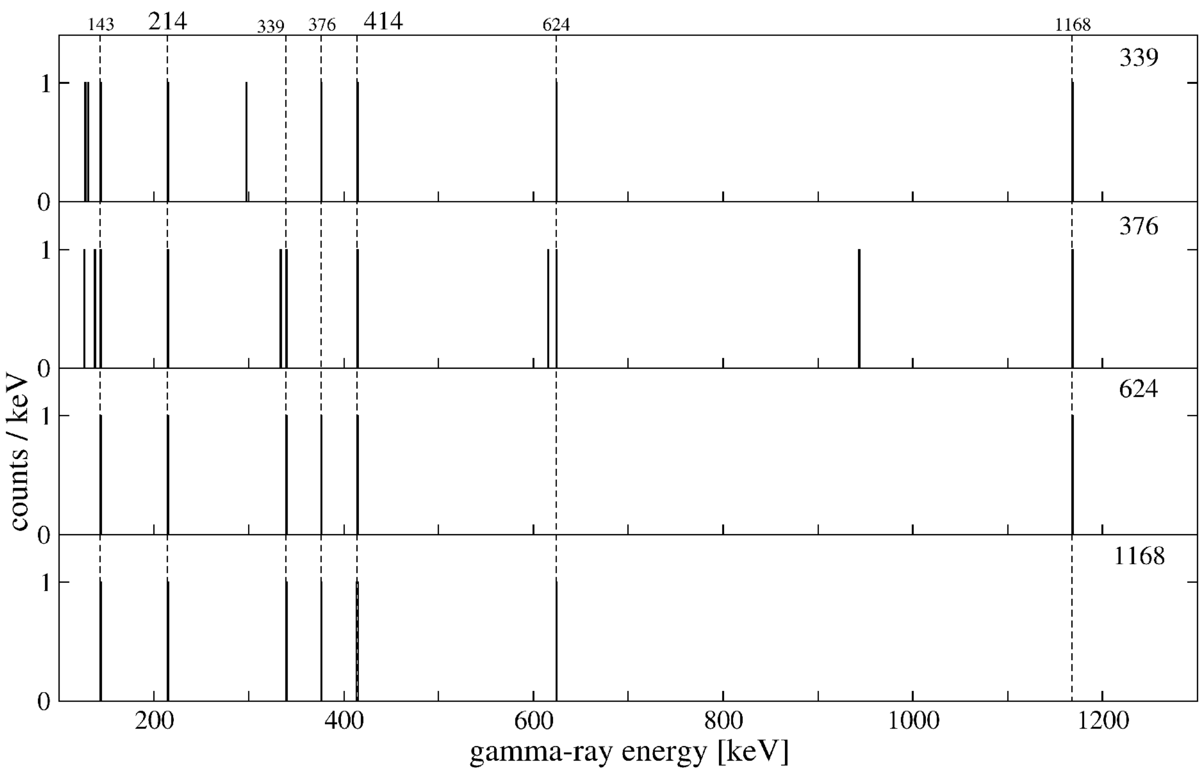

Fig. 4. Spectra projected from the gamma-gamma matrix at 223 MeV beam energy, gated on four candidates for a transition in ^{254}No which came from (probably) one high-multiplicity event. The numbers in the upper right-hand corner indicate the energy used as a gate. The exact widths of the gates and the actual gamma energies are in Fig. 4 Data below.

Gamma energy [keV]	*Coincident gamma energies [keV] between 100 and 1300 keV*
339	127, 143, 214, 297, 376, 414, 624, 1168
340	130
375	126, 137, 333, 943
376	143, 214, 339, 414, 615, 624, 1168
624	143, 214, 339, 376, 414, 1168
1168	143, 214, 339, 376, 413, 414, 624

Fig. 4 data. The gamma-gamma coincidences graphed in Fig. 4. The coincidences that probably came from one high-multiplicity event are underlined.

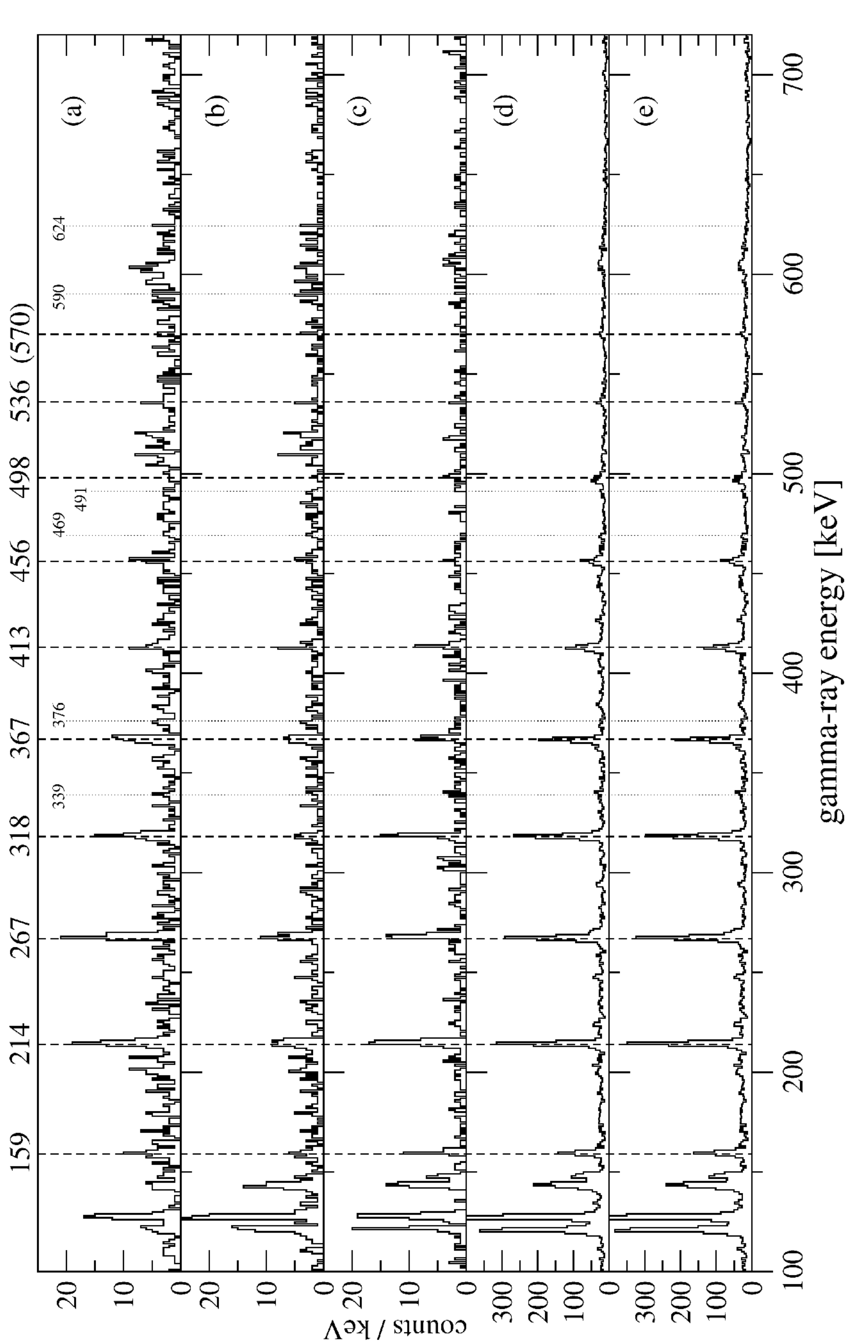

Fig. 5. The total ^{254}No gamma spectra (e.g. all the gamma rays within from ^{254}No events) from: (a) the sum of the spectra for beam energies 219 and 223 MeV, from the present experiment; (b) 223 MeV beam energy from the present experiment; (c) the sum of the spectra from the two experiments at 215 MeV and 219 MeV in ref. [2]; (d) the sum of experiments using Jurogam [1, 3]; (e) the sum of spectra from *all* the ^{254}No experiments discussed in this report. The lines at 842 and 944 represent transitions from an isomer (a long-lived state outside the ground state band) [6]. This figure continues on the next page.

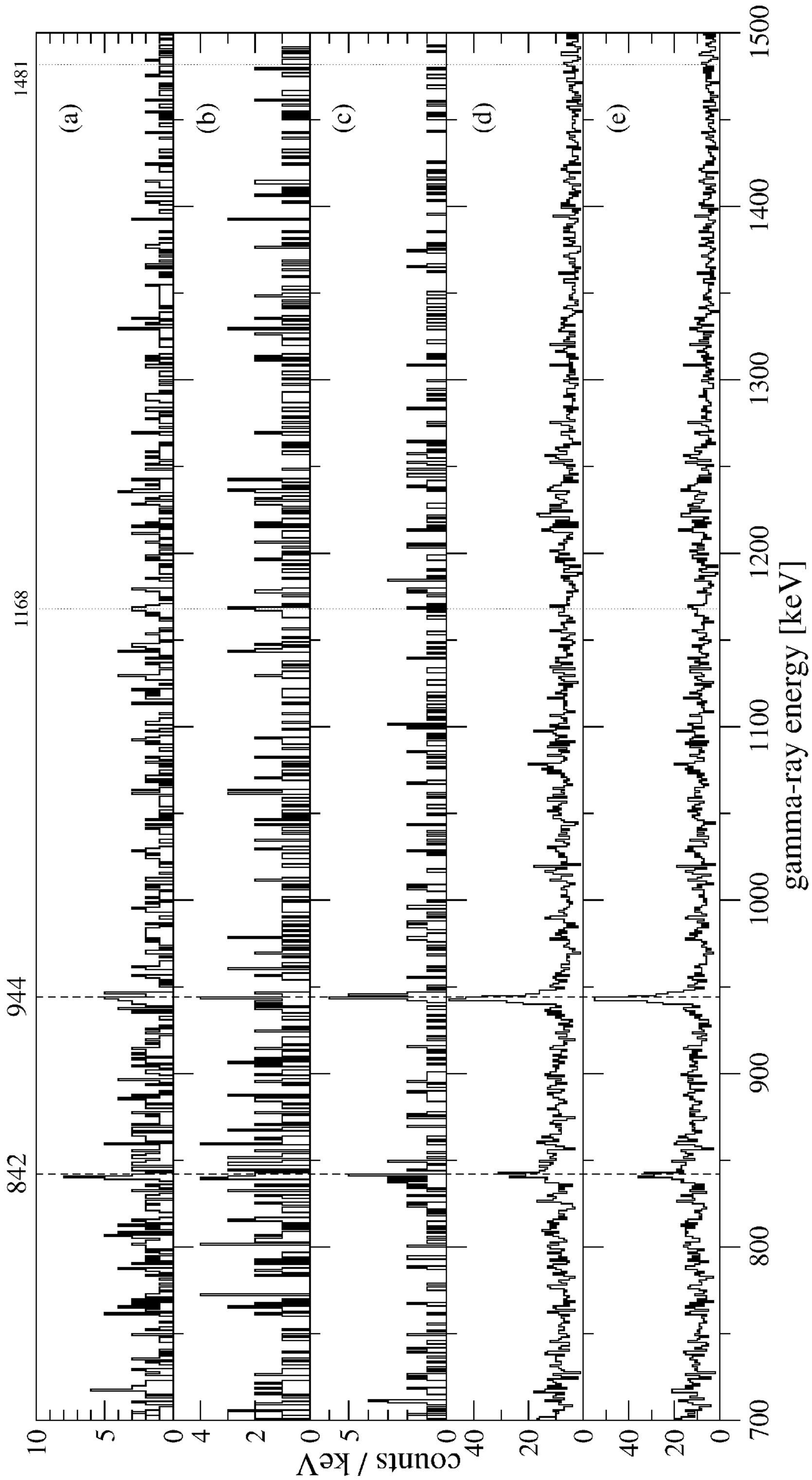

Fig. 5 continued from last page.

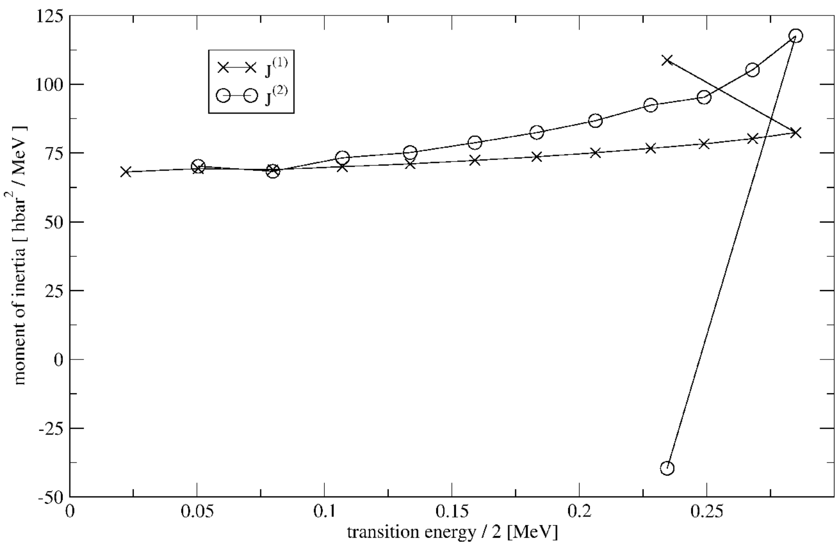

Fig. 6. The moment of inertia of the nucleus, calculated two different ways. The two unusual points represent the hypothesized 469 keV transition feeding in to the top of the ground state band.

keV	**159**	**214**	**267**	**318**	**367**	**413**	**456**	**498**	**536**	**570**	**841**	**944**	**469**	**491**	**590**	**1481**	**339**	**376**	**624**	**1168**
159	**159**	2	2				1									1				
214	-	**214**	1	3	2	1		1					1				1	1	1	1
267	-	-	**267**	4	3	1		1						1	1	1				
318	-	-	-	**318**	3		3	1	2		1		1							
367	-	-	-	-	**367**	1	1		1					1						
413	-	-	-	-	-	**413**									1		1	1	1	2
456	-	-	-	-	-	-	**456**		2				1	1						
498	-	-	-	-	-	-	-	**498**					1							
536	-	-	-	-	-	-	-	-	**536**			1			1	1				
570	-	-	-	-	-	-	-	-	-	**570**			1							
841	-	-	-	-	-	-	-	-	-	-	**841**				1					
944	-	-	-	-	-	-	-	-	-	-	-	**944**						1		
469	-	-	-	-	-	-	-	-	-	-	-	-	**469**							
491	-	-	-	-	-	-	-	-	-	-	-	-	-	**491**						
590	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**590**					
1481	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**1481**				
339	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**339**	1	1	1
376	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**376**	1	1
624	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**624**	1
1168	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**1168**

Fig. 7. All the coincidences between known transitions and the eight main candidates for new transitions in the 219 and 223 MeV data from *gsfma116*.

Category	***Description***	***Location***
Raw data	Gsfma116, 219 MeV	/dk/bgo31/khoo/gsfma116/rawdata/223MEV.data
	Gsfma116, 223 MeV	/dk/bgo40/khoo/greyson/work/resort_219/219MEV.data
Root files	Gsfma116, 219 MeV	/dk/bgo40/khoo/greyson/work/resort_219/219MEV.root
(http://root.cern.ch)	Gsfma116, 223 MeV	/dk/bgo40/khoo/greyson/work/resort_223/223MEV.root
Spectra and gamm-gamma matrices	Gsfma116, 219 MeV	/dk/bgo40/khoo/greyson/work/resort_219/*.spe, *.ascii, gg*
	Gsfma116, 223 MeV	/dk/bgo40/khoo/greyson/work/resort_223/*.spe, *.ascii, gg*
	Gsfma55 + Gsfma23	/dk/bgo40/khoo/greyson/work/gsfma55/*
	Jyväskylä	/dk/bgo40/khoo/greyson/work/finland/*
Utilities	Precise gates used	/dk/bgo40/khoo/greyson/work/doit.cc
This report	This report	/dk/bgo40/khoo/greyson/work/paper/paper.sxw (or .pdf)
	Figure 1 + Data	/dk/bgo40/khoo/greyson/work/paper/eeckhaudt_scheme.png
	Figure 2 + Data	/dk/bgo40/khoo/greyson/work/paper/known_fig/*
	Figure 3 + Data	/dk/bgo40/khoo/greyson/work/paper/cand_fig/*
	Figure 4 + Data	/dk/bgo40/khoo/greyson/work/paper/lesser_fig/*
	Figure 5 + Data	/dk/bgo40/khoo/greyson/work/paper/total_fig/*

Table 1. Locations of files used in the making of this report, on the Argonne Physics Division shared hard-disk system.

Appendix A – Summary of my work

My Summer internship at Argonne National Laboratory lasted 11 weeks from May 31th to August 11th, 2006. This is a summary of what I did during that time.

First, I performed energy and efficiency calibrations for the Clover and Low-Energy-Photon-System (LEPS) detectors, using data recorded in December 2005. Those calibrations are now being used by others.

Secondly, I learned how to use several computer programs in preparation for the work presented in this report:

- Root, a complicated data displaying program designed at Cern.
- GSSort, a program designed at Argonne to sort raw Gammasphere data in to Root histograms.
- GSUtil, a set of functions designed at Argonne to add functionality to Root.

While learning how to use these programs, I discovered some flaws in the instruction files for GSSort, and also in the GSUtil functions. These flaws had to do with historgram bin-numbering conventions. I determined what the correct convention should be, and made a document to explain it. I corrected the flaws in GSUtil, and also wrote more functions for it, to do essential things like write out a two-dimensional histogram in a human-readable format.

Finally, I sorted and analyzed the data from *gsfma116*, searched for candidates, and wrote this report. I spent most of my time at Argonne writing this report.

Appendix B – Personal note

Thank you! I had a great time living and working at Argonne, and I will certainly consider pursuing a research career here.

--David Grayson