LBL-15282

CONF-821143--3

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

LBL--15282

DE83 005860

Presented at the Conference on High Angular Momentum Properties of Nuclei, Oak Ridge, TN, November 2-4, 1982

FUTURE DIRECTIONS FOR HIGH-SPIN STUDIES

F.S. Stephens

November 1982

MASTER

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

FUTURE DIRECTIONS FOR HIGH-SPIN STUDIES

F.S. Stephens

Nuclear Science Division, Lawrence
Berkeley Laboratory, University of
California, Berkeley, CA 94720

This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

FUTURE DIRECTIONS FOR HIGH-SPIN STUDIES

F. S. STEPHENS
Nuclear Science Division, Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720

Abstract Some future directions for experimental high-spin studies are discussed, concentrating mainly on the region above I ~ $30\hbar$, where the γ-ray spectra are currently unresolvable. The 4π NaI balls offer a means to exploit the temperature effects recently shown to exist in such spectra. Large arrays of Compton-suppressed Ge detectors, on the other hand, lead to higher effective resolution as it becomes possible to study triple and quadruple coincident events.

INTRODUCTION

Predicting the future is a difficult and dangerous business. In fact, the closer I came to preparing this talk, the more I wondered why I ever agreed to give it. I guess it is because such a talk, when it is more than 6 or 8 months away, gives the illusion of being a challenge. I am reminded of a dream I have occasionally where I'm standing before a very serious audience, who obviously expect me to say something intelligent, and not only do I have absolutely no idea what to say, I don't even know what subject I'm supposed to be talking about. But things are not that bad today since I do have a few transparancies here.

Where should we begin in discussing the future? I decided to begin with a brief look at where we stand now in high-spin studies. This is not a profound analysis; I do it mainly as a justification for the things I'm going to discuss in the remainder of this talk. However, I give it also in the hope someone might be willing to comment on this subject later. I thought that a field, or an area of a field, goes through three phases of development. The first, phase one, is a time when there is very limited experimental data. The theorists are trying to identify physical concepts that could be relevant. The word to characterize this phase is speculation. Phase two has much more experimenal data accumulating, though it is still limited and often qualitative. The objective of this phase is to determine which concepts are really important in describing the processes occuring. The key word here is specification. In the third phase the experimental data are extensive and quantitative. The important processes are understood and subject to calculation, and the detailed comparison of theory and experiment allows one to sharpen the concepts of what is occuring. This is a time of real spectroscopy.

To apply these phases to high-spin states, I divided the high spins into two regions: ~10–30ħ and 30–65ħ. These just correspond to the regions where there are resolved lines in the heavy-ion fusion spectra, and where there are not. Prior to 1970 both regions were in phase one. Not much thought had been given to either of these spin ranges. There had been some discussion of shapes, both in connection with centrifugal stretching and with the liquid-drop model. And, of course, Mottelson and Valatin[1] had discussed the effects of high spins on the pairing correlations.

In the decade 1970–1980, backbending was discovered, and a lot more data were accumulated in the lower spin range. We were able to determine which effect was most important, and it turned out to be none of the above, but rather the alignment of a pair of $i_{13/2}$ neutrons. Later this process was seen to be related to the single-particle behavior near closed shells, and we came to the nice overview of high-spin phenomena as a competition, or perhaps interplay is a better word, between these single-particle alignments and collective rotations. The 10-30$\hbar$ region was clearly in phase two. However, above 30$\hbar$ progress was more elementary, as we learned how to measure multiplicities and multipolarities of unresolved spectra. This region was still in phase one.

Anyone who sat through Tuesday's talks must realize that the lower spin region has come into phase three in the years since 1980. We heard detailed calculations and measurements of energies, B(E2) values, magnetic moments, alignments, signatures, and the various properties of backbends. Perhaps for me the best illustration of this was the Copenhagen work[2] reported by Jerry Garrett. They used the precise backbending frequencies to learn about the contribution of particular orbits to the pairing correlation. I would not dare try to predict the details of future developments in this lower spin region. It is clear, however, that much remains to be done. We do not yet know how, where, or even if, the pairing correlations in nuclei are finally quenched. Also, we are just now beginning to explore the shapes of nuclei in this spin range. I will return to some future developments in the experimental studies of nuclei at these spins.

In the 30-65$\hbar$ spin range we seem just to be starting phase two. We do not really know yet which, if any, of the processes occurring at lower spins dominates this higher-spin region. It seems clear that we must either learn how to treat unresolved spectra or learn how to resolve the spectra in this spin range. This is one of my safer predictions, as the only alternative is to give up and I'm quite sure we are not going to do that. I want to spend the rest of my time discussing these two possibilities.

STUDYING UNRESOLVED SPECTRA

One of the few real predictions I'm going to make is that if we have to deal with unresolved spectra the γ-γ correlation technique will be one of our most important tools. It is a beautiful technique - both scientifically and artistically. One of the earliest correlation plots is shown in Fig. 1, where the rotational valley is seen rather clearly up to ~1 Mev. But this is also a dangerous technique. One usually subtracts the uncorrelated events - about 98% of all events - and then symmetrizes to improve the statistics. This can make it unclear what is really in the data and what comes from the data analysis. We must learn exactly what the subtraction method does and how to

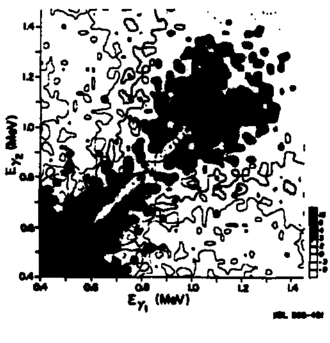

FIGURE 1.
Correlation spectrum from the reaction $^{124}Sn(^{40}Ar,xn)^{164-x}Er$ at 185 MeV. The plot shows contours of equal numbers of correlated events, where the darker regions have more counts according to the scale at the right edge.

evaluate and improve the statistics. It is now clear that the statistics are soon going to improve considerably as arrays of Compton-suppressed Ge detectors come into use. It is perhaps worth noting that NaI detectors do not have the energy resolution to be very useful for this purpose in the rare-earth nuclei. The valley width at 1 Mev is something like 100 keV, and the NaI resolution at this energy is already half that large. All the details would be lost.

One way to evaluate a subtraction method is to invent another method and compare the two. The recent method Herskind, Anderson, et al[3] invented is called the multiple matrix method. It is more general than the earlier method and solves many of the problems in the earlier method. One can easily estimate the statistics by solving the problem a number of statistically independent times and looking at the variation of each point. These new correlation plots show strong vertical and horizontal stripes not present in Fig. 1. It was found that the original method systematically suppresses such stripes - each row and column in that method must sum to zero. The question is: are there other features added to or subtracted from these plots. I do not know the answer to this, but it is perhaps significant that the inventors of both correlation methods are still working on evaluating them, rather than analyzing and publishing a lot of data. One can see, however, that such spectra are rich in detailed information and there is no doubt that, if we need to, we will learn how to understand it.

Now a short commercial. We must also learn complementary techniques. In this respect I am enthusiastic about the method[4] Marie Agnes Deleplanque talked about yesterday. This is a method to extract a new moment of inertia which, when combined with the $\mathcal{J}^{(2)}_{band}$ band from the correlation plots, can indicate what fraction of the additional angular momentum comes from bands (probably mostly collective) and what from alignment. Her plot, Fig. 2, shows that in the frequency region around 0.4 Mev the angular momentum generated comes mostly from collective rotation; whereas, above ~0.5 MeV it comes mostly from alignments. This is an excellent way to connect with theory which can calculate such properties. In this context I am not so concerned whether the new moment of inertia is defined exactly right or extracted completely correctly. If enough people are interested, we can surely learn how to do such things with these unresolved spectra, and, no doubt, much more. In that connection the more detailed information beginning to come from the NaI crystal balls will be of great help. I feel sure we can struggle into phase three without resolving the spectrum, but it would be much better to resolve it and I want now to look at the prospects for doing that.

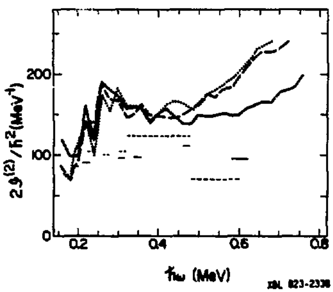

FIGURE 2. $\mathcal{J}^{(2)}_{eff}$ as a function of $\hbar\omega$ for the systems ^{124}Sn + ^{40}Ar (thick solid line), ^{126}Te + ^{40}Ar (dotted line), and ^{130}Te + ^{40}Ar (thick dashed line). Also shown are some values of $\mathcal{J}^{(2)}_{band}$ for ^{124}Sn + ^{40}Ar (thin solid lines) and ^{130}Te + ^{40}Ar (thin dashed lines).

FUTURE DIRECTIONS FOR HIGH-SPIN STUDIES

RESOLVING THE CONTINUUM

In resolving the "continuum" spectrum coming from spins above 30ħ, let us try first the assumption that we might succeed by isolating a smaller initial population. The hope here is that such a population, particularly if it lies along the yrast line, might not spread out again into so many pathways as to be unresolvable. How can we restrict the initial population? One way might be to find a reaction better than heavy-ion fusion: i.e., one that populates a narrower spin range. The only type of reaction I can think of that might do this is the one called massive transfer, or partial fusion, or sometimes incomplete fusion. In these reactions a small piece of the projectile continues on at, or near, beam velocities, while the rest fuses with the target. Since this only happens at the edge of the target nucleus it might correspond to a narrow l-range. Mel Halbert[5] discussed these reacions earlier today, and he did not find a narrow l-range; however, as far as I understand, he did not distinguish whether the remainder of the projectile nucleus fused completely with the target or not. Thus, to my knowledge, there is no convincing answer as to whether these reactions offer an improved spin range. I am pleased that the NaI balls are being used to study this problem, and hope we might have an answer soon.

There is, of course, another way we can isolate a reasonably small initial population. That is by using the 4π NaI balls recently put into operation at Oak Ridge and Heidelberg. Fig. 3 is a plot of excitation energy _vs_ spin for a nucleus of mass around 160. The heavy lines delimit the regions that will γ-decay. (Particle evaporation

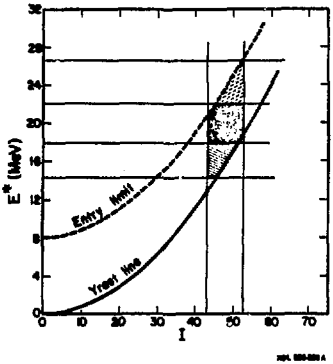

FIGURE 3. Excitation energy vs spin for a nucleus of mass about 160. Total-energy and fold cuts that can be made with the NaI balls are shown superimposed on a realistic yrast line and entry limit.

dominates above the entry limit and there are no states below the yrast line.) The lighter lines show the "best possible" slices in excitation energy and spin could result from putting gates on the total energy and fold (or multiplicity) respectively. The instrumental resolution in both these quantities is optimally about 20% full width at half maximum (FWHM). The hatched areas then indicate the smallest regions that can be isolated (FWHM) by this method. It is worth noting that the sum crystals, which have been in use for several years now, give about the same resolution in total energy, but, of course, no spin cut. Looking at the region, bounded by the central sum-energy cut, the entry limit, and the yrast line, one sees the kind of regions that have been extensively studied. At high angular momentum, the spin region so defined is not much wider than the NaI balls can impose (~30% instead of ~20%), so the big gain with the balls is not so much in the width of the spin slice, but rather in the ability to control the temperataure of the initial population. The first question is: does the temperature affect the spectra. Yesterday

I.Y. Lee[6] showed us, and today Jaaskelainen[7] did also, that there are clear changes in the continuum spectrum when the total energy slice is varied for a given fold slice. This shows that there are temperature effects and is perhaps the most important result that has so far come out of the studies of high-spin states with the NaI balls. We will surely want to understand just what these temperature effects are. On the other hand, this does not yet tell us whether these effects can help resolve the continuum spectrum. (Some temperature dependence is a necessary but not sufficient condition for this). The next question is: does the temperature affect the quality of the resolved spectra. The only data I have seen on this point was shown briefly yesterday by I.Y. Lee[5], and I show his data in Fig. 4. These are spectra from five different total energy slices (differing by 3 Mev) in coincidence with one rather high (k=20)

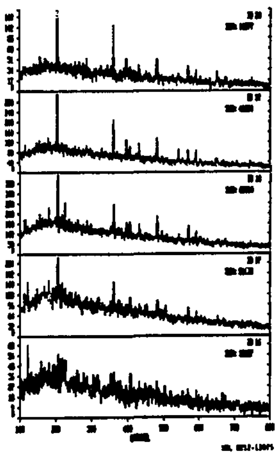

FIGURE 4. Ge spectra for different total-energy cuts of the fold cut 20 (I~40). The total-energy cuts run from the yrast line (bottom) to the entry limit (top) in steps of 3 Mev. Figure due to I.Y. Lee (Ref. 6).

fold slice. The reaction is $^{34}S + ^{100}Mo \rightarrow ^{134}Ce^*$. The strong resolved lines are due mainly to ^{130}Ce. There does not seem to be a large change in quality as measured either by peak-to-background ratio or by relative side feeding, except for the lowest-energy cuts, which look worse. This is a little disappointing as the lowest-energy cut isolates the region nearest the yrast line . It is much too early to draw a conclusion based on this single early result, but I would say some of the optimism, generated by the observed temperature dependence of the continuum γ-rays, has to be damped a bit when it comes to resolving more states using the NaI balls.

Do the NaI balls represent the only hope to resolve higher-spin states from the heavy-ion fusion reactions? I would not have asked that question if the answer were yes. There is an approach different from the one so far discussed of isolating a small initial population. This approach is to use the resolved lines at the bottom of the spectrum together with large arrays of high-resolution detectors to look further up the known bands. We are presently building in Berkeley a detector system that combines both approaches, and I want to describe that briefly for you.

An overall view of this device is shown in Fig. 5. It consists of an inner, approximately 4π, ball of bismuth germanate, (BGO), surrounded by 21 Compton-suppressed Ge detectors which view the source through small holes in the ball. The Ge detectors are arranged in three rings of seven each, one in the median plane of the ball, and the other two above and below that plane. The BGO ball has 44 elements arranged in three concentric cylinders. (The phototubes, etc. that attach to these elements at the top

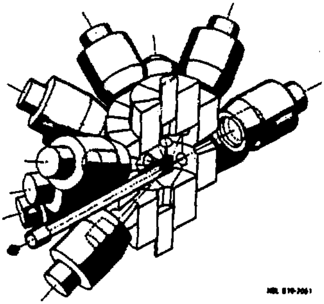

FIGURE 5. Perspective view of the High Resolution Ball system currently under construction in Berkeley.

and bottom of Fig. 5 are not shown.) The elements are about 5 cm thick, giving an overall efficiency for energies around 1 MeV of 80%, not much different from the NaI balls. On the other hand, for multiplicities as high as 30, the resolution in multiplicity will be ~50%, twice that of the NaI balls. At lower multiplicities, of course, it approaches the NaI ball. Thus this device gives an energy-spin cut twice as large as that for the NaI balls shown in Fig.3, but at the same time we have the power of a Ge array far larger than any now existing. An analysis of the performance of the Ge array is given in Table 1. In the top section the improved quality due to the Compton suppression is shown. The analysis is for 20% Ge detectors, which have peak (full energy)-to-total ratios around 0.15. In a coincidence arrangement, the probability of obtaining a useful event (full energy-full energy) is only $0.15^2 \approx 2\%$. That means 98% of all the events give no information, and serve only to obscure the good 2%. For triple or quadruple coincidences the situation is hopelessly bad. Using a prototype of our cylindrical BGO Compton suppressors (whose walls are 3 cm thick), we find we can

TABLE I Analysis of the performance expected for HRB.

Ge	20% (of 1.33 MeV c.f. 3x3 in. NaI)			
	1 Ge	Ge x Ge	Ge^3	Ge^4
Peak/Total	0.15	0.022	0.0034	0.0005
Compton Supp. Peak/Total	0.5	0.25	0.13	0.06
Improvement	x3	x10	x30	x100

10^5 Triggers/sec $M_\gamma = 20$	(counts per second) (days to collect 2.5×10^8 events)		
	Ge x Ge	Ge^3	Ge^4
5 Detectors 17 cm	230 13	3.3 2.4 yr	0.02 345 yr
5 Detectors 12 cm	870 3.3	25 116	0.35 23 yr
21 Detectors 12 cm	11000 0.26	2200 1.3	280 10

achieve peak-to-total ratios of about 0.5. A coincident event thus has 25% probability of being useful, an improvement of more than a factor of ten. Futhermore, a triple event has 13% chance to be composed of three full energy peaks, and a quadruple event, a 6% chance to involve four full energies. This last figure is more than 100 times better than a quadruple event with no Compton suppression, and is even three times better than a double coincidence with no Compton suppression. Thus the quality of the events from our array will be 10 to 100 times better than those from an array without Compton suppression.

The lower part of Table 1 shows the quantity of events that will be produced by this array. We start with an event rate (rate of forming compound nuclei) of 10^5 per second (this is a rate we use routinely in current experiments) and an average multiplicity of 20 (also a normal value). Then we can evaluate rates coming out of various arrays. Listed are the counts per second, and below that the number of days to collect 2.5×10^8 events, a number which corresponds to the best current experiments. The first line in the lower part of Table 1 gives rates for the best Compton-suppressed array so far used, 5 detectors located 17 cm away from the target. The estimate is that it takes 13 days to collect 2.5×10^8 double events, and years to collect that many triples or higher. Such an experiment was run at the Copenhagen tandem accelerator[8], and it did, in fact, take about two weeks. In the next lower line of Table 1, the effect of solid angle is emphasized. Bringing those detectors in to 12 cm (impossible in the experiment due to the large NaI Compton suppressors), would produce a factor of ~4 in the doubles rate, and change the experiment from the "heroic" class to the "normal" class. The expected performance of our array is shown in the bottom line of Table 1. The doubles rate is ~50 times the previous one and the "classic" experiment can be done in a quarter of a day. For the first time in nuclear physics triple coincidence experiments become really feasible, and 2.5×10^8 such events can be accumulated in a little over a day. Quadruples will be accumulated at about the rate of doubles in the "classic" experiment, an improvement of more than 10^4 over quadrupules in that experiment. Thus while the NaI balls will explore for the first time the temperature effects on high spin states, this ball will explore for the first time what can be done with high quality triple and quadrupole coincidence data. I will mention a few possibilities we see now for such data.

First, consider the usual experiment to identify high spin states. For a collective nucleus, there are normally ~10 bands appreciably populated at the highest spins, and one must find a "clean" line rather high up in a band (above known branchings) to serve as a coincident gate in looking for higher unknown members of that band (or branch). The limit (apart from present-day statistics) comes when no sufficiently clean line can be found, and one cannot be sure if weak observed lines are band members or not. An obvious use of triple coincidences is to set double gates in a band, thereby greatly increasing the purity of the observed spectrum. Exactly how much one would gain is not clear, but an average of 3 or 4 states seems reasonable.

A more general and exciting overall approach to this problem is to make triple (or quadruple) correlation studies. Here one looks for sets of three or four γ-ray energies that occur more frequently than would be expected statistically. The existing subtraction methods can easily be expanded to three or four dimensions in order to subtract out the uncorrelated events. What will we learn from a triple correlation plot? It is not so easy to answer that question. At a simple level, it is a way to extend the known high spin bands or sequences. This is essentially the method discussed in the previous paragraph, but with an uncorrelated background subtracted and a systematic look at all sets of three γ-rays, rather than preselecting two. To take a slightly more sophisticated tack; we saw almost no structure in one dimensional Ge spectra from the high spin regions of these heavy-ion fusion reactions; but there is a lot of structure in the two dimensional corrrelation plots. These structures are broader than individual coincidence pairs would be. In a triple correlation plot, we can expand these interesting regions out along a third dimension. This seems to be one of our best hopes to resolve features from individual bands or sequences at very high spins. Once we can get down to resolving sets of individual γ-rays, I am confident they can be put together into level schemes. The challenge here will be to handle the very large data arrays and learn methods to extract the information we want. If we can do that, this is the way to much higher effective resolving power.

CONCLUSION

In concluding I must apologize to the theoreticians: this has been almost purely an experimental talk, concentrating mostly on experimental methods and techniques. My excuse for this is that such a talk is much rarer these days than is its inverse; a purely theoretical talk with no reference to experiment. I might also add that I am sure the theoreticians are much happier this way than they would be if I had discussed the future theoretical developments in our field.

REFERENCES

1. B. R. Mottelson, and J. G. Valatin, Physical Review, Lett.5, 511 (1960).
2. J. Garrett, this volume,
3. O. Anderson, B. Herskind, C. Ellegaard, J. D. Garrett, M. A. Deleplanque, R. M. Diamond, F. S. Stephens, Nordic Meeting on Nuclear Physics, Fuglsø, Denmark, August 1982; Contributions, Pg. 46.
4. M. A. Deleplanque, this volume.
5. M. Halbert, this volume.
6. I. Y. Lee, this volume.
7. Jaaskelainen, this volume.
8. B. Herskind, private communication, 1982.

This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.