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GAMMA-RAY DE-EXCITATION OF COMPOUND-NUCLEUS-REACTION PRODUCTS†

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Abstract

The data currently available on the gamma-ray de-excitation of compound-nucleus-reaction products are summarized. They are shown to be consistent with the de-excitation process outlined by Grover and co-workers, when this is extended to include admixed collective bands. It appears that the presence or absence of an energy gap at a given angular momentum may play a crucial role in the gamma-ray cascade, thereby providing a source of information on nuclear pairing in states with large angular momentum.

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1. Introduction

A number of studies[1-25] have been made of the gamma rays emitted in the de-excitation of the product nuclei following compound-nucleus reactions. It is now well known that when this product nucleus is doubly even, the strongest discrete lines in the gamma-ray spectrum are the transitions between members of the ground-state collective band (gsb). This has been found to be true for projectiles ranging all the way from protons to ^{40}Ar. The nature of this de-excitation process following (^{4}He,xn) reactions has been considered in a number of previous works[18-20]. A fairly reasonable account was given of the observed properties, though some difficulties remain. In this paper we are particularly interested in the cascades following heavy-ion reactions, because they emphasize a new feature, the yrast cascade, which we believe may be especially informative. This more general picture of the de-excitation process reduces to essentially the previous[18-20] picture for (^{4}He,xn) reactions.

The following points regarding the (HI,xn) reactions have been established: 1) The maximum spin observable in the gsb (states populated to the extent of $\gtrsim$ 10% of the 2^{+} state) ranges from 14-18 for rotors to around 6 for vibrators[23]. In a 3n or 4n reaction this maximum spin appears to be the same, irrespective of the angular momentum brought in by the projectile. We have found this to be true, for example[13], in a (^{11}B,4n) reaction ($\ell_{max} \sim 15$) and an (^{40}Ar,4n) reaction ($\ell_{max} \sim 40$) leading to the same product nucleus ^{160}Er. 2) When reactions are induced by lighter ions, states of the gsb are fed both from higher states of the band and also independently from other excited states in the region of high level density. For example in

^{11}B induced reactions this independent feeding typically amounts to ∿ 10 to 20% of the intensity of the 2 → 0 transition to each band member. On the other hand with ^{40}Ar projectiles essentially all of the independent feeding goes to the two or three highest observed members of the band[13]). 3) The alignment of the angular momentum introduced by the reaction is typically almost completely preserved throughout the de-excitation process[11,12,19,20]). 4) The mean time interval between the reaction and the population of the gsb in three ^{40}Ar induced reactions was found[26]) to be ∿ 10 ps. Although in one case there appeared to be two components with somewhat different feeding times, less than 5% of the feeding was appreciably slower than this. If these three studied cases (^{156,158,160}Er) are representative, the feeding time for rotors like ^{160}Er(∿ 6 ps) is appreciably less than that for vibrators like ^{156}Er(∿ 16 ps). Preliminary results for a number of other reactions indicate that the feeding times for these are also in the above range.

2. Discussion

We believe these features of the gsb population follow rather naturally if one extends the description of the de-excitation process recently given by Grover and co-workers[27,28]. We shall first outline this description of the de-excitation process and show that it gives a good qualitative explanation for the first three points above. We shall then consider the situation in more detail, with particular reference to the feeding times (point 4) and attempt to show that an extension of Grover's model is required to explain the data.

2.1. GENERAL DESCRIPTION OF GAMMA DE-EXCITATION SCHEME

The gamma de-excitation of a final product nucleus (with $A \sim 160$) on this model is illustrated in fig. 1. Here the excitation energy is plotted against angular momentum I. The thin line is an estimate for the non-gsb states of lowest energy for each angular momentum. The exact location of this line is not important for our present argument but will be discussed later. Grover calls the lowest level for each spin the yrast level. It is clear that the gsb members are the yrast levels for the lowest angular momentum values, and the dots and dashes indicate gsb energies for a vibrator like ^{190}Hg and a rotor like ^{160}Er, respectively. The short heavy lines in fig. 1 indicate the initial angular-momentum ranges and average excitation energies in this nucleus following (^{4}He,4n) and (^{40}Ar,4n) reactions. The spread in angular momentum for the (^{4}He,4n) reaction is estimated by assuming that all the cross-section goes into the 4n reaction, and that the neutrons carry off a negligible amount of angular momentum. That for the (^{40}Ar,4n) reaction is estimated from the measured cross sections[13], assuming that the higher-angular-momentum collisions go into (^{40}Ar,3n), (^{40}Ar,αxn) and surface reactions, and that the lowest-angular-momentum collisions lead generally to the (^{40}Ar,5n) reaction. The average excitation energies are taken to be about one neutron-binding energy above the yrast levels[27].

In the de-excitation process, high energy photons, probably mostly dipole, will first be emitted down to the vicinity of the yrast levels[27]. In the case of the (^{4}He,4n) reaction producing a rotational product nucleus, these high-energy transitions can populate directly all the various observed gsb members, since these members comprise the yrast levels over the populated angular-momentum range. However, on the average, several transitions occur and several units of angular momentum are lost prior to entry into the gsb[18-20]. This results in independent feeding to all the gsb members. For the (^{40}Ar,4n) reaction, however, the observed gsb members do not lie under the populated angular-momentum range and hence cannot be populated until another process removes about 20 units of angular momentum. Thus, the population collects first in the vicinity of the yrast line and then cascades down near this line, generally losing angular momentum as quickly as possible. (The region of energy levels above the non-gsb yrast line which receives significant population, we call the yrast region.) The gsb is first populated at the point where its members become the yrast levels. If several levels for each spin are contained in the yrast region, we would not expect to see strong discrete gamma-ray lines arising from the yrast decay due to the multiplicity of pathways available. This expectation is in accordance with observation. Such a simple picture then accounts very nicely for points 1) and 2) above. It also offers an explanation for the fact that β- and γ-vibrational bands are not observed in reactions with medium or heavy ions, but are observed in proton and alpha-particle induced reactions. In the first case practically all of the feeding into the lower levels is via the yrast cascade. In a well deformed nucleus, states of a given spin for the gsb are at a considerably lower energy ($\sim$1 MeV) than those of the β- or γ-vibrational bands. Therefore the point at which β- or γ-vibrational bands intersect the non-gsb yrast line will occur after this line has been depopulated by the gsb. Thus one would expect negligible population of these bands. However, in the case of the proton and alpha induced reactions the yrast cascade plays a much less significant role. The relative amount of feeding to the gsb and to the β- and γ-vibrational bands should then depend mainly on the relative energies of the feeding gamma rays. Clearly this would still favour the gsb members, since these lie lowest, but one would expect significant population to the vibrational bands as well.

Regarding point 3), Rasmussen and Sugihara[29]) have shown that if the initial angular momentum is rather large and the band is fed at a reasonably high spin value, then the alignment will be preserved for almost any intervening cascade. In fact, the observed alignments[11,12,19,20]) are in accord with those expected.

2.2 DISCUSSION OF FEEDING TIMES AND EXTENSION OF THE MODEL

We shall now consider the yrast region in more detail to see if feeding times as short as 10 ps are plausible and whether several levels are likely to occur within the yrast region for each spin value.

One can easily estimate that the yrast cascade following an (^{40}Ar,4n) reaction must carry off $\sim$ 20 $\hbar$ of angular momentum and $\sim$ 10 MeV of energy[13]. Thus the cascade could involve about ten E2 transitions of average energy $\sim$ 1 MeV, whose average lifetime would have to be $\sim$ 1 ps in order to account for the observed feeding times. Such transitions would be about 10 times faster than the Weisskopf single-particle estimate[30] for E2 transitions (10 spu). Similarly it could involve around twenty M1 or E1 transitions having average strengths of about 0.1 and 10^{-3} spu, respectively. None of these average strengths seems implausible, and the yrast cascade probably involves transitions of all these multipolarities to some extent. Higher multipolarities are, however, excluded. In the Er nuclei not more than 5% of the population involved feeding times greater than 10 ps. This result would be surprising if the yrast levels were simply excited quasi-particle levels, as in Grover's scheme. For in this case one could expect large variations in spacing between the yrast levels differing by one or two units of $\hbar$ (fig. 2). Such irregularities would require a considerable increase in the average transition matrix elements in order to agree with the experimental results. Let us assume for example, that all of the decay is by E2 transitions, half having energies of 1.5 MeV and the other half of 0.5 MeV. Then we would require them to have an average strength of 150 spu, an increase of 15 times over the case when the energies are equal. This result already becomes rather unlikely and would become quite unreasonable if, as might well be expected on this scheme, just one transition had an energy of 250 keV or less. Thus the systematic absence of traps (states with lifetimes greater than 10 ps) preceding the gsb population in the Er nuclei suggests that the levels in the yrast region have considerable regularity. The presence of collective bands would seem to be the most likely origin of this regularity, and at the same time such bands provide a natural explanation for E2 transitions of about the required lifetime.

The very sparse experimental evidence on the multipolarity of the unresolved de-excitation gamma rays in (HI,xn) reactions[31]) suggests that they are mainly E2, though further measurements should be done before this result can be considered certain (great care needs to be taken to eliminate effects due to the fast neutrons). Grover's calculations also suggest that a considerable fraction of the transitions in the yrast region should be E2. In fact, almost any model is likely to lead to this conclusion. Thus an explanation for the fast E2 transitions seems essential.

For further discussion it is convenient to consider a fairly realistic example of the outlined situation as shown in fig. 2. The heavy jagged line is an estimate of the energies of the lowest quasi-particle states for each spin value in an even rare-earth nucleus. The line actually comes from Grover's calculation for ^{152}Dy, which is probably a vibrational nucleus, but we take it simply as a line whose energy and irregularity are typical of what might be expected. Whether we take a vibrational or rotational nucleus for our estimate of the quasi-particle levels is probably of little consequence. The heavy smooth line corresponds to the gsb levels of a rare-earth rotor. We prefer to discuss a rotor here because we know better what to expect of the collective bands, although we feel a vibrator would not be qualitatively different. In fact, there may be no distinguishable difference between the two for high spin states[32]). For the gsb moment of inertia we start at a value typically observed and increase it to the rigid-sphere value ($\hbar^2/2\mathfrak{I} \sim 8$ keV) at I = 20 according to the formula:

$$\left(\frac{\hbar^2}{2\mathfrak{I}}\right)_{I\leqslant 20} = A + BI(I+1)$$

with A = 14 keV and B = - 14 ev. The light lines in fig. 2 correspond to the rotational bands based on several of the quasi-particle states. For these bands we have used a larger initial moment of inertia than for the gsb, and also increased it to the rigid value at I = 20; here, A = 11 keV and B = - 6.5 ev. These relationships were picked because they are simple and have the correct gross features.

It should be emphasized that there is considerable uncertainty in the moments of inertia chosen and in the quasi-particle energies, which could change the details of fig. 2. What happens at higher spins depends on how the energies of the lowest quasi-particle levels and of the rotational bands, which presumably have $\mathfrak{I}_{rig}$, vary with angular momenta. If the energies of the quasi-particle levels rise faster with I than do those of the rotational bands, than the lowest bands around I = 20 will continue to be the lowest bands for larger I. If both rise roughly at the same rate, then the density of levels in the yrast region will become very large as more and more bands are added to those already present. However, if the quasi-particle energies rise less quickly than those of the rotational bands, then a given band would rise slowly out of the yrast region. This could give nearly the original irregularities in the energies and level densities in the yrast region if this difference in rate of rise were large. We would then expect to get traps and consequently long feeding times. The experimental data seem to exclude this last possibility, at least for the studied cases. Grover's calculated quasi-particle states for ^{152}Dy do, in fact, fall below rotational bands having $\mathcal{J} = \mathcal{J}_{rig}$ for large spins. However, these calculations may not be sufficiently accurate to deal with such rather detailed features.

In order to explain the short feeding times, we have to explain not only the fast transitions within the yrast cascade, but also those from the non-gsb yrast levels into the gsb. This might seem to present a problem, because in rotational nuclei, K, the projection of I on the symmetry axis, can often be a good quantum number at low spin values ($I \lesssim 8$). Violations of the K selection rules can then result in very slow transitions. This must somehow be avoided at the higher spin values ($I \sim 14$) where the gsb in such nuclei is fed. The most obvious way to avoid these delays is to invoke considerable mixing among the bands at high spins, so that K is not a good quantum number. In fact, such mixing will always tend to remove the structural differences among states in the same energy region, and hence solve the problem under discussion in a more general way. These arguments might suggest that for spherical nuclei, in which the gsb is fed at lower spin values, the feeding times should be longer, in accordance with the (limited) observations.

All of the above requirements appear to be met naturally within our proposed scheme. The regularity of spacing is provided by the collective bands, as are also the enhanced E2 transitions within them. Heavy mixing amongst levels of the yrast region for spin I may be caused by the Coriolis force. The mixing arising from this increases with increasing angular momentum and can become very large for large I. However, since the Coriolis operator[33]) only couples states with $\Delta K = \pm 1$, for heavy mixing it is necessary that states with a complete range of K values up to the maximum I occur within a limited energy region, say 1 MeV. One can see from fig. 2 that the rotational bands based on the quasi-particle states are likely to produce just this situation, giving fairly high level densities in the yrast region. On the other hand this would not be so if most of the levels in the yrast region were quasi-particle levels, since they would have $K = I$. This situation is illustrated schematically in fig. 3, for the yrast region for spins $I, I + 1, I + 2$ with $I \sim 30\ \hbar$. Only a few of the many possible transitions amongst the levels are indicated. The energy separations between the three yrast levels correspond to those given by the rigid body moment of inertia. Clearly E1 transitions must compete frequently with E2 and M1 transitions, since traps corresponding to the termination of negative parity bands were not observed.

A further important point concerns the width of the region above the yrast levels over which population occurs; we have loosely referred to this as the yrast region. If this region were very narrow, so that very few levels of each spin were populated, then we would expect to see lines in the gamma spectrum, with intensities comparable to those of the gsb, arising from transitions between the levels of the yrast region. Such lines are not observed and this implies that many levels of the yrast region are populated. On the other hand if the width of the yrast region were very large, say several MeV, then one would not expect to see nearly all of the population of the gsb in the (^{40}Ar,4n) reaction going to just the top two or three members of the observed band. We can estimate a minimum width for this energy region in our model. If the levels are completely mixed so that the only differentiation amongst them is the energy dependence of the E2 transition probabilities, then the relative population of a level versus its energy above the yrast level can be represented by the insert in fig. 3. One sees that the population would be spread over 200 or 300 keV. (A similar result is obtained for M1 or E1 transitions, taking into account the fact that these have half of the average energy for E2 transitions.) A lack of complete mixing of the levels would probably increase this somewhat. This estimated width seems in good accordance with the requirements above. For example we can estimate from fig. 2 that four or five levels would be expected to occur within it.

From figs. 1 and 2 we see that, on our model, the population enters the gsb at the point where an energy gap develops between the levels of the gsb and of the yrast region. If this hypothesis is correct, we should be able to estimate roughly the average energy of the yrast region as a function of angular momentum for nuclides in a limited region of the periodic table. We can do this by plotting the energy of the highest observed member of the gsb against angular momentum for nuclei ranging from vibrators to rotators in this region. In fig. 4 we show such a plot for nuclei with $82 < N < 126$. The information comes from the published literature. The points of this plot are compared with the non-gsb yrast line from fig. 2. It can be seen that there is reasonable accordance between them, particularly when one remembers that the yrast region is probably about 0.5 MeV wide. This result can either be interpreted as giving some support for our scheme or, alternatively, as giving some information about the yrast region if one trusts the model. When more and better data are available this may prove to be of theoretical interest. For the moment two points must be stressed about such a plot. The data we have used here were not taken with our present purpose in mind and there is some ambiguity as to which is the highest observed state of the gsb. There must also be an uncertainty in the deduced energy of the yrast region of the order of about half of the energy of the highest observed transition. Secondly we must expect to get a considerable scatter of the points for low spins, because for these the position of the non gsb yrast line depends critically on the quasi-particle energies (see fig. 2). These may vary considerably from one nucleus to another. One might expect, on our model, rather less fluctuation in the energies of the higher spin yrast levels. One reason for this, which is evident from fig. 2, is that they are not so dependent on the energies of just one or two quasi-particle states.

3. Conclusions

It seems to us that the scheme outlined above can explain very nicely the features that have so far been observed in the population of the gsb following compound nucleus reactions induced by heavy ions. It seems also that, at least for rotational nuclei, the general scarcity of isomeric states having spins higher than 8 or 10 can be understood in terms of the model. The lowest two-quasi-particle states (I up to 8 or 10) occur at energies of the order of an MeV below those of the lowest four-quasi-particle states. This energy difference arises from the difference in pairing and in single particle energies, the latter being higher than one might first expect owing to restrictions on the available orbits due to the Pauli principle. The rotational states from the two-quasi-particle states usually therefore would be expected to have lower energies than four-quasi-particle states of the same spin. Only when four single-quasi-particle states, each with high spin, lie exceptionally close to the Fermi surface will it be at all likely that a four-quasi-particle state can lie below the two-quasi-particle rotational states, thus giving rise to an isomer. As can be seen from inspection of the Nilsson energy levels[34]) this situation occurs rarely in the rare-earth region, though it might be more common in the actinide region. It is uncommon even for two single-neutron states or two single-proton states of high spin to lie close together. Hence the most favourable chance for a four-quasi-particle isomer to exist is likely to be when two high-spin neutron states and two high-spin proton states lie very close to the Fermi surface. In this case one may see in the same nucleus, a high-spin two-quasi-neutron isomer, a high-spin two quasi-proton isomer and a four-quasi-particle isomer with a spin equal to the sum of the other two. An example of this rare situation, so far the only one seen, has been reported for the nucleus ^{178}Hf [35]. Here there are two 8^- two-quasi-particle isomers and a 16^+ four-quasi-particle isomer.

One interesting point should be emphasized. This scheme says that following a heavy-ion reaction, the gsb is fed at a particular point <u>because</u> at that point its members fall below other levels of comparable spin. Thus it is fed at or near the point where an energy gap develops, and presumably this energy gap is caused basically by the pairing of nucleons. The scheme then, implies that there is a relationship between the pairing as a function of angular momentum in a nucleus and the onset of population into the gsb of that nucleus following a heavy-ion, compound-nucleus reaction. If the nature of this relationship can be understood, the feeding point of the gsb can provide some very interesting information on nuclear structure.

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Figure Captions

Fig. 1. Schematic figure showing the energy levels in a nucleus of mass ∿ 160 <u>versus</u> angular momentum. Indicated on the figure are 1) the lowest non-gsb energy levels for each spin (yrast levels), 2) the regions of populated states following (He,4n) and (Ar,4n) reactions, and 3) the gsb levels of a typical vibrator (dots) and rotor (dashes).

Fig. 2. Energy levels in a rare-earth rotational nucleus plotted versus angular momentum. The heavy jagged line is an estimate of the lowest quasi-particle state for each value of I, and the light lines correspond to rotational bands built on these states. The heavy smooth line represents the gsb levels and, to avoid confusion in the figure, is not drawn in beyond $I = 16$.

Fig. 3. Schematic illustration of levels, and transitions between them, in the yrast region for $I \sim 30$. The energy spacing between consecutive yrast levels is taken to be the same as would be obtained if the nucleus were rotating as a rigid body. All of the levels vertically above an yrast level have the same spin; the actual level density would probably be considerably larger than shown here. The insert shows the relative population of these levels if the only differentiation amongst them is the E2 energy dependence.

Fig. 4. Energies of gsb states of highest spin (dots) observed in (HI,xn) reactions leading to final even nuclei plotted against spin. The line is the non-gsb yrast line derived from fig. 2. The region of nuclei included is for $82 < N < 126$.

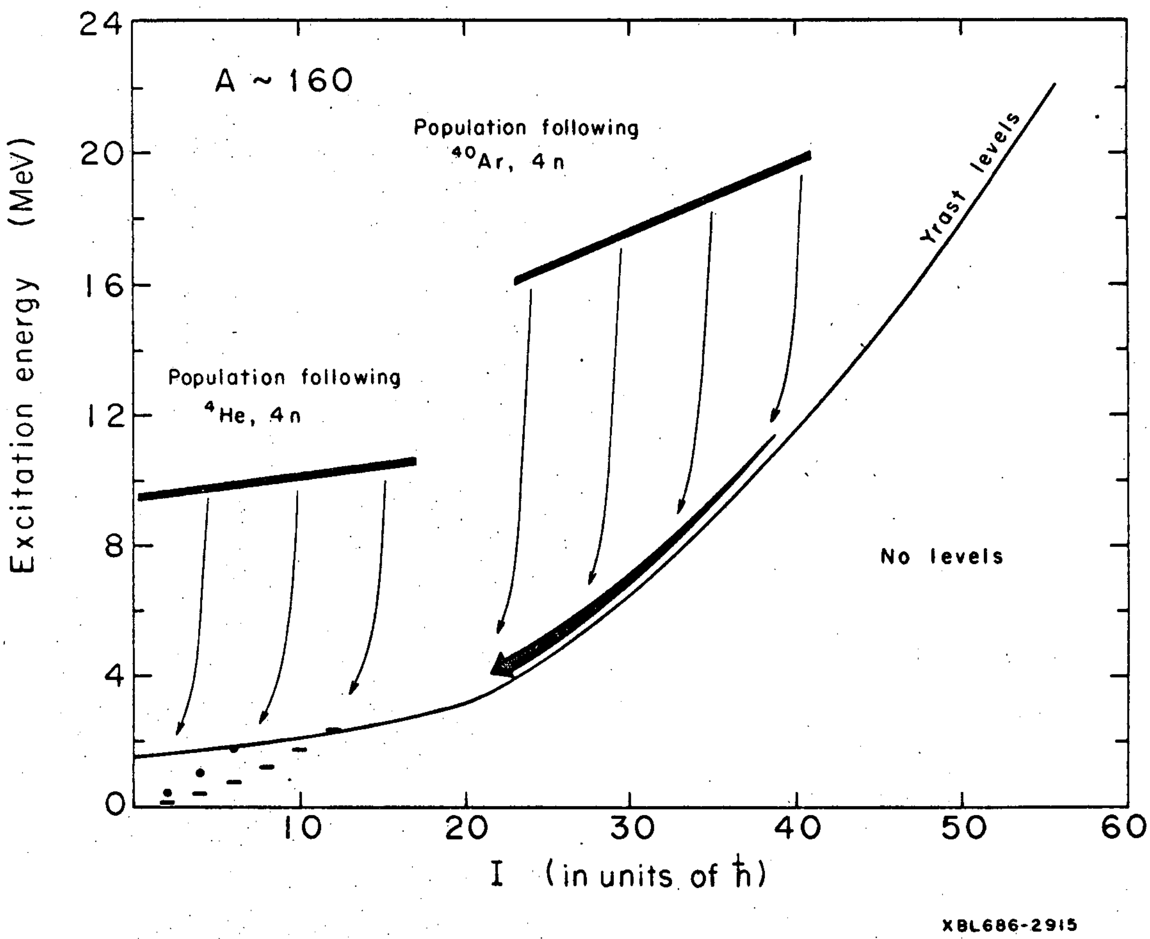
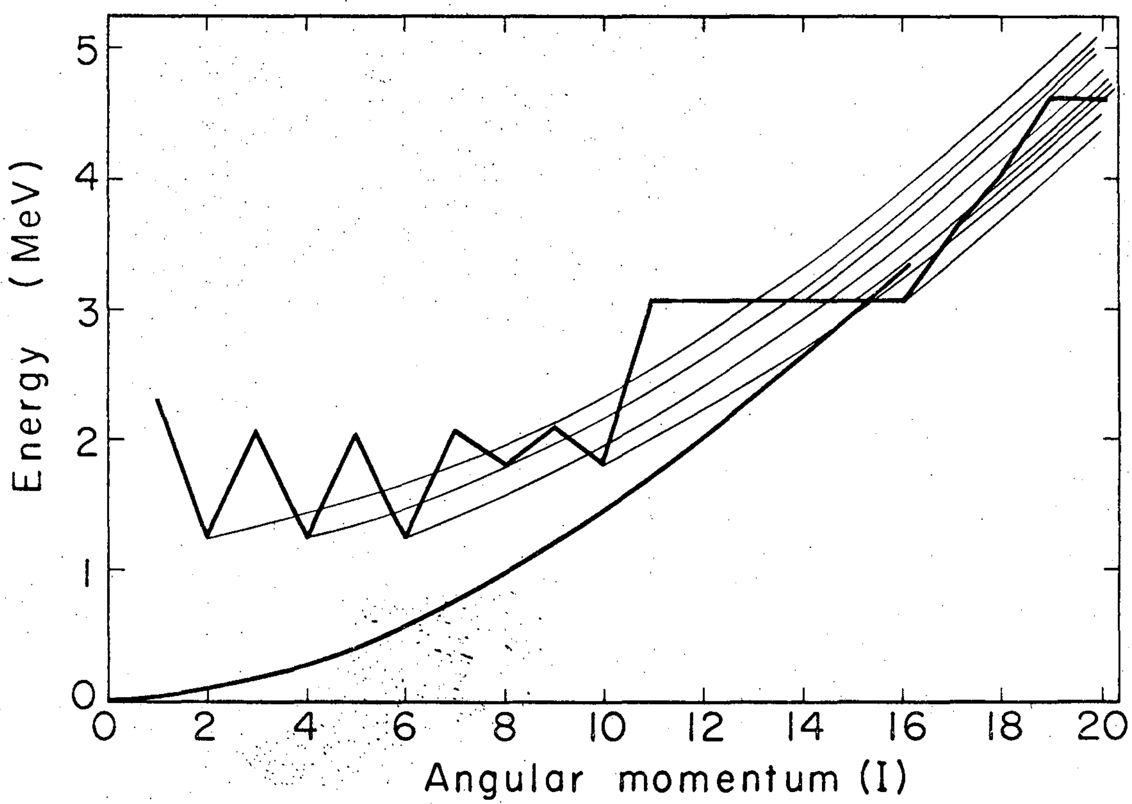

A ~ 160
Population following
^{40}Ar, 4n
Population following
^{4}He, 4n
Yrast levels
No levels
Excitation energy (MeV)
I (in units of ħ)
0
4
8
12
16
20
24
10
20
30
40
50
60
XBL686-2915

Fig. 1



XBL694-2610

Fig. 2

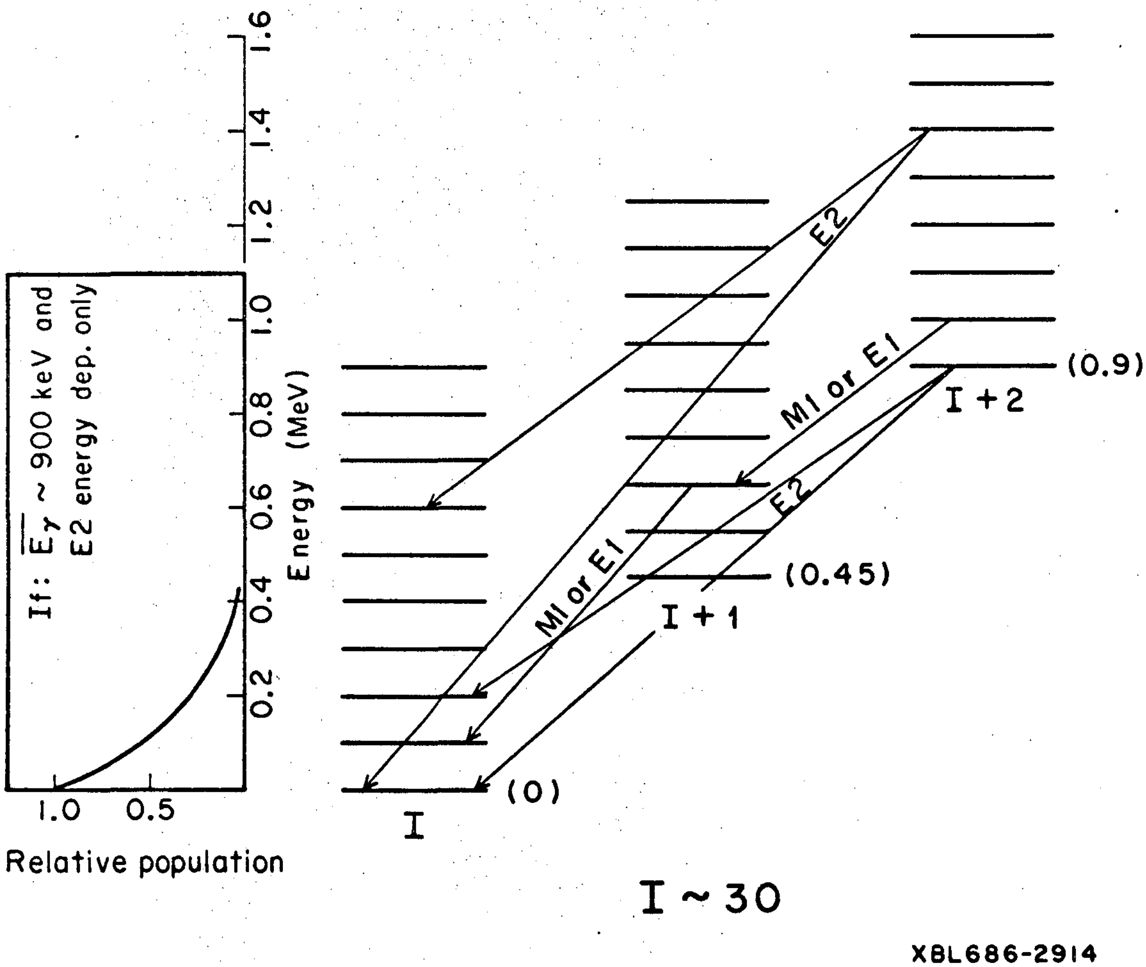
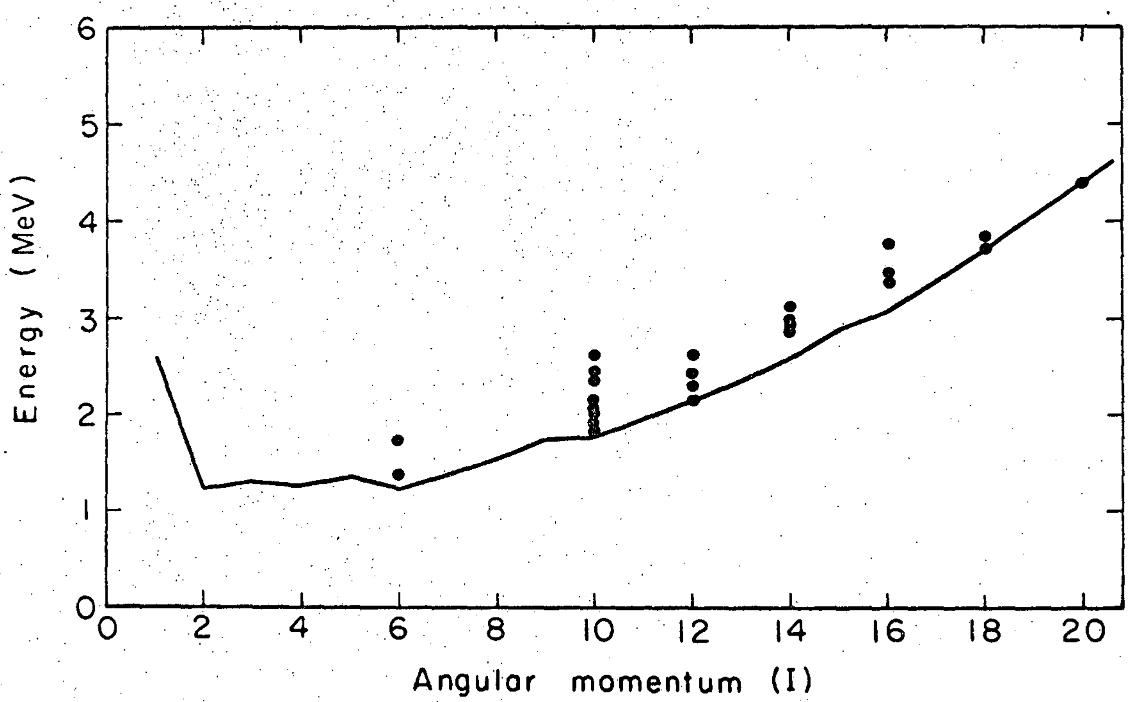

If: $\overline{E_\gamma}$ ~ 900 keV and
E2 energy dep. only
Relative population
1.0
0.5
Energy (MeV)
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
E2
M1 or E1
M1 or E1
E2
(0)
(0.45)
(0.9)
I
I + 1
I + 2
I ~ 30
XBL686-2914

Fig. 3



XBL698-3656

Fig. 4