Title
SOME PERSPECTIVES ON HIGH-SPIN PHYSICS

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SOME PERSPECTIVES ON HIGH-SPIN PHYSICS

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I would first like to point out that the title of this talk was rather carefully chosen. There are two key words in it. The first is "perspectives" which implies particular viewpoints, and is intended to justify both my choice of subject matter and perhaps also my treatment of it. The second key word is "some" which implies that I will not try to be comprehensive, but will discuss only several areas which especially interest me. It should be clear that this is not a summary talk. There are two reasons for that, the first of which is statistical. I have found that at least 90% of summary talks leave something to be desired (often that they did not refer to my talk), and I was not optimistic enough to try for the remaining 10%. The second reason (no doubt important to some speakers) is that someone else has also realized these statistics and I was not asked to give a summary talk. So whatever happens you should not add this to your list of bad summary talks.

I do want to begin, however, by looking at the organization of this field. I believe it divides rather naturally into four areas, depending on how the nucleus carries angular momentum, and how we study it. Certainly the main theme of this meeting has been the interplay of collective and non-collective modes for carrying angular momentum. Those speakers who discussed regions of collective nuclei were looking for non-collective (single-particle) effects at high spins; whereas, those speakers who discussed non-collective regions were looking for collective effects (e.g. deformation). The other dividing feature is experimental and depends on whether the γ-rays deexciting the states are resolved (normal spectroscopy) or unresolved (continuum spectroscopy). These considerations lead to the following outline:

High-Spin Phenomena

I. Collective regions

A. Resolved γ-rays $I \lesssim 30\hbar$
B. Unresolved γ-rays (continuum) $I \lesssim 70\hbar$

II. Non-collective regions

A. Resolved γ-rays $I \lesssim 40\hbar$
B. Unresolved γ-rays $I \lesssim 70\hbar$.

Even within these limits I do not want to summarize what has been said at this symposium. Instead, I will remind you of a few things and discuss several areas that interest me - some of which have been covered here and some of which have not.

Considering first the study of resolved γ-rays in collective regions, there has been a lot said and I have nothing to add. For completeness I will just remind you that the upper limit of spins that can be studied this way is about $30\hbar$; and this is strictly an experimental limitation. By Coulomb excitation we can only climb up this high, even with Pb projectiles, and in the compound-nucleus reactions the population is spread too widely above this spin value. This limitation seems unfortunate; however, we should remember that if there were strong resolved lines up to the highest spins populated, this field would probably have reached its peak 10-15 years ago. Collective motion implies band structures, and studies of the resolved γ-rays are aimed at extracting information on the details of these structures. A good fraction of the effort has involved studying backbending, or more generally, band crossings. While there are several processes occurring in these nuclei as the spin increases (a decrease in pairing correlations, and sometimes shape changes), the basic change seems to be the onset of non-collective modes for carrying part of the angular momentum. The mechanism for this is the sequential alignment of particle angular momenta along the rotation axis of the nucleus, and in the opening talk of this symposium Mottelson showed how far we have come in understanding this process.

If we want to learn about spins higher than 30ħ in these collective regions, we must study the unresolved γ-rays. It is now clear that under the proper circumstances these γ-rays can come from states with spins up to 70ħ, which is the maximum limit of stability of nuclei against fission. Many experiments have now been made studying continuum γ-rays, and I just list here eight types of measurements so far made: 1) shape of spectrum; 2) angular correlations; 3) polarizations; 4) conversion electrons; 5) X-rays; 6) lifetimes; 7) multiplicities; and 8) total γ-ray energies. To remind you briefly, the shape of the spectrum shows a low-energy bump which contains the transitions that carry away the angular momentum of the system and a higher-energy tail that is composed of "statistical" transitions that "cool" the nucleus down to (or toward) the yrast line. Measurements of type 2, 3, 4, and 5 all aim at defining the multipolarity of the γ-rays, and show that the statistical tail is probably mostly E1 transitions, and the bump in some cases is composed of pure stretched E2 ($I \rightarrow I-2$) transitions, and in other cases is more complex. The lifetime measurement showed that (in one case) the stretched E2 transitions are strongly enhanced (collective), and the multiplicity measurements give information about the average spin of the states emitting γ-rays of a particular energy. Finally the total γ-ray energy studies have so far been used mostly to fractionate the events into regions that differ in average spin (higher total energy corresponds to higher average spin). I do not want to go into more detail on these types of measurements, but rather to emphasize just one feature of these collective spectra - the correlations - that have helped enormously in understanding these spectra, and promise even more.

The strongest correlations from collective nuclei seem to be associated with rotational cases, and since many of the observed spectra are rotational, I will discuss that case. In the left portion of Fig.1 a rotational band is shown with the usual $I(I+1)$ energy spacings. The γ-ray spectrum from this band is shown in the right portion of the figure. This spectrum is a sequence of equally spaced lines whose energy is proportional to the spin. The bump region of the continuum spectrum consists (in some cases) of many such bands shifted somewhat relative to each other, so that a rather flat "continuum" results. However, such a continuum spectrum contains strong correlations, and I want to discuss two kinds of those.

The first kind of correlation is between γ-ray energy and spin. It is apparent in Fig. 1 that the highest γ-ray energies (in the bump) come from the highest spin states. Thus if we change the maximum spin observed, there should be a corresponding shift in the maximum γ-ray energy seen. The maximum spin can be changed in several ways; for example, varying the bombarding energy or projectile; selecting different reaction channels; or selecting different regions of total γ-ray energy. It is perhaps worth pointing out that the first direct evidence for rotational behavior of continuum γ-rays was the movement of the edge with bombarding energy. To illustrate this behavior, Fig. 2 shows spectra from the ^{124}Sn + ^{40}Ar system as seen[1] in a 7.5x7.5 cm NaI detector at 0^{o} to the beam direction for three different slices of total γ-ray energy. The total energy was measured in a 33x20 cm NaI crystal having a 2.8 cm diameter hole along the axis, with the target located at the center. The principal change as the total energy is increased is the movement of the upper edge of the bump to higher γ-ray energies, although (1) the edge is not very sharp due to the poor selectivity (resolution) in spin of this method, and (2) there is a small backbend peak at about 600 keV that comes in with the 4n channel which is favored at higher total energies. This movement of the edge shows clearly the rotational relationship of γ-ray energy with spin for the nuclei produced in this reaction (mainly ^{159}Er and ^{160}Er).

Another illustration of this correlation is in the multiplicity spectra, which show the number of coincident γ-rays as a function of γ-ray energy. (In this discussion, as well as some other places in this talk, I will tend to imply that there is a simple connection between multiplicity and spin. This is sometimes true, as in the rotational nuclei I will discuss here, but it is far from a simple connection in other cases, and one must be careful not to assume that it is always the same. Nevertheless, when the multiplicity is high it is very likely connected somehow to spin and is perhaps the best incicator we have for the spin). In Fig. 3 a γ-ray spectrum[2] is shown for the reaction $^{124}Sn + ^{40}Ar$ at 185 MeV, and superimposed is the multiplicity spectrum. The multiplicity is roughly constant ($\sim$18) in the region of the statistical tail, since these statistical γ-rays come equally from all spin values. However there is a peak near the upper edge of the bump, which then falls at lower γ-ray energies. The reason for this is clearly evident in Fig. 1. The γ-rays at the edge of the bump come from the highest spin states and always have many γ-rays following them, whereas the lower-energy γ-rays come from lower-spin states which sometimes are populated in the deexcitation of a high-spin state but other times come from lower-spin states. This kind of correlation of multiplicity (spin) with γ-ray energy is the specific signature of a rotor.

The second kind of correlation I want to discuss is the one between γ-ray energies in a rotational nucleus. The solid lines in Fig. 4 represent a portion of the rotational spectrum shown in Fig. 1. I have focussed arbitrarily on a γ-ray energy of 1100 keV, which might correspond to a spin of $40\hbar$ ($40\rightarrow38$) for a moment of inertia ($\mathcal{J}_o$) reasonable for a rare-earth rotational nucleus. The other lines then correspond to other initial spin values as indicated. The dashed and dotted transitions in Fig. 4 correspond to moments of inertia 5 and 10% larger and smaller than $\mathcal{J}_o$, with always one transition exactly at 1100 keV (these bands might have the same or different spin values). In general any other γ-ray energy is equivalent to the 1100 keV chosen here so that a continuum γ-ray spectrum results. However, if we gate on a narrow energy region at 1100 keV, then we select <u>only</u> the transitions shown in Fig. 4, without the 1100 keV line itself. We then should see the peaks corresponding to $I_0 \pm 2$, $I_0 \pm 4$, etc. The separation of the peaks gives directly the average moment of inertia, and the width of the peaks gives the spread in moments of inertia. Furthermore, we can gate on different energies (than 1100 keV) and thus study different spin regions ($E_\gamma \propto I$). Several groups have tried to see these correlations without success, but recently the Copenhagen group of Andersen et al.[3] have developed new methods for processing such data and have seen these correlations. This is exciting both because it gives more detailed information about the rotational properties, and because it can select a very narrow region of spins. The spread of spin values is just proportional to the spread in moments of inertia, which might be as small as ±5%. This is much better than can be done by any other method at present. These correlations offer a unique opportunity for studying rotational nuclei, and I suspect we will be hearing much more about them.

There has recently been considerable interest in resolved spectra in non-collective regions. These spectra go to somewhat higher spins ($\sim 40\hbar$) than in collective regions due to a more rapid cooling to the yrast region. Two outstanding level schemes here[4,5] are those for ^{152}Dy and ^{154}Er, which reach spins of 36 or $37\hbar$, the highest yet seen. Fig. 5 shows the spectrum of ^{152}Dy as deduced by Khoo et al.[4]. Perhaps the most intriguing aspect of this scheme is the plot of energy vs. I(I+1) shown in Fig. 6, where one sees that above about spin 16 the data points fall surprisingly close to a straight line having a slope that would correspond to a moment of inertia 10-15% larger than the rigid sphere value. This is the type of behavior suggested by Bohr and Mottelson[6] for a system effectively rotating about a symmetry axis, and the question arises as to whether these data for ^{152}Dy indicate such a behavior, corresponding to an oblate (most likely) deformation around $\beta \simeq 0.25$. An answer to this question has been suggested by Leander in his talk at this symposium, and it is confirmed by calculations due to Moretto[7], which I will discuss briefly.

Moretto considers a cranked Nilsson potential with pairing in the BCS approximation. The curves he calculates for spherical shapes having Z=66 (Dy) and N=84, 86, and 88 are shown in Fig. 7, compared with the $^{152}_{86}$Dy data. One sees that the observed behavior of ^{152}Dy is very well reproduced without any deformation at all. The calculated curves are straight above $I \approx 16$, and although the slope calculated for N=86 would correspond to a moment of inertia about 20% larger than that indicated for ^{152}Dy, one expects this overestimate from the Nilsson potential due to the ℓ^2 term. The conclusion is that the slopes of these lines are not giving us information about the shapes of nuclei, but are simply shell effects in spherical or near-spherical nuclei, and vary considerably in this region due to the number of valence neutrons. It is, however, not so clear why both the calculations and experiments give such straight lines over such long spin intervals.

I would like to make one additional point about these weakly collective nuclei in the N=86 region. This is perhaps more a plea to the theoreticians than anything else. In Fig. 8 I have plotted $4I/E_\gamma$ vs I (initial) for all the stretched E2 transitions in ^{152}Dy and ^{154}Er. The choice of $4I/E_\gamma$ is somewhat arbitrary (E_γ would have done as well), but I selected stretched E2 transitions because they should be sensitive to the onset of collective effects. Two regions of differing collectivity are apparent in Fig. 8. Up to about spin 16 the transitions are quite regular (correlated) and, in fact, all have energies within the range 0.5-0.8 MeV. This type of behavior might be called "vibrational", though the exact nature of such collective motion is not really known. By analogy with nuclei like ^{144}Nd or ^{148}Sm, where transition probabilities and quadrupole moments of similar levels have been measured, these E2 transitions are probably enhanced 30-40 times over the single particle values, and indicate deformations (probably prolate) around $\beta \approx 0.15$. Between spin 16 and 36 there is less regularity of the levels, indicating less collectivity, though these E2 energies are by no means randomly spread. It is difficult to estimate how collective these nuclei are in this region, but Aguer et al.[8] have measured six E2 lifetimes in this spin region of ^{154}Er, and though they vary from 0.5 to 50 single particle units, a rough average would be 5-10 single particle units, indicating a deformation, $\beta<0.1$. Above spin 40 there is evidence that these nuclei very probably become strongly deformed and rotate. Trautman mentioned this possibility in his talk here, and in Fig. 9 I show you recent spectra of Deleplanque et al.[9]. The ^{124}Sn + ^{40}Ar system produces the well known rotational nuclei ^{159}Er and ^{160}Er, while the ^{119}Sn + ^{40}Ar system produces mainly ^{154}Er and ^{155}Er in the N=86 region under discussion. The lower bump in the ^{119}Sn system corresponds to the transitions in the region $I \lesssim 36\hbar$, which have just been discussed. The upper bump is composed almost entirely of stretched E2 transitions, comes from spins greater than about $40\hbar$ and, by comparison with the ^{124}Sn system, is very likely composed of rotational transitions from nuclei with $\beta \sim 0.3$ having spins in the range, $40\hbar \lesssim I \lesssim 60\hbar$.

The point of the previous discussion is that these nuclei, ^{152}Dy and ^{154}Er, very likely have three different deformations in different spin regions. These can be easily recognized by the regularity (or correlations) in the stretched E2 γ-ray energies. Even in a continuum spectrum we could hope to see such correlations. The question, then, is: exactly how does the collectivity (quadrupole-quadrupole interactions) smooth out these transition energies? Or, put more explicitly: can these correlations in the γ-ray energies tell us more about the shape and dynamics of nuclei at high spins? It would also be interesting to know how the nucleus makes the transition between these regions of different deformation (collectivity) without measurable delay. I would like to challenge the theoreticians to help us get more information out of the kinds of measurements we can make on these weakly or non-collective nuclei.

I have already shown you a non-collective (or weakly collective) unresolved spectrum, and you could see (hopefully) the interesting information it contained. Many other cases have been studied, and the onset of rotational behavior is a feature often observed. The nuclei just above Z=50 begin to rotate at $I \sim 35\hbar$, for example, and the Sm nuclei around N=82 begin only around $I \sim 55\hbar$. Other types of behavior are more difficult to establish, since they lack the strong rotational correlations that we know how to identify. In such cases we must isolate narrow regions of high spin values for study, and up to the present time we have not been so successful at that.

Three methods have so far been used to select regions of high spins. These are: (1) multiplicity filter; (2) total-energy crystal; and (3) selecting a particular reaction channel. In Fig. 10 I have sketched the sensitivity of these methods to different spin (multiplicity) values. The dotted curve shows the sensitivity of the third fold (3 counters firing) of a multiplicity filter with six counters each having a solid angle of 2.5% of 4π. The dashed curve shows that the fourth fold of a filter with 15 counters, each with Ω=1%, differs very little. Both have a full width at half maximum of around 100% of the average multiplicity, and can be used to enhance high spins, but not really to select spin regions. The light solid line shows that a slice of total γ-ray energy (Ω=80%) is not so much better as a spin selector. It has a full width at half maximum of about 70%. The measured values for separate reaction channels are also of approximately this width ($\sigma \sim 0.3\bar{M}$). You should recall here that the rotational correlations might be able to select regions as narrow as ±5%, which is enormously better than these other methods.

The question then arises as to how we can select experimentally a narrow region of multiplicity (spin), and it is easy to show that to do so requires nearly the full 4π solid angle. This leads to the concept of the crystal ball, a shell of NaI about 15 cm thick and 50 cm inner diameter, divided into 100-200 elements. There is now considerable interest in such detectors and several have been designed. One of 70 elements is being built by Sarantites[10]. These detectors can give about

20% full width at half maximum in multiplicity, which is shown as the heavy curve in Fig. 10. Here one can really begin to talk of selecting a region of multiplicity (spin). In addition a crystal ball can give the total γ-ray energy, the γ-ray angular distribution and some individual γ-ray energies, all on an event-by-event basis. I believe one of the main hopes for the continuum studies, especially in weakly collective regions, lies in such counters.

It seems to me that this field of high-spin phenomenon is an exciting one at the present time. I have tried to emphasize where I believe the excitement now is, and to indicate some of the places where I think it may develop in the near future.

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Figure captions

Fig.1. Rotational levels (left) and corresponding rotational transition energy spectrum (right).

Fig.2. Continuum spectra in coincidence with 4 MeV wide slices of total γ-ray energy having average energies of: 20 MeV (solid line); 24 MeV (dashed line); and 28 MeV (dotted line).

Fig.3. Continuum spectrum (solid line) with γ-ray multiplicities (dots) for each energy interval.

Fig.4. Rotational transition energies for bands having one transition energy at 1100 keV and moments of inertia: 143 MeV^{-1} (solid line); ±5% (dashed lines); and ±10% (dotted lines).

Fig.5. Level scheme of ^{152}Dy.

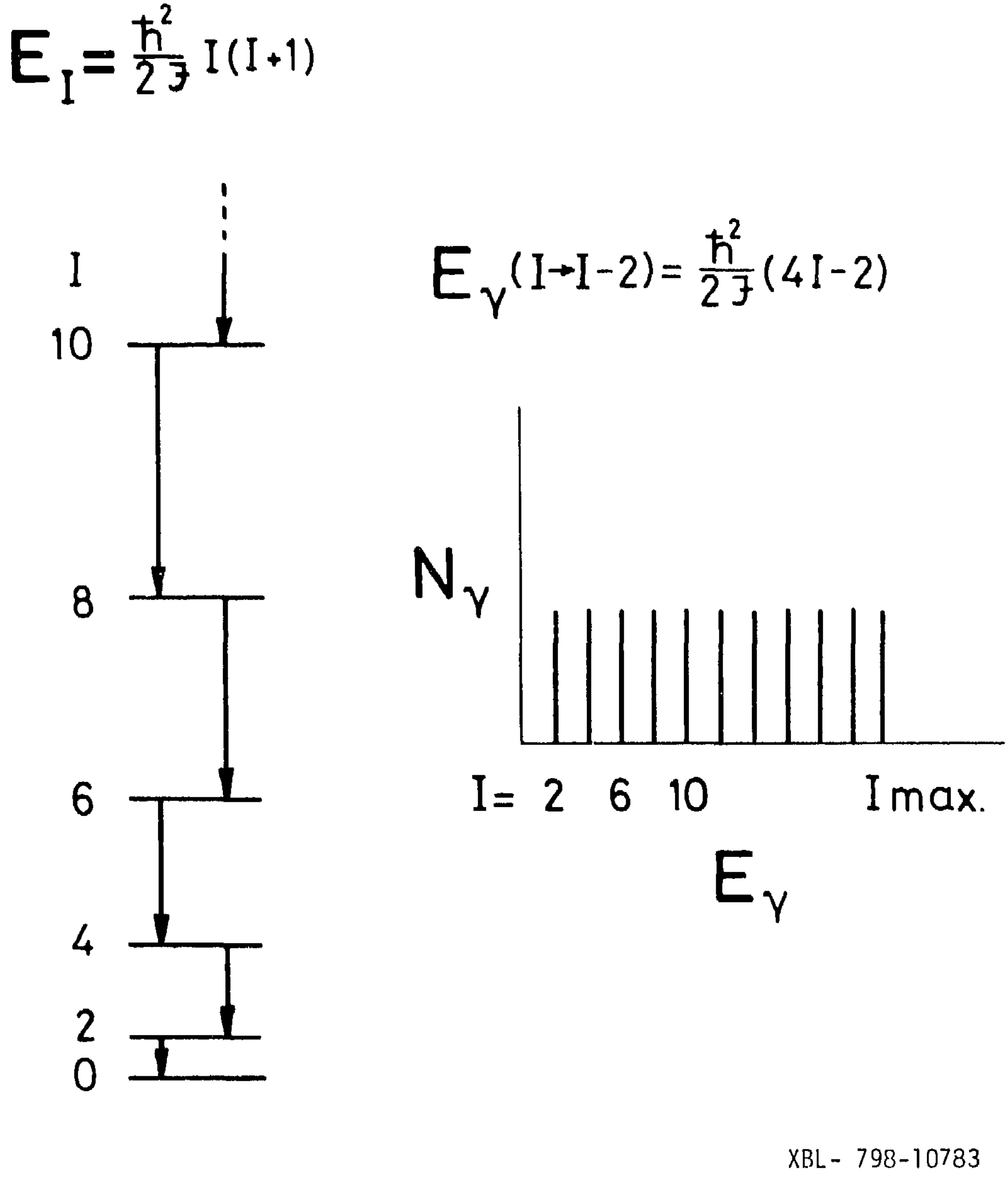
Fig.6. Plot of energy vs I(I+1) for the levels of ^{152}Dy.

Fig.7. Calculated curves of energy vs I^2 for nuclei with Z=66 compared with the data for ^{152}Dy. An effective moment of inertia, $2\mathcal{J}/\hbar^2$, extracted from the slope of the high-spin straight portion of each curve is indicated.

Fig.8. The quantity $4I/E_\gamma$, is plotted vs I for all the observed stretched E2 transitions in the ^{152}Dy and ^{154}Er level schemes. Three transitions (top) fall outside the figure.

Fig.9. Continuum γ-ray spectra from ^{119}Sn and ^{124}Sn targets bombarded with ^{40}Ar projectiles. Both spectra were taken at 0° and in coincidence with 4 detectors from a 6-detector multiplicity filter (fourth fold).

Fig.10. Relative sensitivity to multiplicity of the third fold from a multiplicity filter with 6 detectors each having a solid angle of 2.5% of 4π (dotted line); the fourth fold from a filter with 15 detectors, each of 1% solid angle (dashed line); a slice of total energy from a large NaI detector having 80% of 4π solid angle (light solid line); and a spherical shell of NaI with 90% of 4π solid angle and 162 elements (heavy solid line).



XBL- 798-10783

Fig. 1

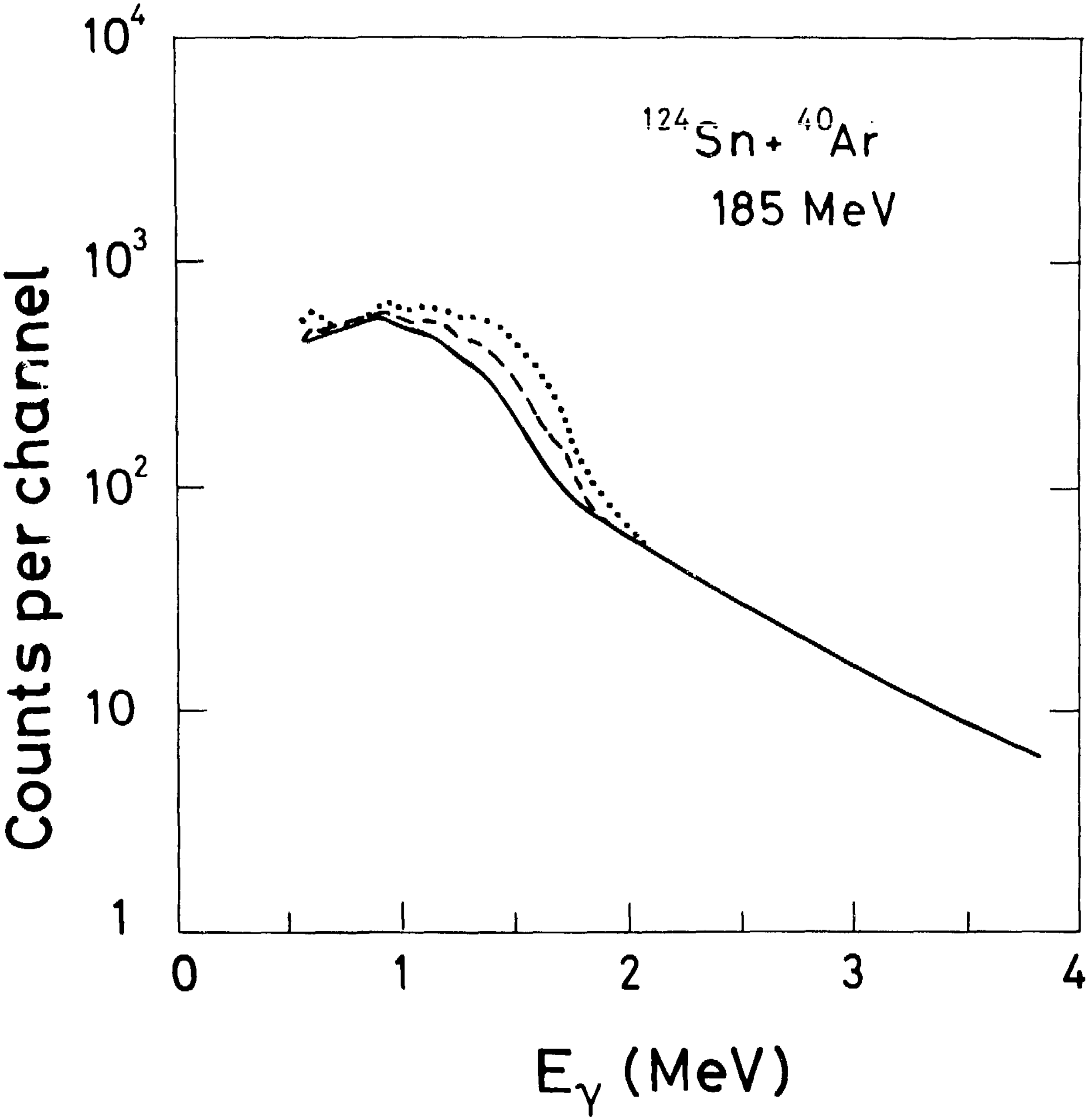


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Fig. 2

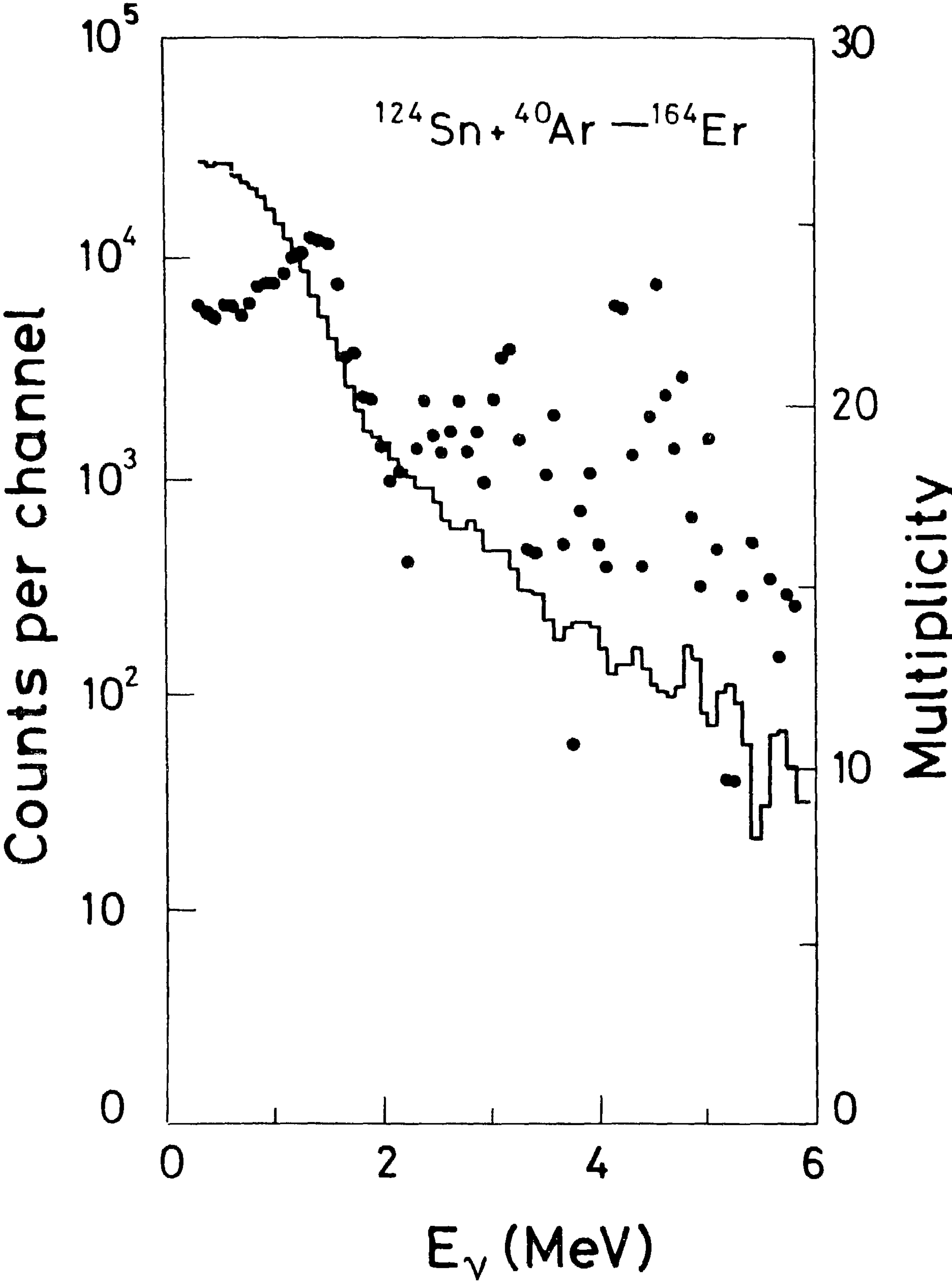

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Fig. 3

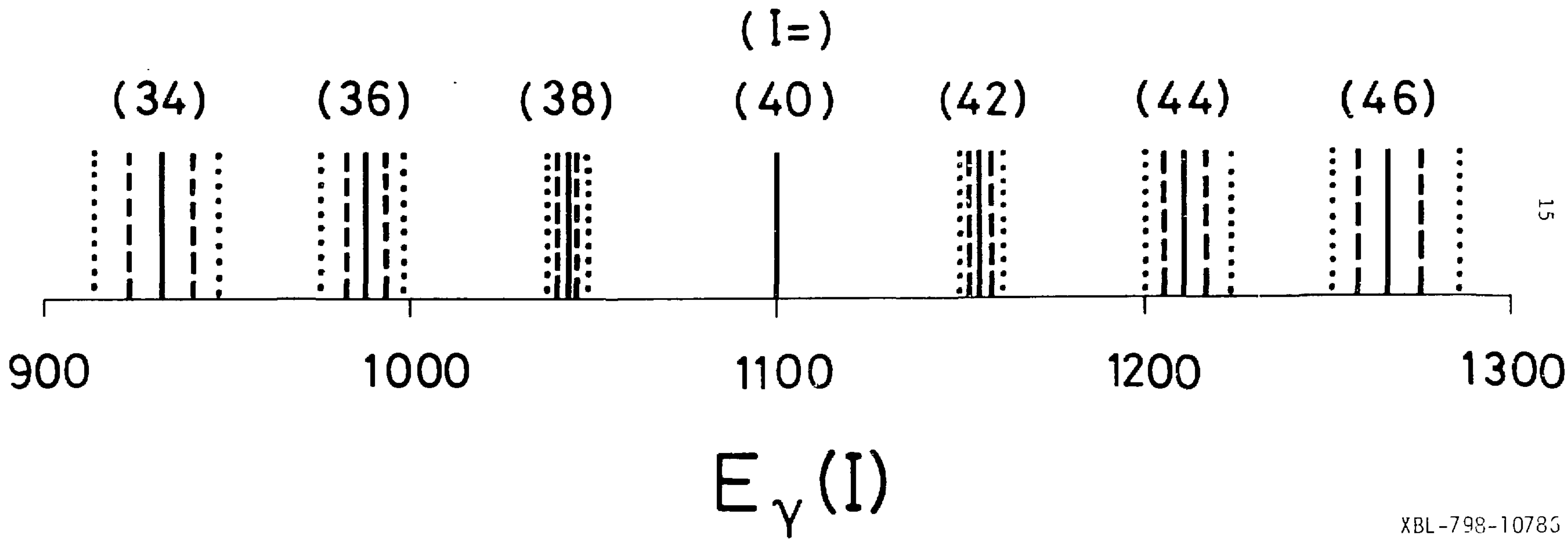

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Fig. 4

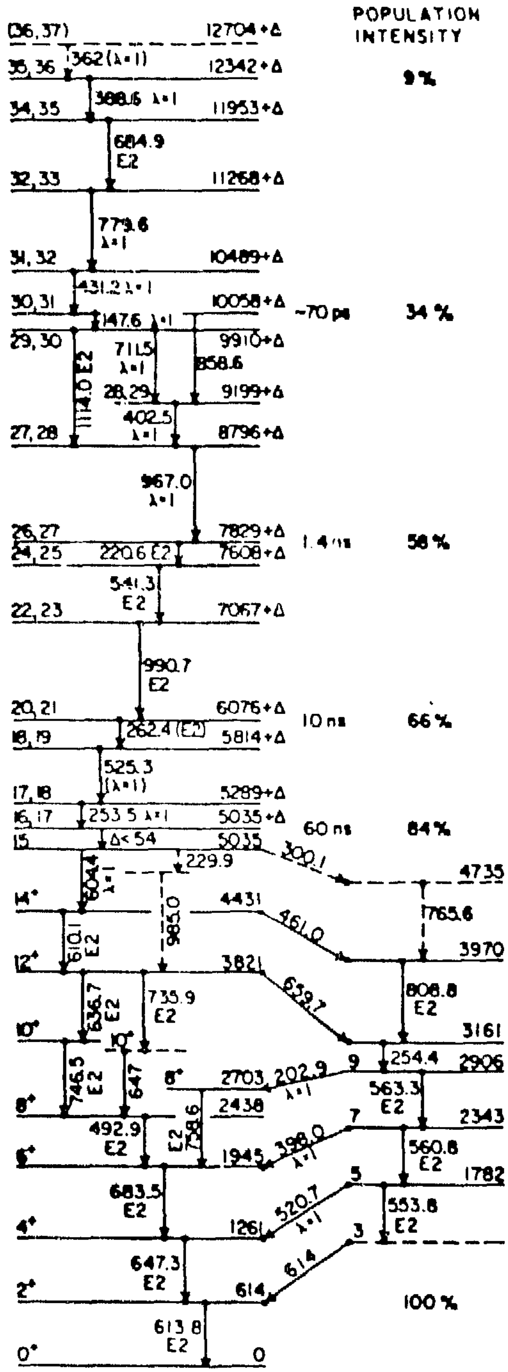

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Fig. 5

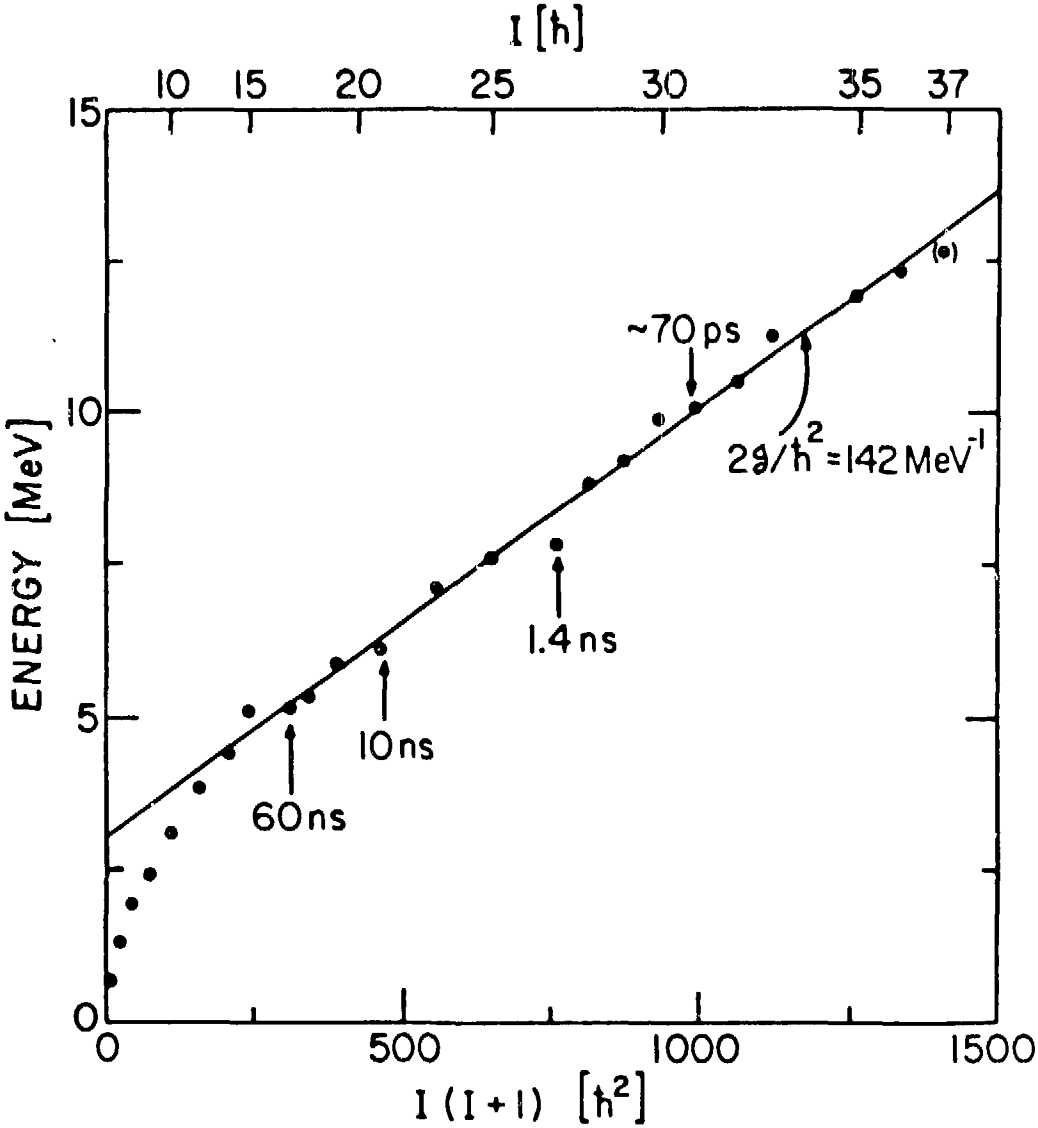

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Fig. 6

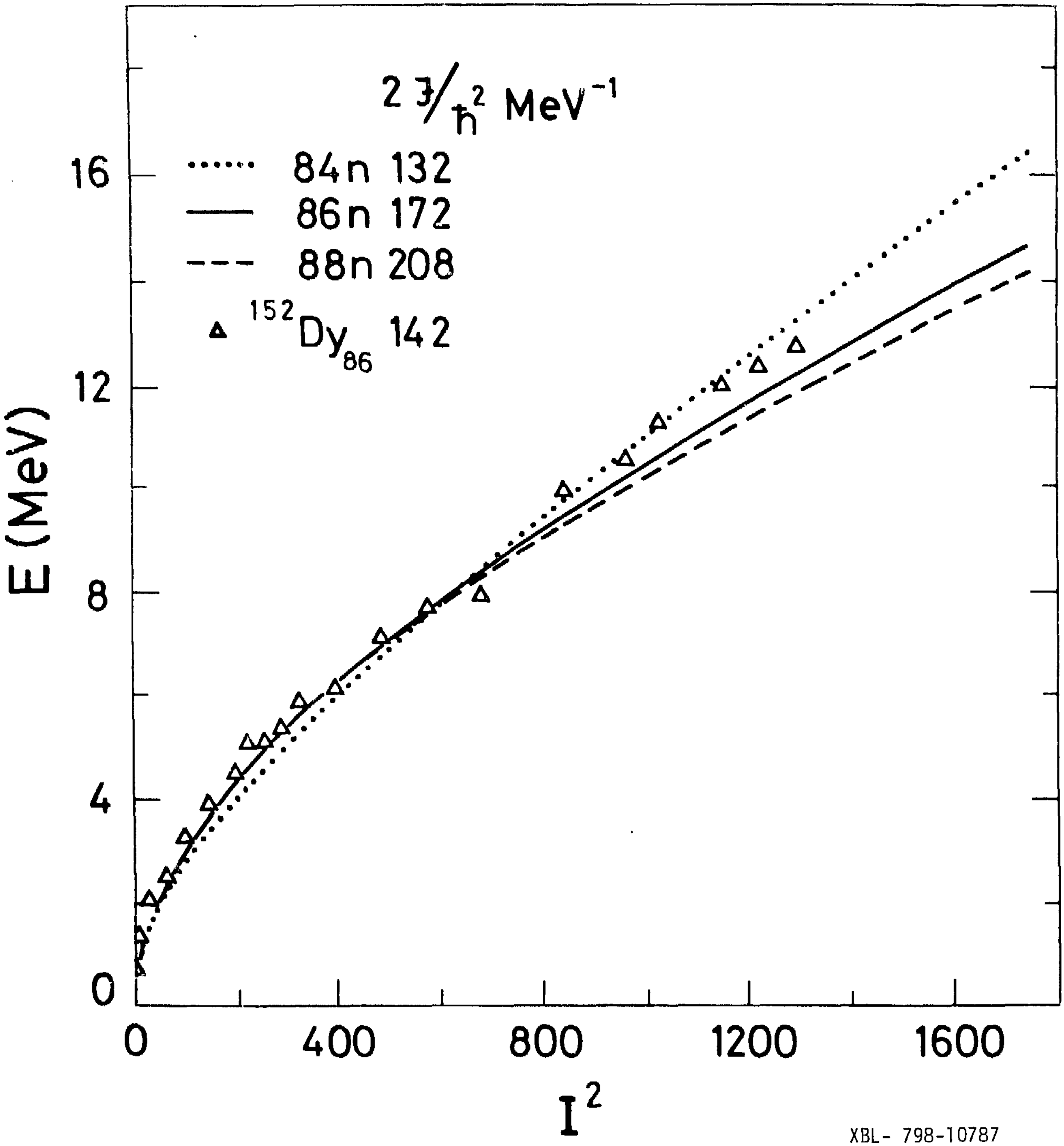

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Fig. 7

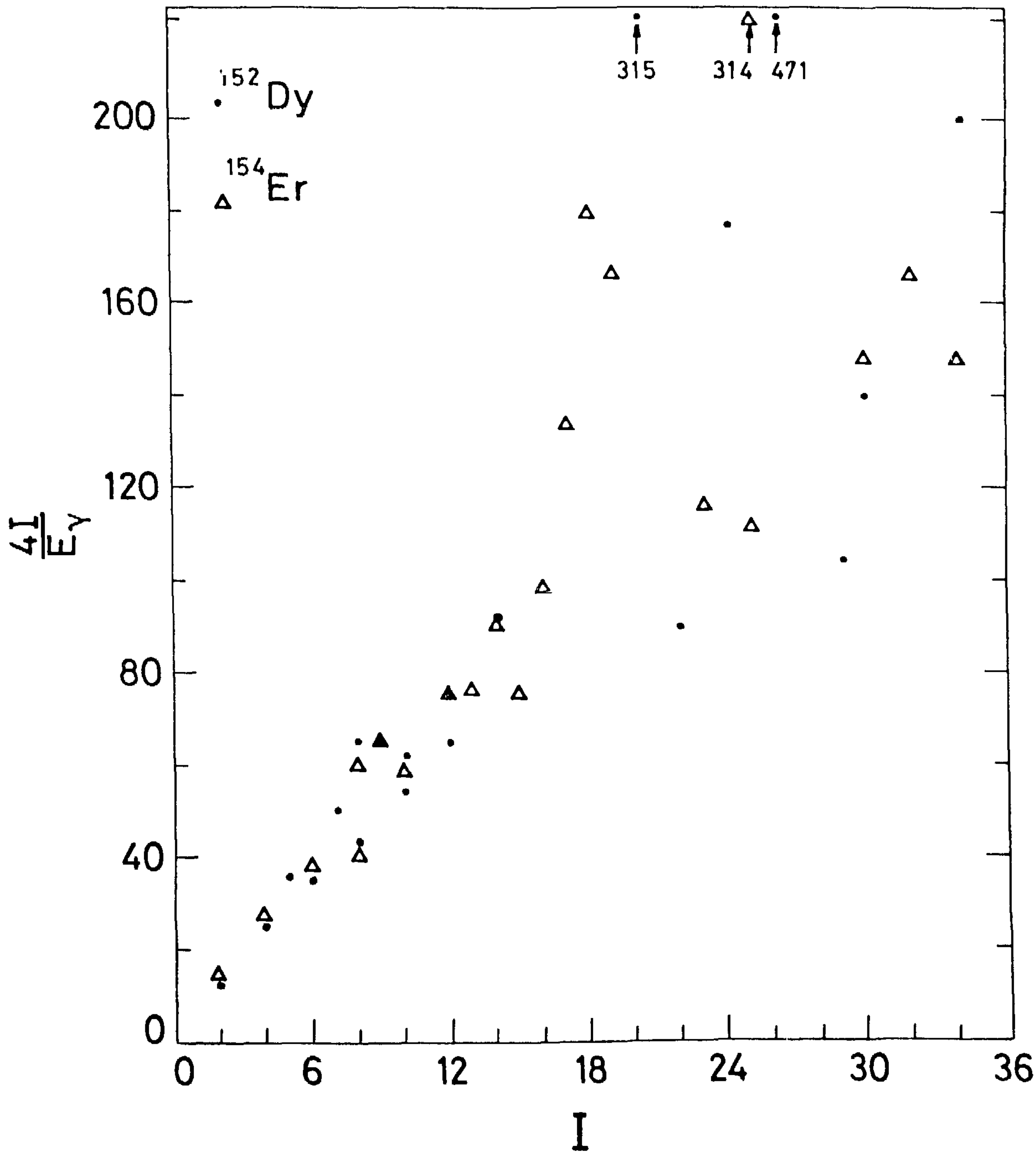

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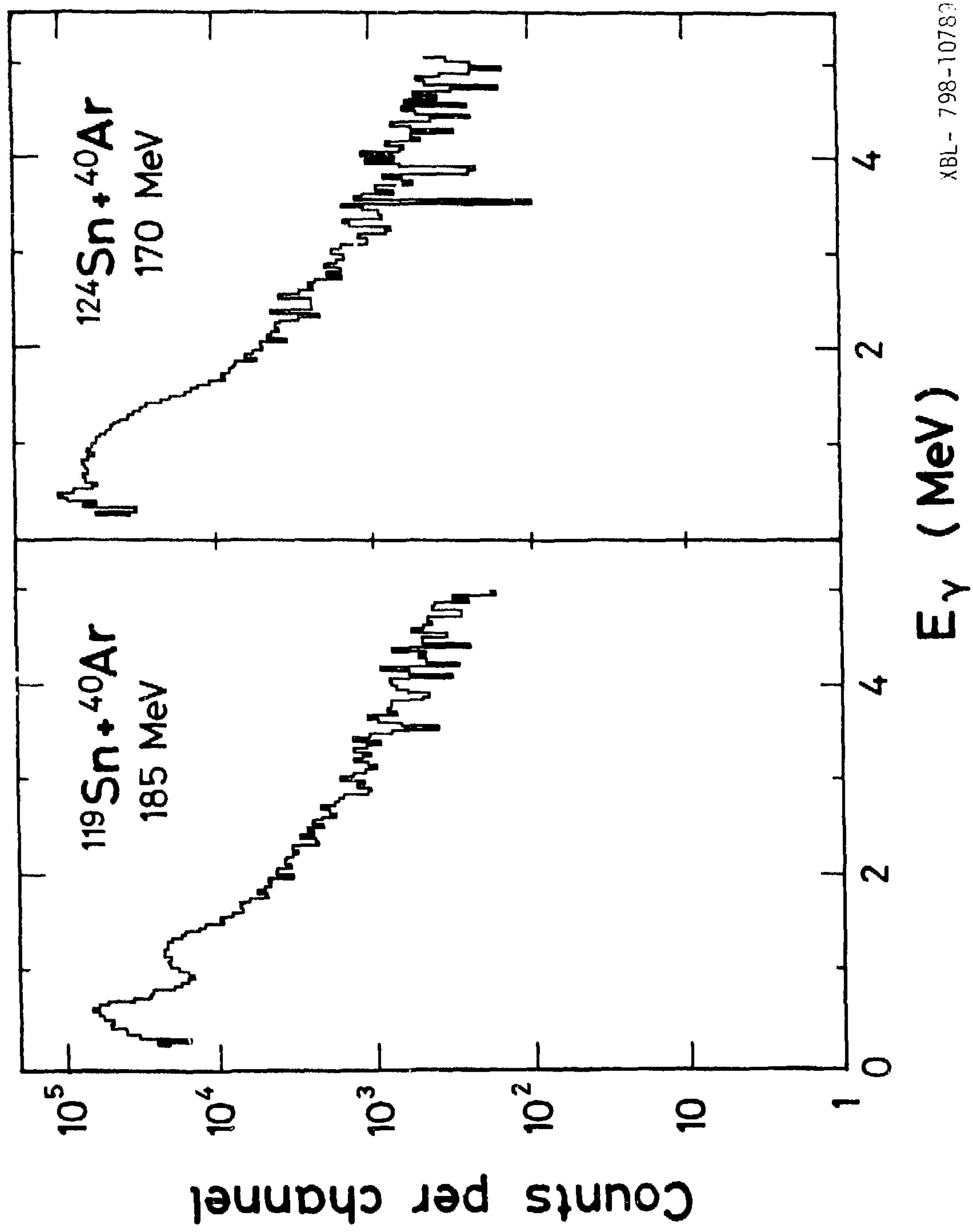
Fig. 8



^{119}Sn + ^{40}Ar
185 MeV
^{124}Sn + ^{40}Ar
170 MeV
Counts per channel
E_γ (MeV)
XBL-798-1078

Fig. 9

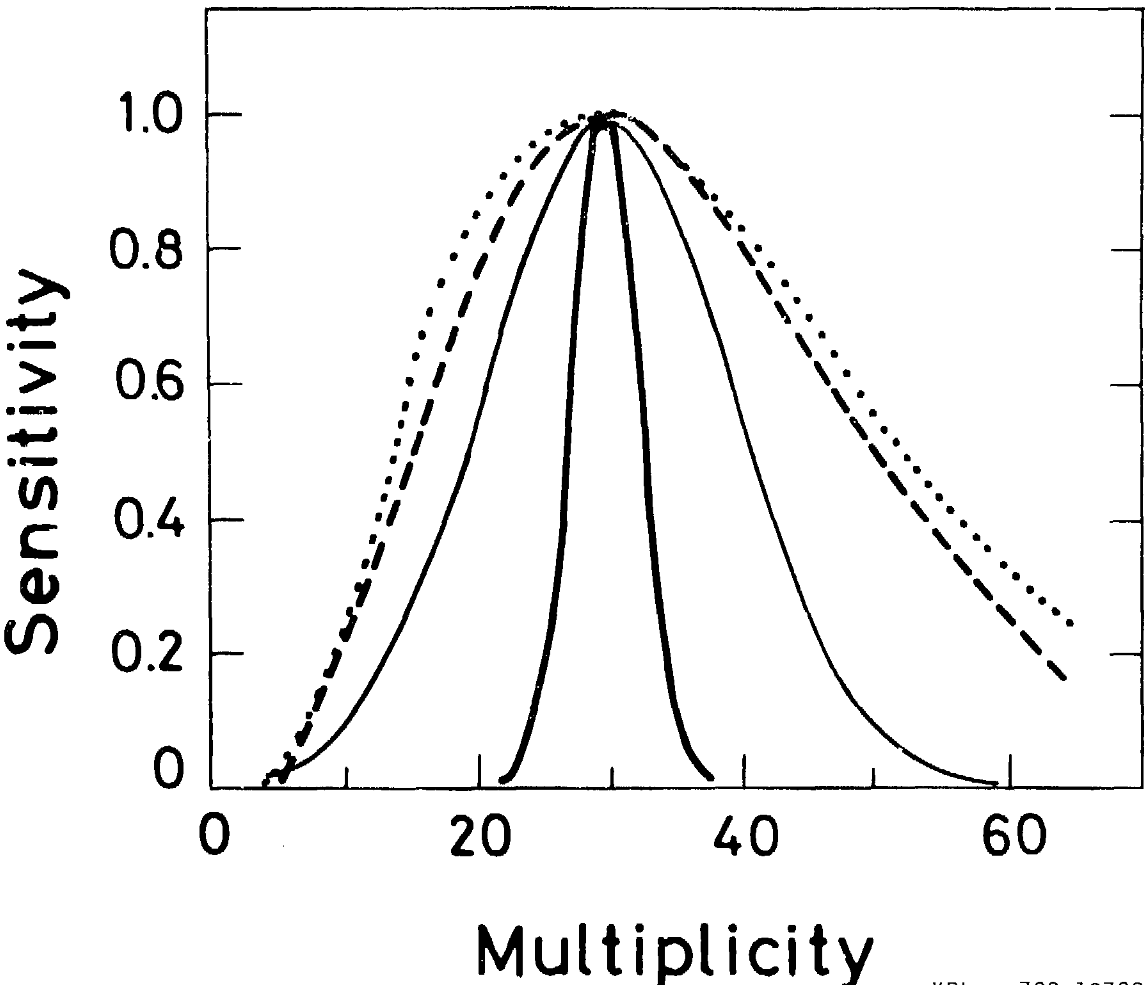


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Fig. 10