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ON THE USE OF ISOMER RATIOS IN ^{44}Sc FOR PREDICTING SPIN POPULATIONS IN HIGH ENERGY HEAVY-ION NUCLEAR REACTIONS

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ABSTRACT

From fits of isomer ratio as a function of projectile kinetic energy, we have calculated the centroids in the E-J plane for the ^{44}Sc* population generated in the reactions ^{29}Si(^{18}O,p2n) ^{44m,g}Sc and ^{41}K(α,n)^{44m,g}Sc. It is shown that ^{44}Sc isomer ratios can be used to predict average spins in ^{44}Sc*, particularly if such ratios are low. As isomer ratios increase, unique identification of average spin populations becomes more difficult because average excitation energy becomes important in determining the isomer ratio.

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INTRODUCTION

It has been suggested that isomer ratios can be used to determine the spin distributions in the evaporation chains of different products formed in spallation reactions.[1] The possibility of being able to trace back the development of such chains is interesting because it may be of help in studying the mechanisms of angular momentum transfer in high energy heavy-ion nuclear reactions. In the present work we wish to discuss the feasibility of using measured isomer ratios in ^{44}Sc for predicting angular momentum populations in initial products of these reactions.

As has been mentioned in a previous paper,[2] ^{44}Sc is a product formed in many high energy reactions and has a number of desirable properties which make it convenient for use. Also, a reasonable methodology has been developed for calculating isomer ratios, and the important parameters that describe the gamma-ray decay of the evaporation residues in ^{44}Sc have been determined within the model previously described.

CALCULATIONAL PROCEDURE

Since we are ultimately interested in determining how different angular momentum distributions affect the isomer ratio, we have proceeded to calculate the centroids of the population distributions in the excitation energy-angular momentum plane resulting from reactions in which compound nuclei, which eventually decay to ^{44}Sc, are formed with widely different amounts of angular momentum. For this purpose, we have used two different reactions. The system $^{29}Si(^{18}O,p2n)$ $^{44m,g}Sc$ was used because the projectile is reasonably heavy and the compound nucleus ^{47}Ti would, on the average, be formed with a respectable amount of angular momentum. We also chose the reaction $^{41}K(\alpha,n)^{44m,g}Sc$ for two reasons: First, isomer ratio data for this system have been extensively published in the literature,[3,4,5,6] thus providing a good check on both our methodology and on the validity of the parameters extracted in a previous study[2] from the $^{29}Si(^{18}O,p2n)^{44m,g}Sc$ system. Second, the low mass of the projectile should result, within the model, in populating low angular momentum states of the compound nucleus $^{45}Sc^*$. With these two systems, a reasonable range of angular momentum populations would be covered.

The experimental points given by ref. 6 have considerable scatter on the high energy side due to the low cross sections for formation of the ^{44}Sc isomers. We determined the isomer ratio of ^{44}Sc from the $^{41}K(\alpha,n)$ reaction at projectile energies of 12 MeV and 21 MeV as a check of the literature data. Targets of $\sim 50 \mu g/cm^2$ ^{41}KCl (99.2% isotopically enriched) on 500 mg/cm^2 Ta metal backings were irradiated at the Lawrence Berkeley Laboratory 88-inch Cyclotron with between 0.5 and 1.0 particle microamperes of ^{4}He for 30 minutes each. Reaction products recoiled into the Ta metal. The targets were counted whole for gamma-rays, and decay curve analysis was performed to result in the ^{44}Sc isomer ratios, as described in ref. 2.

For the sake of completeness, we have calculated the ^{44}Sc* energy-angular momentum distributions for the reaction ^{41}K(^{6}Li,p2n)^{44m,g}Sc, assuming that it proceeds via a compound nuclear reaction. Although it has been shown that similar reactions proceed overwhelmingly through direct reaction mechanisms[7,8,9,10,11], our purpose for conducting this calculation was to generate a third set of angular momentum distributions from a system with masses comparable to those of the previous light-projectile system, but with ^{47}Ti* as the compound nucleus. The populations in the E-J plane after particle evaporation were calculated by means of the computer code "ALERT."[12] The methodology employed in calculating the isomer ratios from the calculated ^{44}Sc populations is identical to the one described in a preceding paper.[2] The ratio of dipole to quadropole gamma-ray strengths was 97:3; which is reasonably close to values reported in the literature.[13]

RESULTS AND DISCUSSION

Figure 1 shows a plot of the isomer ratio vs. projectile kinetic energy in the reaction ^{29}Si(^{18}O,p2n)^{44m,g}Sc. The solid line represents a fit to the data using a dipole to quadrupole strengths ratio of 97:3. This result is taken from ref. 2. Figure 2 shows a similar plot for the reaction ^{41}K(α,n)^{44m,g}Sc. For the same dipole to quadrupole strengths ratio, the calculation reproduced the experimental situation reasonably well for ^{4}He ions up to about 18 MeV. Above this energy, the experimentally determined isomer ratio peaks and then decreases. Although it is not quite clear what the nature of the process is in the higher energy region, it is certain that it is not a compound nuclear mechanism.[14] The excitation function shows a high energy tail, typical of direct processes.[3]

Assuming that the model is reliable in describing the behavior of populations in the E-J plane, judging from the fits of the isomer ratios as a function of projectile kinetic energy, we now proceed to calculate the average positions in the E-J plane of the ^{44}Sc populations from both the ^{29}Si(^{18}O, p2n) and ^{41}K(α,n) reactions. The lines that describe the loci of such points for the reactions in question are shown in Fig. 3. Also shown in Fig. 3 are "tie" lines that join points of equivalent isomer ratio in both reactions. Notice that there is a tie line corresponding to a value of the isomer ratio of 6.15. Ratios near this value are observed in the ^{29}Si(^{18}O,p2n) reaction but not in the ^{41}K(α,n) case. Since it is our intent to generate a more or less continuous set of populations in the E-J plane, we have simply extended our calculations to higher energies in the ^{41}K(α,n) reaction, assuming a compound nucleus mechanism. What we are saying is that if the centroid of a given population distribution falls in the region of the tie line in question, the resulting calculated isomer ratio would be around 6.15.

Figure 3 indicates that in regions where the isomer ratios are small ($\lesssim$1.8) the average angular momentum of the ^{44}Sc population can be estimated with little ambiguity. However, as the isomer ratios increase, the average spins of the parent populations become more and more uncertain. Although we must admit that these assertions are model dependent and also that we are restricted to speaking about the region between the two lines describing the loci of the average locations of the populations generated in both reactions, it seems obvious that isomer ratios would depend strongly on the energy distributions of the populations as well as on angular momentum distributions.

In the context of this model, we might guess, for example, what the average angular momentum might have been for the ^{44}Sc formed in the reaction of 25 GeV ^{12}C on a Cu target as described by Cumming et al.[15] From the ^{44}Sc^{m} and ^{44}Sc^{g} yields we can infer an isomer ratio of about 1.2. Our graph would then tell us that the average spin for the ^{44}Sc population must have been close to 5.7 $\hbar$. Very little can be said in this case about the average energy of the population.

The question now arises as to whether we can say anything else about the average properties of the populations in the precursor chains. In order to help us answer this question, we might look at Fig. 4 in which we have conveniently plotted the log of the average excitation energy vs. the average spin, not only for ^{44}Sc, but also for some of its precursors, namely ^{47}Ti and ^{45}Sc. Note that joining the two ^{47}Ti curves there is a tie line (A-B) which generates, after proper emission of a proton and two neutrons, a population in ^{44}Sc which results in an isomer ratio of about 4.1. The tie line in question joins two points with similar excitation energies, but whose spins are about 5 $\hbar$ apart. The implication is that, as far as this simple calculation shows, there is an ambiguity in relation to the average spin of a relatively close ^{44}Sc precursor responsible for a given isomer ratio in this nuclide, even if the average excitation energies of the precursor population is known. This situation is expected to become worse with increasing energy, as could be inferred by the growing separation between the two ^{47}Ti curves. This result would seem to indicate that not too much optimism should be placed on the use of isomer ratios for the purpose of predicting average spins of early products in high energy heavy-ion reactions.

CONCLUSIONS

In synthesis, the results of our previous discussion lead us to believe that isomer ratios can be used to predict angular momentum distributions in ^{44}Sc populations, particularly if such ratios are low. As the ratios become higher, the average energy becomes as important a factor as the average spin, thereby making unique identifications of such properties difficult.

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FIGURE CAPTIONS

Figure 1. Isomer ratio as a function of ^{18}O kinetic energy for the reaction $^{29}Si(^{18}O,p2n)^{44}Sc^{m},^{44}Sc^{g}$. The solid line represents a fit to the data using a dipole to quadrupole strengths ratio of 97:3 (ref. 2).

Figure 2. Isomer ratio as a function of ^{4}He kinetic energy for the reaction $^{41}K(^{4}He,n)^{44}Sc^{m},^{44}Sc^{g}$. The experimental points are taken from ref. 6. The solid line is a fit using exactly the same procedure as in ref. 2 and a dipole to quadrupole strengths ratio of 97:3.

Figure 3. Average energy-average spin diagram for the reactions $^{29}Si(^{18}O,p2n)^{44}Sc$ and $^{41}K(\alpha,n)^{44}Sc$. The solid lines represent the loci of $^{44}Sc^{*}$ population centroids as calculated for both reactions from the fits shown in Figs. 1 and 2. The broken curve is an extrapolation of the $^{41}K(\alpha,n)^{44}Sc$ reaction to higher energies assuming a compound nucleus mechanism. The dashed lines join centroids of populations which give rise to equal isomer ratios.

Figure 4. Semilog representation of the calculated average energy-average spin plane for the reactions $^{29}Si(^{18}O,p2n)^{44}Sc^{*}$ and $^{41}K(\alpha,n)^{44}Sc^{*}$ (dot-dash), and also for their $^{47}Ti^{*}$ and $^{45}Sc^{*}$ initial precursors respectively (solid lines). Also shown is the calculated <E>-<J> distribution of $^{47}Ti^{*}$ produced in the reaction $^{41}K(^{6}Li)$ assuming for

comparison that it proceeds exclusively through compound nucleus mechanism. Dashed lines join centroids of populations which give rise to equal isomer ratios; line A-B is discussed in the text.

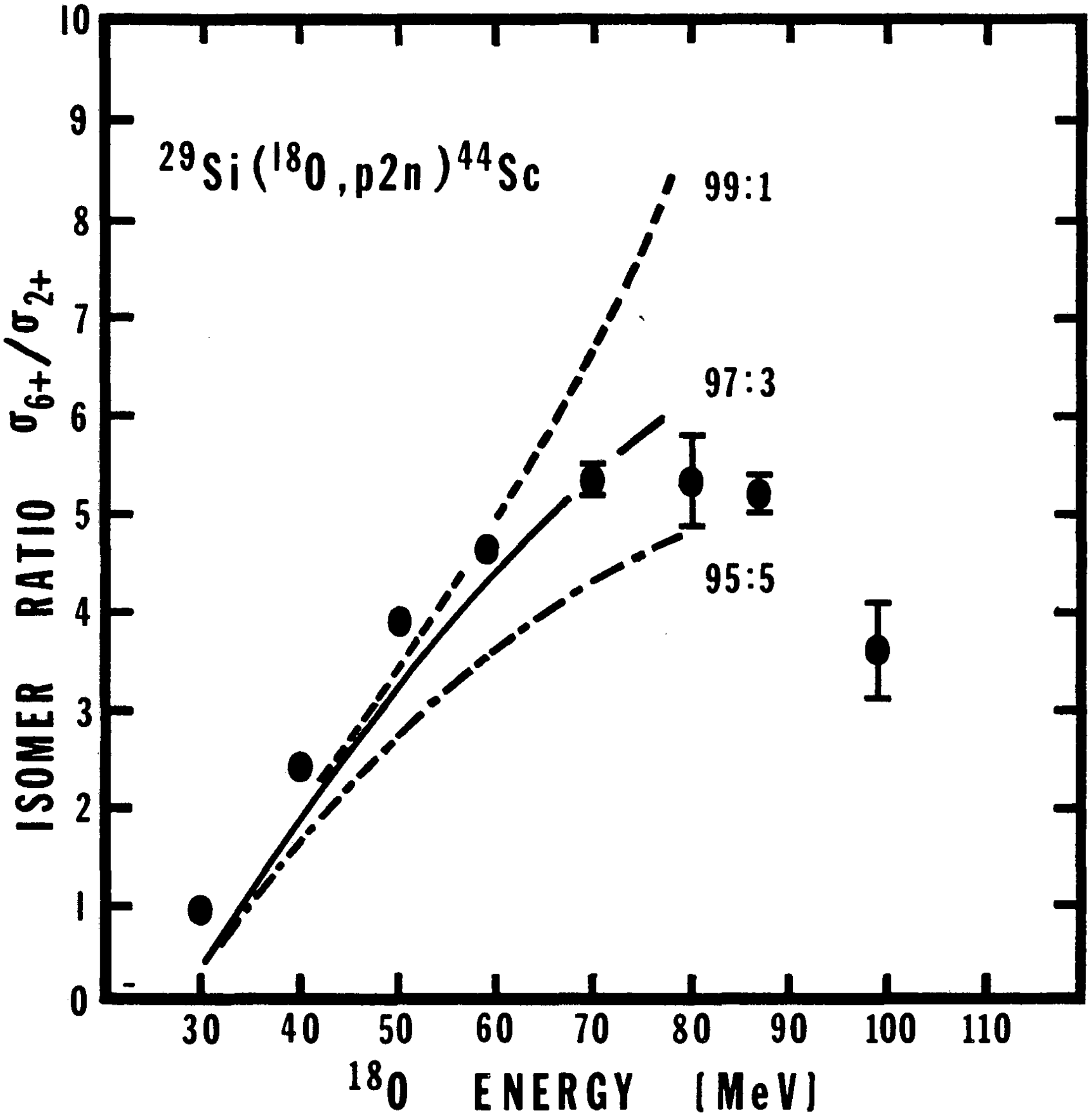

Fig. 1

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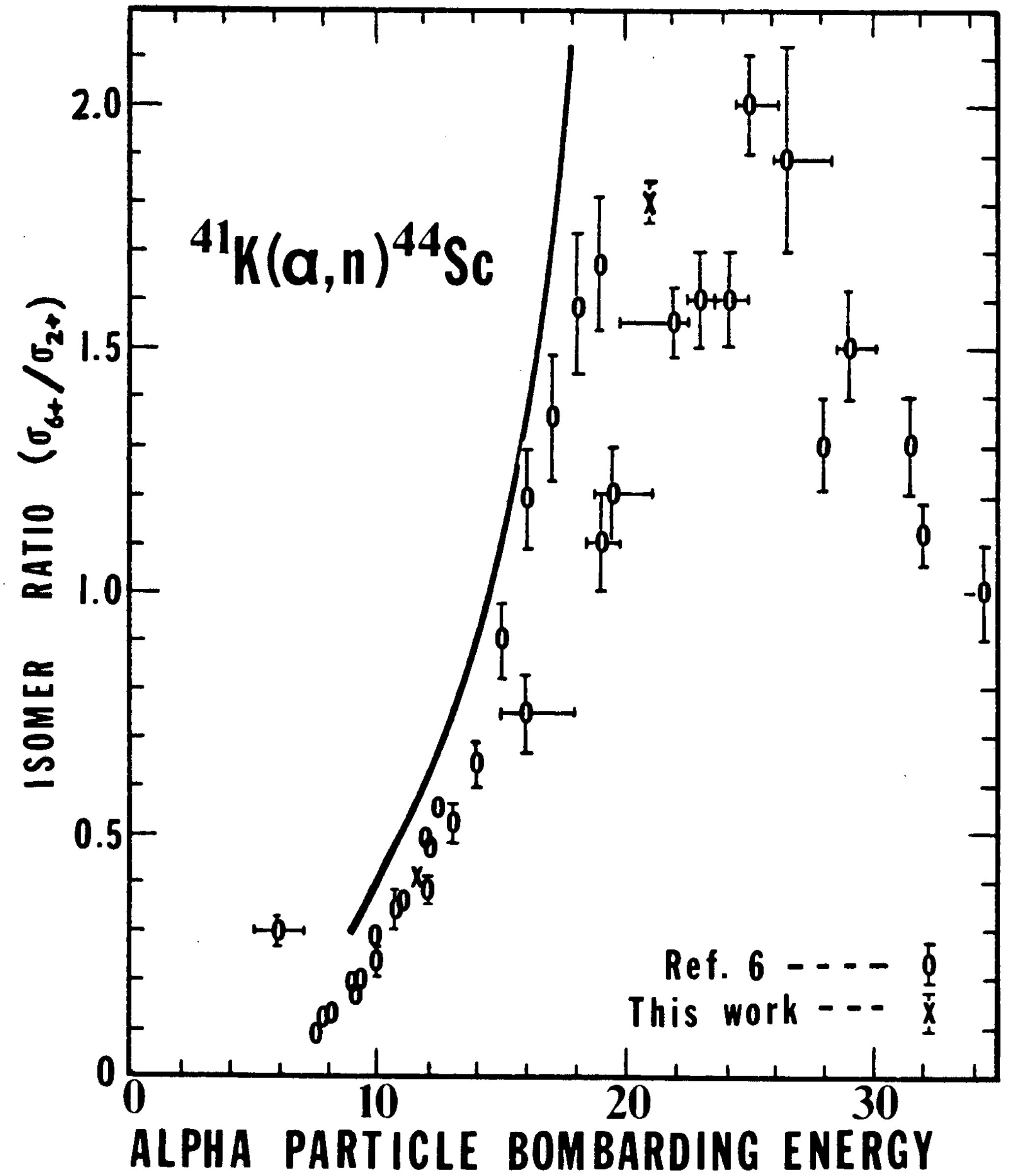

Fig. 2

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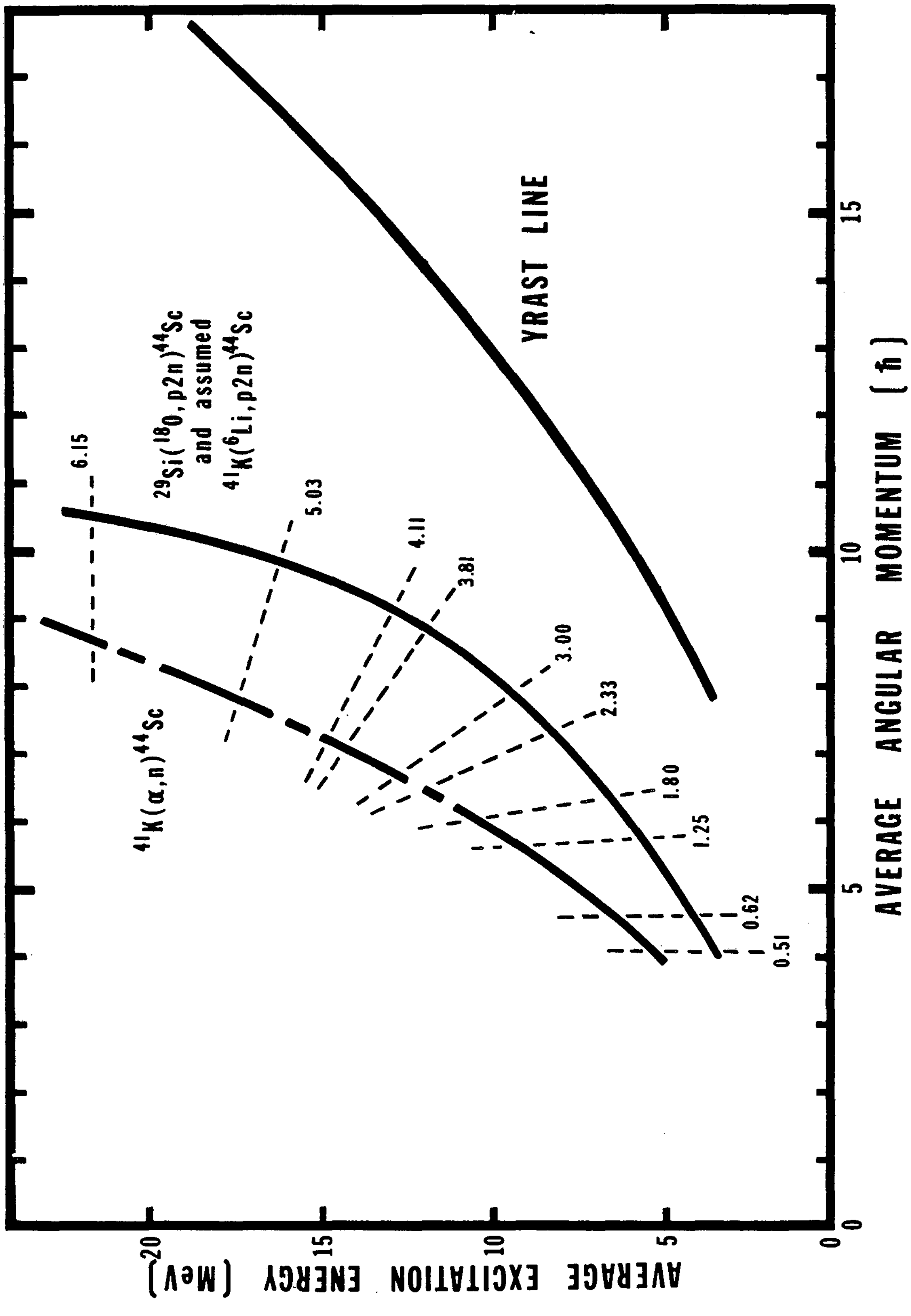

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Fig. 3

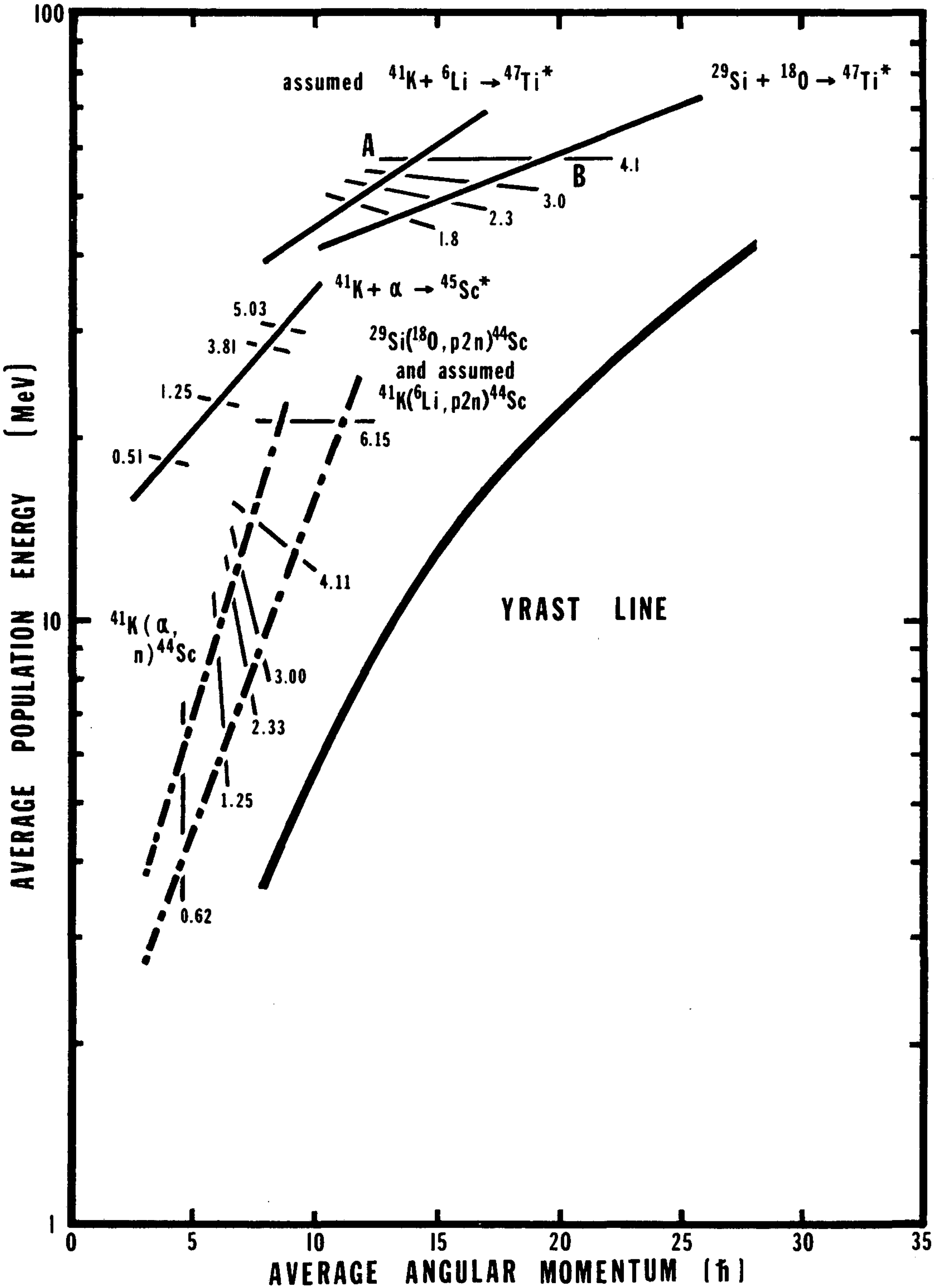

Fig. 4

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