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GAMMA RAYS FOLLOWING ^{40}Ar-INDUCED REACTIONS*

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We have bombarded separated Sn and Te isotopes with ^{40}Ar projectiles in order to study the (^{40}Ar,xn) reactions and evaluate them as a means to produce excited nuclei for spectroscopic studies. This proves to be an excellent method for populating ground-band collective levels, and such levels have been identified in the 88-, 90-, and 92-neutron Er and Yb isotopes.

When medium and heavy nuclei are bombarded with heavy ions of moderate energy, the dominant reaction has been found to be complete fusion followed by the evaporation of neutrons, (HI,xn), and a correct choice of bombarding energy can often lead to an almost unique product. A number of studies[1-4] have recently been made of the γ-ray cascade which occurs as the last step in the de-excitation of a (HI,xn)-reaction product, and this technique promises to become an important one in nuclear spectroscopy. Thus far the "heavy ion" used in these studies has ranged from protons to ^{19}F. The purpose of this Letter is to report our results using ^{40}Ar as the projectile in such studies.

The interest in heavier ions for these studies lies in (a) the considerably greater linear and angular momentum given to the compound system; (b) the accessibility to regions of the periodic table that cannot easily be reached with lighter ions; and (c) the production of very neutron-deficient compound systems with lower excitation energy. The minimum excitation energy of a compound system increases with projectile mass up to around 20 and then decreases slowly because the larger negative Q value for the reaction with heavier projectiles more than offsets the increased bombarding energy necessary to exceed the Coulomb barrier. This is of considerable importance for spectroscopic studies because a lower excitation energy, in general, permits the (HI, xn) product to be made more specifically, resulting in cleaner spectra.

We have studied γ-ray spectra from ^{40}Ar reactions using a lithium-drifted germanium counter that measured 6 cm^2 by 0.8 cm deep and operated at 2.0-keV resolution for γ rays around 600 keV. In all cases this counter was at 90° to the beam direction and about 2 cm from the target. The targets generally used were prepared by evaporating about 700 μg cm^{-2} of separated isotope onto a 0.003-cm thick

lead backing. The purpose of this backing was to stop the recoiling compound nuclei; otherwise the Doppler broadening was observed to be serious.

In order to compare the ^{40}Ar reactions with those using lighter projectiles, we produced the compound nucleus ^{170}Yb* both from ^{40}Ar + ^{130}Te and from ^{11}B + ^{159}Tb. Spectra were taken close to the peaks of the $4n$ and $6n$ reactions for these systems. The excitation energies in ^{170}Yb* required to maximize the $4n$ yields from the two systems were measured to be equal within the experimental error of ~10 MeV. The prominent γ rays from the two systems are identical in energy, and correspond to the transitions between members of the ground-state rotational bands in ^{166}Yb and ^{164}Yb. The peak-to-background ratio of these rotational transitions was observed to be poorer by a factor of 2 or 3 in the ^{40}Ar reactions. These results also showed that the increased angular momentum of the ^{40}Ar system, over that of ^{11}B, does not result in the appearance of higher members of the ground-state rotational bands. However, for the ^{40}Ar reactions the yields of the cascade transitions are approximately equal up to nearly the last observed one; whereas, for the (^{11}B, $4n$) reaction, the yield of successively higher cascades drops steadily by increments of about 15% of the yield of the $2^+ \rightarrow 0^+$ member.

Gamma-ray spectra from the reactions ^{124,122,120}Sn(^{40}Ar, $4n$)^{160,158,156}Er are shown in Fig. 1. Morinaga[5] has previously studied ^{160}Er. Energies for the ground-state band transitions in the 88-, 90-, and 92-neutron erbium and ytterbium isotopes are given in Table I, and are expected to be accurate to 0.2%. In other works[6] we will discuss these energy levels more fully; however, it is apparent that the 88-90 neutron discontinuity is smearing out with increasing proton number.

The peak cross sections for (^{40}Ar, $4n$) reactions on the Te isotopes were measured both absolutely, and by comparison on the same spectrum with the yield of the Coulomb-excit-

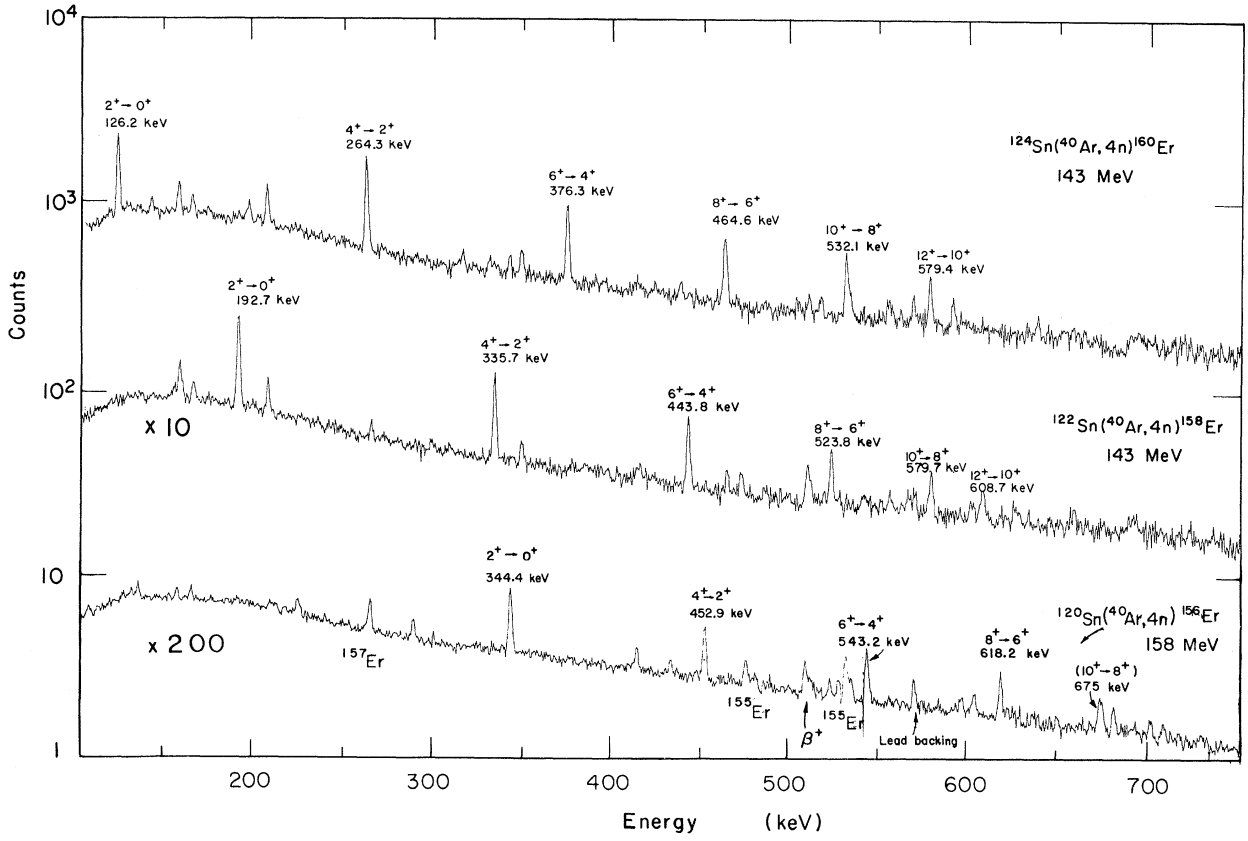

FIG. 1. Gamma-ray spectra following (^{40}Ar, $4n$) reactions on separated Sn targets. The Er isotopes produced are those having 88, 90, and 92 neutrons. The Ge(Li) detector was 6 cm^2 × 0.8 cm deep.

Table I. Rotational transition energies (keV).[a]

	$N=92$		$N=90$		$N=88$	
	^{160}Er	^{162}Yb	^{158}Er	^{160}Yb	^{156}Er	^{158}Yb
$2\rightarrow 0$	126.2	166.5	192.7	243.0	344.4	357.9
$4\rightarrow 2$	264.3	320.2	335.7	395.3	452.9	476.0
$6\rightarrow 4$	376.3	436.2	443.8	508.8	543.2	548.3
$8\rightarrow 6$	464.6	521.2	523.8	588.7	618.2	
$10\rightarrow 8$	532.1	569.4	579.7	~636	~675	
$12\rightarrow 10$	579.4		608.7			

[a]The accuracy of these transitions is ±0.2%.

ed $2^+\rightarrow 0^+$ transition of the Te target.[6] The agreement between the two methods was good. Cross sections for the reactions on the Sn isotopes were measured only by the absolute method, as the Coulomb excitation lines were seriously Doppler broadened. These results are summarized in Table II. We have assumed that the yield of the $4^+\rightarrow 2^+$ or $2^+\rightarrow 0^+$ transition in the ground-state rotational band represents the entire (^{40}Ar, $4n$) cross section. Our cross sections are around half of that found by Kumpf and Karnaukhov[7] from radiochemical studies of the (^{40}Ar, $4n$) reaction on ^{114}Cd. These $4n$ cross sections on Sn and Te peak rather near the Coulomb barrier, and this undoubtedly reduces them considerably, particularly for the highest mass-number targets which peak at the lowest bombarding energy. The drop in (^{40}Ar, $4n$) cross section for the lightest targets may arise from increasing neutron binding energy and decreasing alpha binding energy with decreasing mass number.

It is interesting to try to draw some conclusions about the evaporation process from the cross sections. We will assume that the system may be treated classically, and that the (HI, xn) cross section, σ_{xn}, may be related to an "interaction radius" within which all collisions lead to neutron-evaporation reactions,

Table II. (^{40}Ar, $4n$) peak cross sections (mb).[a]

	Target mass number					
Target	120	122	124	126	128	130
Te		85	150	210	200	190
Sn	135	200	150			

[a]These cross sections are based on the yield of the ground-state rotational band of the product nuclei. The accuracy is expected to be ±20%. The reactions peak at energies between 150 and 170 MeV.

and outside of which none do. From this interaction radius we can then calculate the maximum angular momentum $l_{\max}$ contributing to the neutron-evaporation reactions to be

$$l_{\max}{}^2 \cong 1.5\sigma_{xn}\mu E_{\text{c.m.}}, \quad (1)$$

where $l_{\max}$ is in units of $\hbar$, σ_{xn} is in barns, μ is the reduced mass in mass units, and $E_{\text{c.m.}}$ is the center-of-mass energy in MeV. If we take an (^{40}Ar, $4n$) cross section of 200 mb and add an empirical correction for $3n$, $5n$, and other xn reactions we get a neutron-evaporation cross section of around 400 mb at ~160-MeV bombarding energy. We then find $l_{\max}$ is about $50\hbar$. This interpretation implies that in these cases the compound nuclei formed with spin less than $\sim 50\hbar$ will decay by neutron evaporation, the remaining fraction (greater than $\sim 50\hbar$) going into α emission and other processes. Realistically the alpha competition must build up smoothly with increasing angular momentum, and the $50\hbar$ calculated here represents only some point where alpha emission (or other process) becomes dominant. Furthermore, it seems clear that this point varies somewhat from nucleus to nucleus, probably with the relative neutron and alpha-particle binding energies as mentioned above. The result of $50\hbar$ appears to be in disagreement with the calculation of Jagare[8] which suggest that α emission becomes important at spins of only $20\hbar$ in this region.

Since each evaporated neutron is unlikely to decrease the angular momentum of the system by more than (2 to 3)$\hbar$, the products of the neutron evaporations must have spins up to at least $40\hbar$. The fact that states of spin greater than 14+ are not observed indicates that the level scheme of the final nucleus must play an important part in determining the populations of the ground-state rotational band members. We can try to go further and consider how the level scheme could produce the observed rather sharp feeding of the band around a particular spin value. It appears to us that in each case the feeding occurs at an excitation energy above which other states of a given spin might lie near or even below the ground-band states of that spin. Such states would compete for population, and thus make it difficult to detect the higher ground-band transitions. The point at which this kind of competition cuts off the ground-band population would be sensitive to the ground-band energy spac-

ings, and could plausibly vary like the observed cutoff points—from a high of at least 18 or 20 for some good rotational nuclei to a low of 6 for many vibrational nuclei. Such a scheme would have some interesting consequences, but is rather speculative at the present time.

Using a particle identifier system[9] we have also measured the evaporated α particles from targets of ^{124}Sn and ^{130}Te bombarded with ^{40}Ar projectiles.[6] These cross sections are around 100 mb at 160-MeV bombarding energy. Thus at this bombarding energy we obtain about 0.5 b for the compound nucleus cross section, assuming it to be the sum of the xn and αxn cross sections. The calculated total reaction cross section is very sensitive to the radius parameter used in these cases; however, values around 0.6 b seem most reasonable.[10] The situation then appears to be that most of the ^{40}Ar total reaction cross section goes into compound nucleus formation, as is found with lighter projectiles. Furthermore, for the heavier targets, neutron evaporation is still much the most prominent mode of decay of the compound nuclei, although alpha emission is becoming significant. The poorer peak-to-background ratios observed in the gamma-ray spectra from the system ^{40}Ar + ^{130}Te (compared with ^{11}B + ^{158}Tb) arise partly (perhaps largely) from the fact that the excitation functions of the individual xn reactions are broader, resulting in a smaller fraction of the total (HI, xn) reaction going into a particular value of x at the optimum energy. The high angular momentum is expected to produce this effect.[10]

These experiments show that it is clearly feasible to make spectroscopic studies on the de-excitation cascade of the products of (^{40}Ar, xn) reactions. Extrapolating to heavier projectiles, we see two competing trends: (1) higher angular momentum, leading to a smaller fraction of the total cross section going into a particular (HI, xn) reaction, and (2) lower compound-nucleus excitation energy (compared with ^{40}Ar), which should have just the opposite effect. The former trend may well predominate, giving somewhat poorer spectra from (^{84}Kr, xn) reactions, for example, than from (^{40}Ar, xn). However, it seems likely that spectroscopic studies of such systems will also be possible. One should keep in mind, however, that apart from the projectile involved, the relative binding energies of neutrons and α particles in the compound system affect the (HI, xn) yield, and this consideration, rather than finding a target-projectile combination, may well set the limit on how far toward the neutron-deficient side one can study by this method.

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