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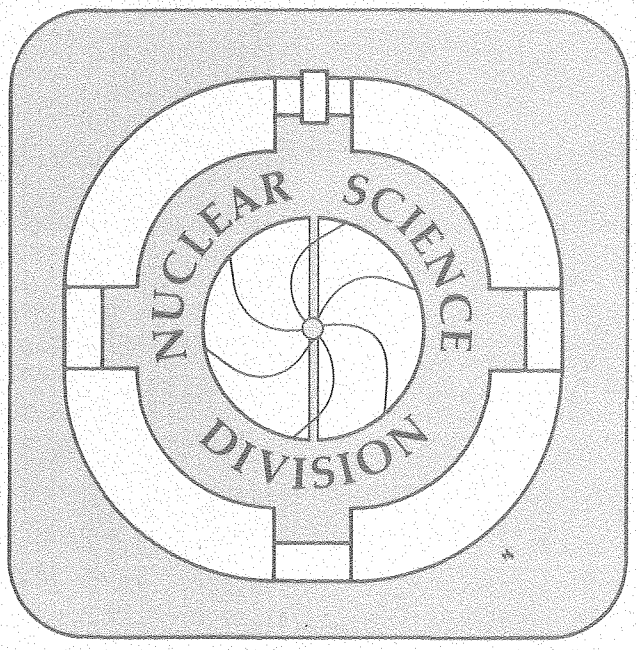
February 1981



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Observation of Giant Dipole Resonances Built on States of High Energy and Spin*

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Abstract

Spectra of γ-rays in the 2-30 MeV range have been observed following ^{40}Ar induced reactions leading to the ^{122}Te, ^{150}Gd and ^{164}Er systems. Shoulders in the spectra for E_γ > 10 MeV are interpreted as arising from the giant dipole resonance (GDR) and are consistent with statistical model calculations using the GDR strength function. Their observation offers the possibility of studying nuclear shapes and dynamics as functions of temperature and spin.

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Studies of the GDR have been mostly restricted to coherent excitation from nuclear ground states which excites only the giant resonances built on them[1]. Brink[2], however, has proposed that every state in a nucleus has a GDR associated with it. A consequence of this idea is that the strength functions for electric dipole transitions from every state would have a Lorentzian-like shape as a function of γ-ray energy E_γ, with a

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magnitude determined from the E1 sum rule[3]. Such a variation of strength with E_γ would affect the shape of the spectrum of γ-rays emitted from a highly excited nucleus, particularly in the vicinity of $E_\gamma = E_G$, the energy of the GDR. Some evidence in favor of this hypothesis is given by the shape of the γ-ray spectrum for $8 < E_\gamma < 20$ MeV following spontaneous fission[4] of ^{252}Cf. We have observed this effect in the statistical γ-rays following heavy-ion fusion reactions.

The present measurements open the possibility of measuring the energy, yield, width, and general structure of the GDR component of the statistical γ-ray spectrum as functions of excitation energy E_x above the yrast line (temperature T) and spin Iħ. The first three of these can be related through nuclear models to the nuclear size, collectivity and other more detailed features of the nuclear dynamics. The gross structure of the GDR is simply related to the nuclear shape; in deformed nuclei with two (or three) distinct principal radii, the GDR is split into two (or three) components. Thus the observation of only the general structure of the resonance peak should provide information on the nuclear shape as a function of T and I. Such studies provide a new and general method to study nuclear dynamics far from the ground state.

For these experiments it is essential to discriminate effectively against high-energy γ-transitions arising from light element impurities in the target and against cosmic rays. The present experiments make use of a sum-spectrometer-multiplicity technique[5] which selects the γ-rays from moderately high-spin (∿20-65ħ) states produced in heavy-ion compound nucleus reactions. The sum spectrometer consists of two 33-cm diam x 20-cm thick NaI detectors facing the target 2.5 cm above and below the beam axis, each subdivided into four elements. Eight NaI (12.7 x 15.2 cm) detectors

were placed 50 cm from the target at angles of ±160°, ±100°, ±80°, -135° and -45° and were shielded from each other and the beam slits by 5 cm of lead. A Ge(Li) detector, at 135°, monitored the reaction residues. Events were stored only if more than six of the eight elements in the sum spectrometer fired. Thresholds for each detector were set at 1.5 to 2.5 MeV for the various targets. This facilitated recording enough high-energy events in a day so that the statistical γ-rays could be observed over six decades, down to the level of the cosmic-ray background.

Targets (∿1 mg/cm^2) of ^{82}Se, ^{110}Pd, and ^{124}Sn were bombarded with ∿10 nA of 170 MeV ^{40}Ar ions from the LBL 88" cyclotron. Spectra from the eight NaI detectors, associated with three regions of sum spectrometer energy E_s within the range ∿10-40 MeV, were added. On the average, higher E_s windows are associated with higher I. Spectra for the ^{82}Se case are shown in fig. 1. In the energy interval from ∿2-8 MeV, the spectra for each case show an exponentially falling tail, composed of the statistical transitions deexciting the product nuclei after the neutron evaporations. All spectra rise considerably higher than this exponential at energies above ∿10 MeV, indicating a different source of γ-rays. Beyond ∿20 MeV the spectra are flat and probably due to cosmic rays.

It seems likely that these 10-18 MeV γ-rays are emitted in the deexcitation of the product nuclei formed principally from fusion for the ^{124}Sn and ^{110}Pd targets, with increasing deep-inelastic contributions for the ^{110}Pd and ^{82}Se targets. Several experiments were made to rule out other origins of the high-energy shoulder. Light elements are an unlikely cause since the yield from a short run on an Al target (beam energy 1.9 times the Coulomb barrier, E_B) was found to be approximately the same as from the Sn target (1.2 E_B). Pulse pile-up effects were shown to be

small by repeating the $^{110}Pd + ^{40}Ar$ runs with some of the NaI detectors at 50 cm as before and others at 35 or 70 cm from the target. A long run with high beam intensity was made on the Pb backing alone, resulting in a spectrum 10-20 times weaker than that from the targets. Finally, several measurements indicated that the constant background for $E_\gamma \gtrsim 20$ MeV was mostly due to random coincidences between cosmic-rays and the beam-associated events.

The reason for the steep slopes in fig. 1 is that the level densities for the final states, to which the transition probabilities are proportional, vary approximately exponentially with E_x (and thus as $\exp(-E_\gamma/T)$). A rough way to see the shape of the γ-ray strength functions is to remove the level density dependence by multiplying by $\exp(E_\gamma/T_e)$, where T_e is an effective T. For the less interesting region with $E_\gamma \lesssim 8$ MeV, $T_e \approx 1$ MeV. Above 10 MeV the curves are flatter, indicating that these γ-rays are emitted at much higher T_e. We have somewhat arbitrarily taken $T_e = 1.43$ MeV for ^{164}Er (^{124}Sn target), and adjusted the others for the expected mass dependence: $T \propto A^{-1/2}$. The data from the total sum window (with the flat high-energy background subtracted) multiplied by these exponentials are shown in Fig. 2. The peaked structures have maxima ($\sim$14 MeV) and widths similar to those for the GDR based on ground states and strongly suggest GDR strength functions. In addition, the bump becomes higher in energy as the target mass decreases, as would be expected for the GDR ($E_G \propto A^{-1/3}$). Integrating the total-sum spectra between 10 and 20 MeV (and subtracting the flat background) gives 2-3 x 10^{-3} transitions per cascade for all three targets. We have assumed here (and for fig. 1) a peak to total ratio[6] of 0.5 for the NaI detectors.

The effect of the GDR in the γ-ray decay from highly excited states can be roughly estimated if one uses simple expressions for the total neutron width[7] Γ_n and the E1 γ-ray width[3] $\Gamma_\gamma(E_\gamma)$ derived from the statistical model of nuclear decay. Taking the level densities as $\rho(E_x) \propto \exp(E_x/T)$, one can show that:

$$\Gamma_\gamma(E_\gamma)/\Gamma_n \propto E_\gamma^3 f(E_\gamma) T^{-2} [\exp(B_n - E_\gamma)/T] \quad . \tag{1}$$

We have assumed the GDR strength function[3]):

$$f(E_\gamma) = K(NZ/A)\Gamma_G E_\gamma [(E_\gamma^2 - E_G^2)^2 + (E_\gamma \Gamma_G)^2]^{-1} \quad . \tag{2}$$

Here B_n and Γ_G are the neutron binding energy and the width of the GDR, respectively and $K \simeq 5 \times 10^{-6} (\text{MeV})^{-3}$. Since $T \propto \sqrt{E_x}$, it follows that for $E_\gamma < B_n$, Γ_γ/Γ_n decreases with increasing E_x. However if $E_\gamma - B_n \gg T$, which is relevant for $E_\gamma \approx E_G$, this branching ratio increases with increasing E_x. Thus one expects more of these high energy (∿15 MeV) γ-rays to be emitted in competition with neutrons at higher E_x. The bump intensity appears to decrease with increasing E_s in fig. 1 as would be expected, since E_x decreases with increasing I.

These simple considerations are borne out by calculations for the ^{164}Er system with the code[8] GROGI2 (Fig 3a) in which $f(E_\gamma)$ was used with Γ_G = 5 MeV and E_G = 15 MeV. The similarity with the observed spectra is evident. The γ-spectrum calculated with a constant E1 strength function, corresponding approximately to that derived from neutron capture measurements in nearby nuclei, is shown as the dashed line in Fig. 3a. Even in this case the shape of the statistical spectrum changes for $E_\gamma >$ 10 MeV, since these γ-rays originate mainly from high E_x in competition with neutrons. For most γ-rays below 10 MeV, E_x is too low for neutrons

to be emitted. However, the GDR produces a major increase in γ-ray intensity over that from the constant strength function for $E_\gamma \gtrsim 10$ MeV. Integrating the calculated GDR spectrum between 10 and 20 MeV gives 1.9×10^{-3} transitions per cascade, in good accord with the observed values. Multiplying the calculated results by $\exp(E_\gamma/1.43)$ gives the spectrum shown in Fig. 3b. The dashed line here is the Lorentzian $E_\gamma f(E_\gamma)$ put into the calculation, showing that the procedure used in Fig. 2 generates something like the GDR shape in this case.

These measurements demonstrate that one can study the GDR in the γ-ray deexcitation spectra following heavy-ion fusion reactions. Our assumption has been that these γ-rays are emitted from the compound states in competition with neutron (or other particle) evaporation. A simple model based on this mechanism has been shown to be in rather good agreement with the experimental results. On the other hand there is no proof that these γ-rays are not emitted directly (or "semi-directly") from coherent GDR states produced in the initial stages of the reaction, as for example in nucleon capture reactions. However, these processes are rather well understood for light projectiles[9], and for $Z/A \sim 0.5$ the cross sections would be expected to be much lower than observed here. Therefore, unless there is some other coherent process to excite the GDR, a direct origin for these γ-rays seems unlikely. One of the first directions in studying these γ-ray spectra is to vary the bombarding and detection conditions sufficiently to establish E_x and I for the emitting states. Another exciting direction to extend these studies is toward qualitative shape observations. There are suggestions in the data of Fig. 1 and 2 that the resonance is not a simple Lorentzian but may sometimes have structure. Experiments are in progress that should improve the statistics for some of these spectra by

an order of magnitude. Even the approximate shape for I $\sim$ 50 or 60 would be of great interest. In conclusion we feel that these observations open up rather extensive possibilities for studying nuclear shapes and dynamics far away from the ground state.

We are indebted to M.A. Deleplanque for discussions concerning such an experiment. One of us (BH) wants to thank the Danish Research Council for partial support. 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 W-7405-ENG-48.

References

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Figure Captions

1. NaI spectra corresponding to E_s = 10-40 MeV and three windows within this range for the $^{82}Se + ^{40}Ar$ system. The sloping lines show exponential extrapolations of the lower E_γ parts of the spectra. The shapes of the true γ-ray spectra are not expected to differ greatly from these, and hence the ordinate in "transitions per MeV" should be approximately correct.
2. Background subtracted total-window spectra multiplied by $\exp(E_\gamma/T_e)$. Arrows indicate $E_\gamma = 78/A^{1/3}$ MeV, the centroid of the ground state GDR.
3. Gamma spectra from a GROGI2 calculation (see text).

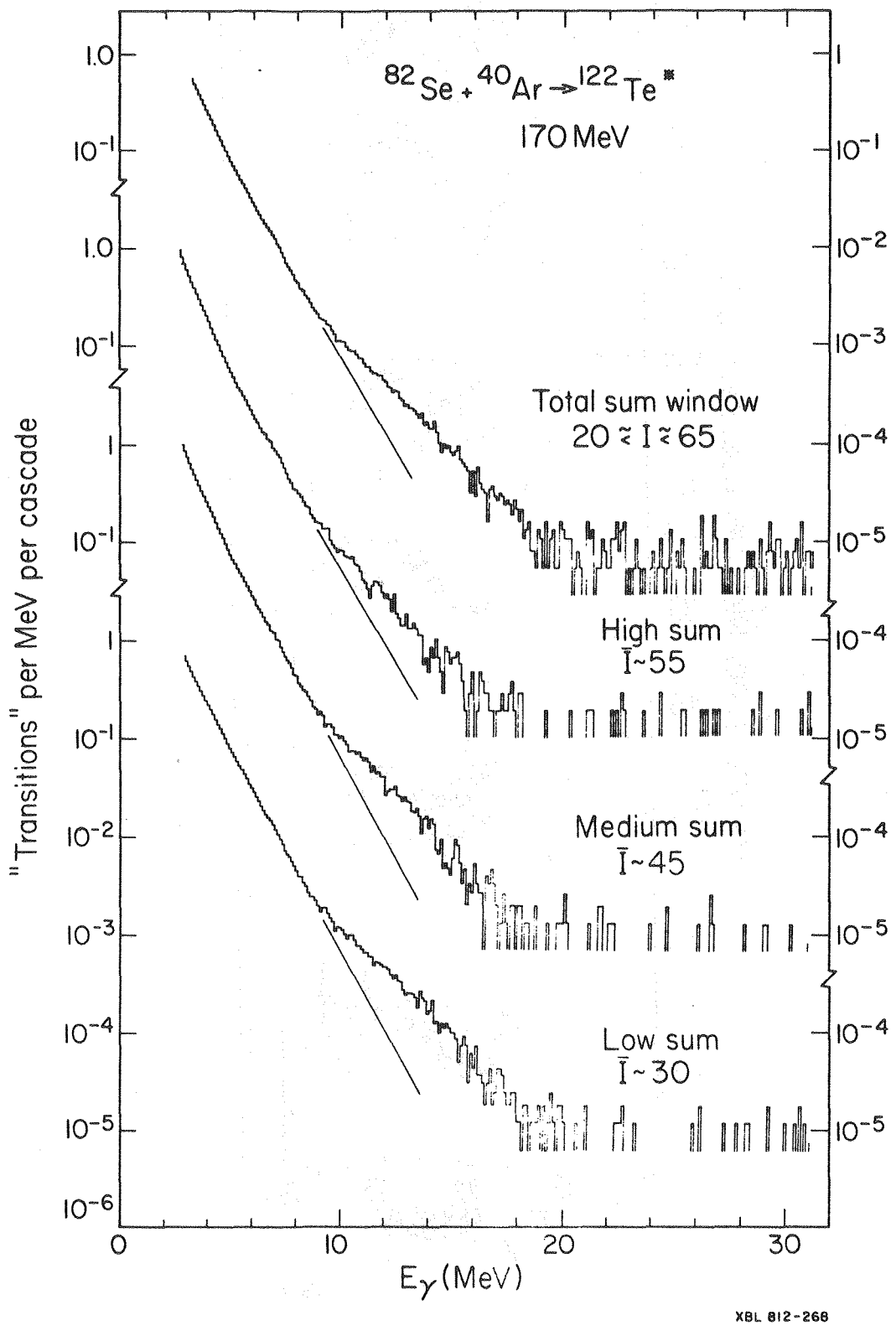

$^{82}Se + ^{40}Ar \rightarrow ^{122}Te^{*}$
170 MeV
Total sum window
20 ≲ I ≲ 65
High sum
Ī~55
Medium sum
Ī~45
Low sum
Ī~30
"Transitions" per MeV per cascade
E_γ (MeV)
XBL 812-268

Fig. 1

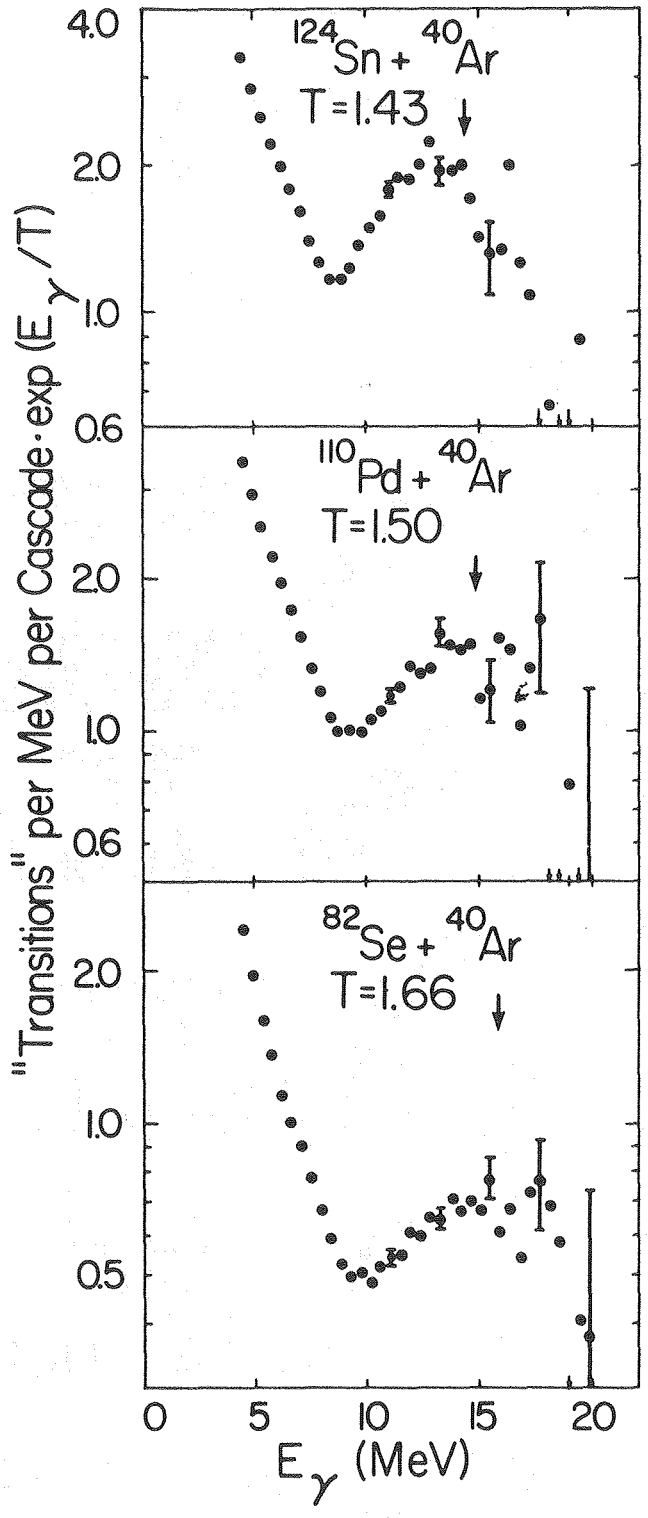
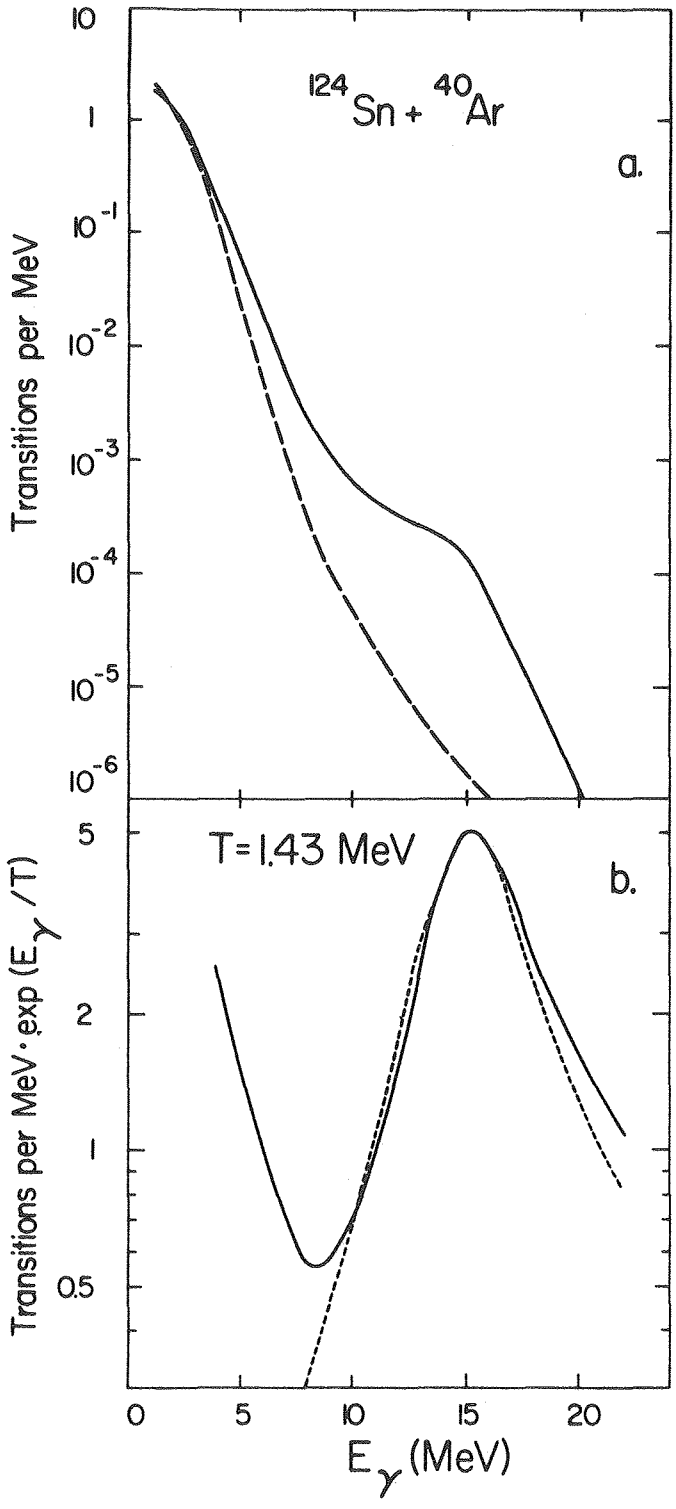

^{124}Sn + ^{40}Ar
T=1.43
^{110}Pd + ^{40}Ar
T=1.50
^{82}Se + ^{40}Ar
T=1.66
"Transitions" per MeV per Cascade·exp (E_γ/T)
E_γ (MeV)
4.0
2.0
1.0
0.6
2.0
1.0
0.6
2.0
1.0
0.5
0
5
10
15
20
XBL 811-71

Fig. 2



XBL 811-70

Fig. 3