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MEASUREMENTS OF (γ,d) AND (γ,np) REACTIONS IN THE THRESHOLD REGION

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MEASUREMENTS OF (γ,d) AND (γ,np) REACTIONS IN THE THRESHOLD REGION*

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I. INTRODUCTION

The investigation of (γ,d) reactions at low energies has attracted some interest recently[1,2]. Sawicki[1] calculated the cross section for the photoemission of deuterons assuming a mechanism in which the outgoing proton "picks-up" a neutron in the outside shells of the nucleus; using the independent particle model he obtains cross sections of a few millibarns, which are of the correct order of magnitude, although bigger than expected on the evaporation model.

It has been noticed in all the investigated cases that the re-

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actions(γ,d) and (γ,np) occur about 10-100 times more frequently than expected. This is the case in sulphur[3] and copper[4,5]. These measurements however give no more information than the cross section at a few energies.

At higher energies (50-150 Mev) a number of measurements have been made[6,7], including the energy distribution of the emitted protons and the angular correlation of protons and neutrons. The "quasi-deuteron" model of Levinger[8] seems to be quite successful in explaining the results.

In the low energy experiments, Katz and Penfold used the residual activity in P^{30} formed in the reactions (γ,d) and (γ,np) in S^{32} to measure the cross section for the reaction. Preliminary work of the same type has been made by S. S. Villaça and J. Goldemberg in several other elements[9]. In this type of experiment the only hope of distinguishing between the emission of deuterons and uncorrelated neutrons and protons is the threshold for the reaction which is 2.23 Mev smaller for (γ,d) than (γ,np). No peculiarity was found in this region by Katz and Penfold who report however the existence of a "bump" in the cross section at higher energies attributed to the fall of (γ,d) and rise of (γ,np) reaction. This interpretation can however be seriously criticized.

In this paper a report is made on measurements of reactions (γ,d) and (γ,np) in S^{32}, Zn^{64}, Zn^{66} and Fe^{54}; radiochemical methods were used to separate the parent from the daughter nucleus respectively P^{30}, Cu^{62}, Cu^{64} and Mn^{54}.

Great care was taken in measurements in the 2 Mev region above the (γ,d) and below the (γ,np) threshold. The results show that in this region the (γ,d) cross section goes through a resonance with a maximum of about 1 mb; at energies above the (γ,np) threshold the cross section rises again to 3mb and goes probably through a second maximum.

II. EXPERIMENTAL PROCEDURE AND RESULTS

Sample of materials containing sulphur, zinc and iron were irradiated in the X-ray beam of the 22 Mev Betatron of the University of São Paulo in energies ranging from 16 to 22 Mev variable in steps of 500 Kev. In Table I pertinent data on the irradiation is given:

TABLE I

Parent nucleus	Material used	Quantity of sample	Daughter nucleus	Half-life	Time of Irradiation
S^{32}	$(NH_4)_2SO_4$	150 gr	P^{30}	2.55 min	5 min
Zn^{64}	Z_nO	20 gr	Cu^{62}	10 min	10 min
Zn^{66}	Z_nO	20 gr	Cu^{64}	12.9 hr	20 min
Fe^{54}	$Fe(NO_3)_3$	5 gr	Mn^{52}	21 m + 6.5 d	20 min

In Table II are the threshold for the pertinent reactions.

TABLE II

Parent nucleus	Daughter nucleus	Threshold for (γ,d)	Threshold for (γ,np)
S^{32}	P^{30}	19.15 Mev	21.38 Mev
Zn^{64}	Cu^{62}	16.01	18.24
Zn^{66}	Cu^{64}	16.42	18.65
Fe^{54}	Mn^{52}	16.54	18.77

The thresholds in TABLE II were calculated from the work of Wapstra[10]. The chemical separations are described in the appendix. In each case a test of purity of the substance used was made, following carefully the decay of one sample and checking the half-life; chemical tests of purity were also made. In the case of Zn^{64} the absolute activity was found by comparison with the activity induced in Cu^{63} by a (γ,n) reaction, which gives exactly the same end product Cu^{62}.

The excitation function and cross section for the reaction $Zn^{64}(\gamma,d)Cu^{62}$ + $Zn^{64}(\gamma,np)Cu^{62}$ are shown in Figs. 1,2.

In the measurements of Zn^{66} a difficulty arises due to the fact that the reaction $Zn^{68}(\gamma,p)Cu^{67}$ contributes appreciably to the counting rate; it was decided not to eliminate this reaction in order to have something to compare with the (γ,d) reaction. The excitation function for the $Zn^{66}(\gamma,d)Cu^{64}$ + $Zn^{66}(\gamma,np)Cu^{64}$ is shown in Figs. 3,4 together with the results of the reaction $Zn^{68}(\gamma,p)Cu^{67}$. The cross section for the (γ,d) and (γ,np) is also shown.

It is seen clearly in the excitation function of Fig. 3 the slope change in the (γ,d) and (γ,np) curve responsible for the first maximum in the cross section curve. This change of slope is absent in the (γ,p) reaction although this is a reaction in which charged particles are emitted too.

It was thought that a good check of the experimental procedure was to remeasure the (γ,d) reaction in S^{32} and the results obtained are shown in Fig. 5, normalized to those of Katz and Penfold at 22 Mev. The good agreement in shape of the two curves indicates that no peculiarity of the kind found in Zn, is present between 19.15 and 21.38 Mev; our measurements do not extend to 25 Mev.

Finally a careful search was made of any activity provenient from the 21 min isomeric state of Mn^{52} and the same was done with the 6.5 day activity; none of these were found and this enables us to put an upper limit in the reaction $Fe^{54}(\gamma,d)Mn^{52} + Fe^{54}(\gamma,np)Mn^{52}$ of 1/30 the value found for the reaction $Zn^{64}(\gamma,d)Cu^{62} + Zn^{64}(\gamma,np)Cu^{62}$. The upper limit of the yield per mole per 100 R/min in Fe^{54} is 2.[illegible] $\times 10^4$ at our maximum energy. No reason for this anomalous low yield was found.

The curves of the reactions in Zn show then a peculiar shape which does not appear in Sawicki's paper; this behavior could not arise apparently, from competition due to the onset of the (γ,np) reaction. The results are more of the kind of a photodesintegration of the deuteron, with a sudden rise and fall down in the cross section; we feel tempted to say that some outgoing neutrons of the nucleus (there are about 100 times as many neutrons as deuterons in this energy region) can "pick-up" protons with the right momentum to form bound deuterons and come out. As the energy of the neutrons increases, less of these processes occur until there is enough energy for the emission of uncorrelated neutrons and protons.

More experimental work is in progress in other elements.

APPENDIX

Separation of Cu from Zn.- The irradiated ZnO was dissolved in 12 N HCl, 20 mg of Cu^{++} added, diluted with H_2O and the Cu^{++} reduced to Cu^{+} with sodium bisulphite. The Cu was precipitated with NH_4SCN, the precipitate of CuSCN was coagulated in an ice bath, filtered, dried, weighed and counted with a NaI scintillation counter.

Separation of P from S.- The irradiated $(NH_4)_2SO_4$ was dissolved in hot water, 1 mg of P as PO_4^{-3} added, then it was added NO_2^{-}, HNO_3 and 20 mg of Fe^{+++}. The Fe was precipitated with an excess of NH_4OH

and it carried the P. The precipitate was quickly filtered and counted with a thin wall Geiger counter.

Separation of Mn from Fe. The irradiated hydrated ferric nitrate was dissolved in hot HNO_3 and 20 mg of Mn^{++} added. The Mn was precipitated as MnO_2 with $KClO_3$, the solution was diluted with water, cooled, filtered, weighed and placed in a test tube thick enough to absorb all the positrons. The samples were counted with a well crystal scintillation spectrometer, set to count annihilation radiation.

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4) P. R. Byerly and W. E. Stephens, Phys. Rev. [illegible] (195[illegible]) [illegible]

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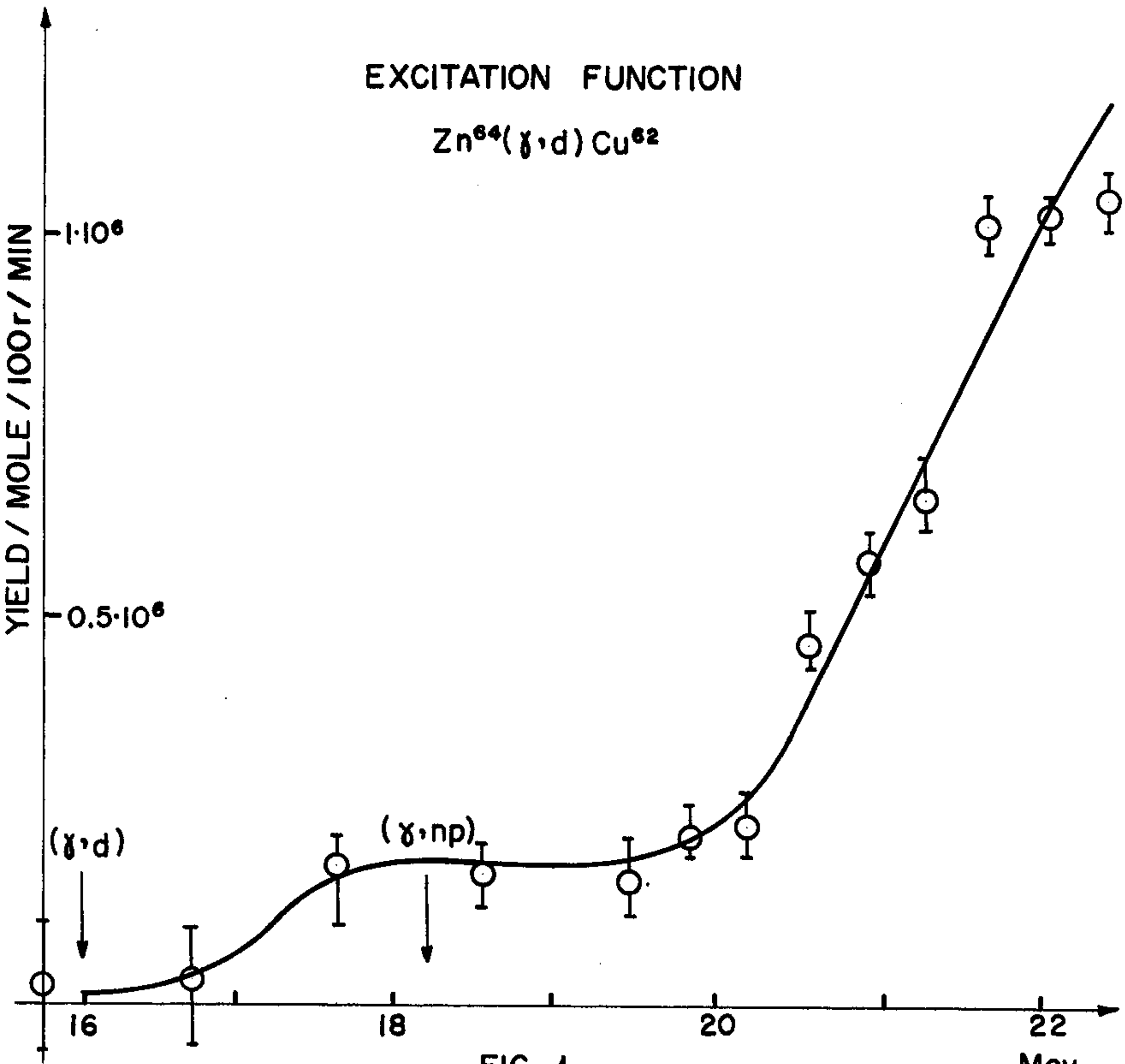
EXCITATION FUNCTION
Zn64(γ,d) Cu62
YIELD / MOLE / 100r / MIN
1·10⁶
0.5·10⁶
(γ,d)
(γ,np)
16
18
20
22
Mev

FIG. 1

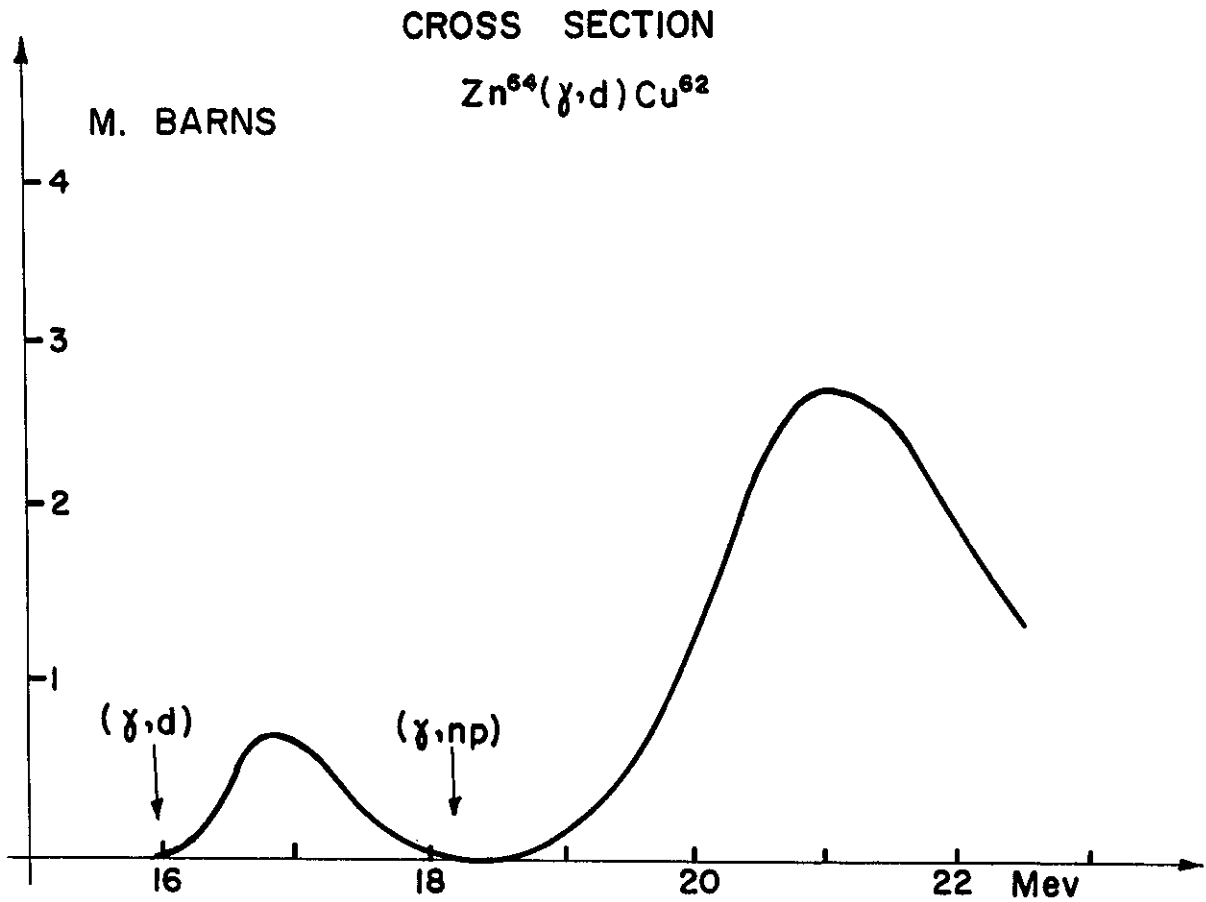

FIG 2

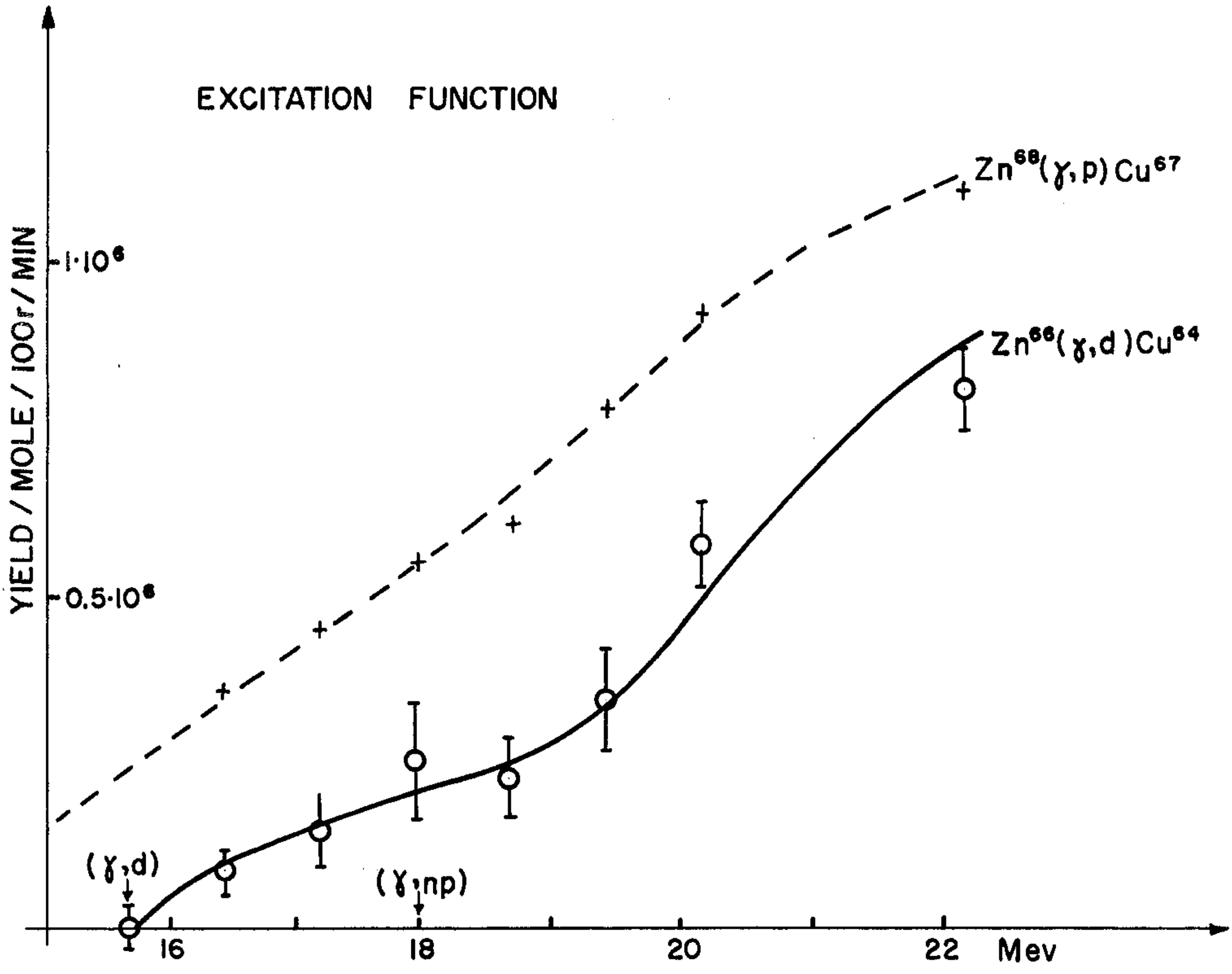
EXCITATION FUNCTION
YIELD / MOLE / 100r / MIN
1·10⁶
0.5·10⁶
Zn⁶⁸(γ,p)Cu⁶⁷
Zn⁶⁶(γ,d)Cu⁶⁴
(γ,d)
(γ,np)
16
18
20
22
Mev

FIG. 3

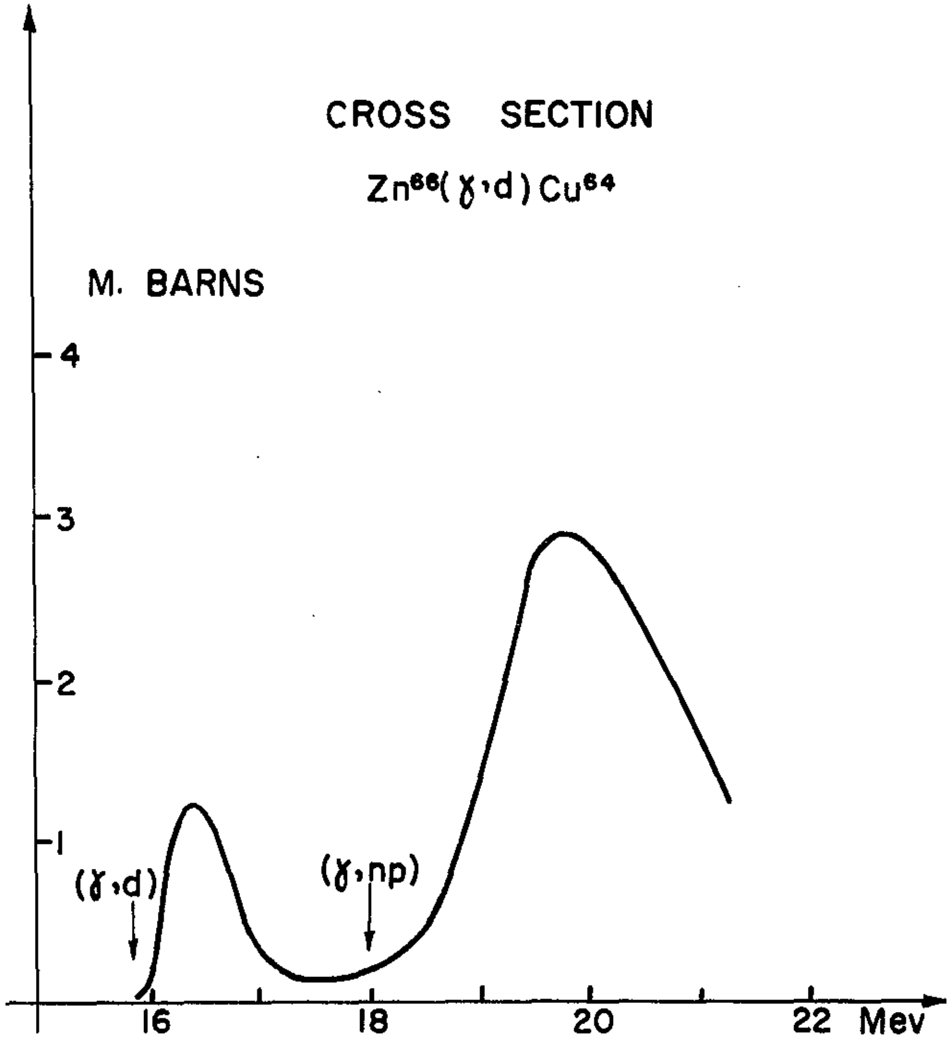
CROSS SECTION
$Zn^{66}(\gamma,d)Cu^{64}$
M. BARNS
4
3
2
1
(γ,d)
(γ,np)
16
18
20
22
Mev

FIG 4

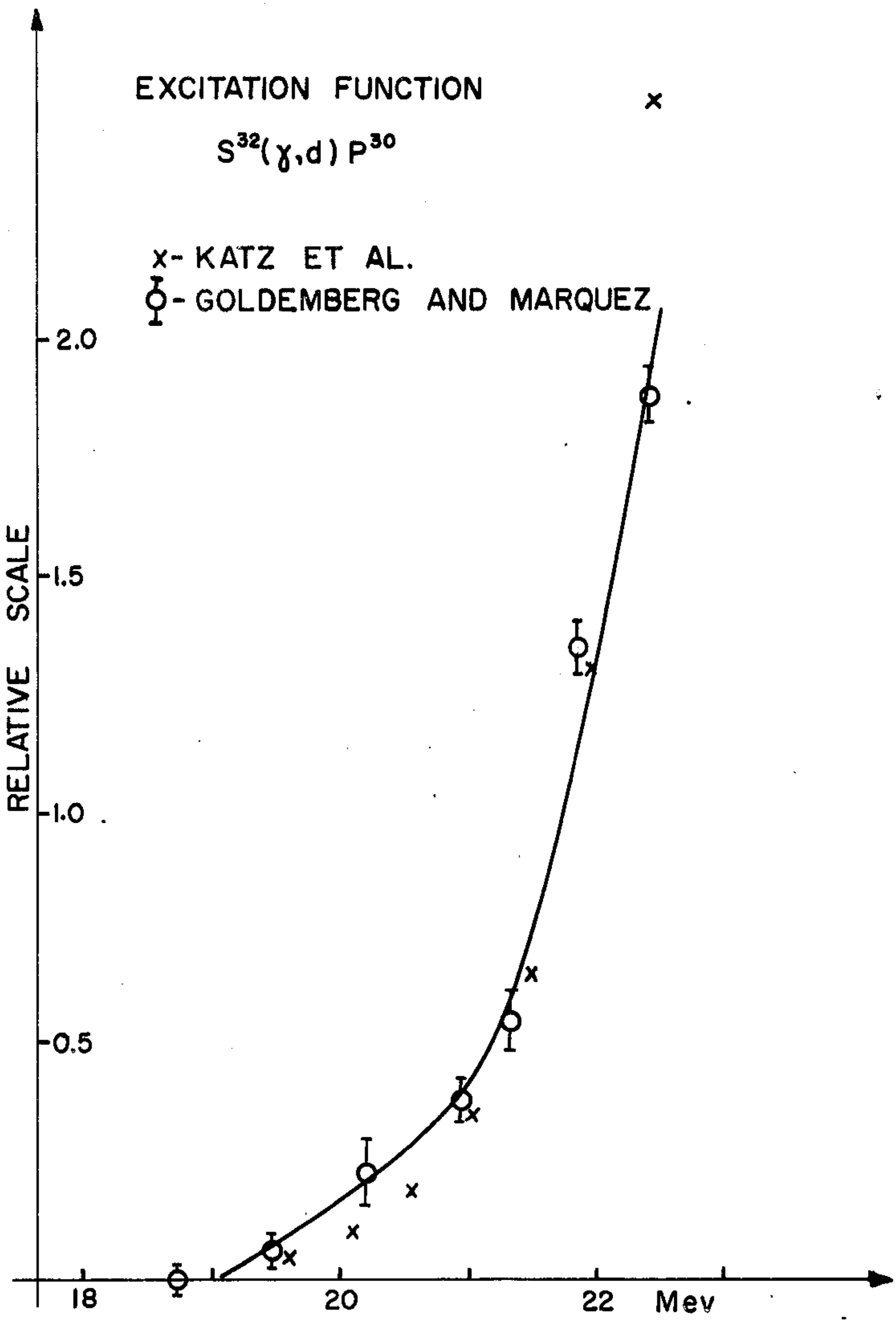
EXCITATION FUNCTION
S³²(γ,d) P³⁰
x- KATZ ET AL.
- GOLDEMBERG AND MARQUEZ
RELATIVE SCALE
2.0
1.5
1.0
0.5
18
20
22
Mev

FIG. 5