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THE (n, d) REACTION ON Cu AND Zn ISOTOPES. -

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ABSTRACT -

Deuteron energy spectra and angular distributions from the (n, d) reaction on the isotopes Cu^{65} and $Zn^{66, 68}$ initiated by 14 MeV neutrons are given. The angular distributions are fitted with DWBA and the results are interpreted in terms of the Cu isotopes structure as predicted by the unified model.

INTRODUCTION -

The possibility of describing the Cu isotopes in terms of a core excitation model has been recently studied by several authors both from the theoretical and the experimental point of view. In the simplest form of the model the last odd proton, in the $2p_{3/2}$ state, is coupled to the Ni core in its ground and one-phonon first excited state(1). The more extended models take into account also the possibility of single particle excitation to the $2p_{1/2}$ and $1\ f_{5/2}$ proton states(2, 3).

The single particle aspects of the various predicted levels have also been investigated in the line of the "pairing-plus-quadrupole" form for the neutron and proton interaction(4). The effect of a short range component in the interaction between neutrons and protons in the filling shell added to the quadrupole-quadrupole long range interactions has also been considered(5).

(x) - On leave of absence from the University of Alma-Ata (URSS).
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Several elastic and inelastic scattering experiments have been reported$^{(6\div9)}$. More recently the single-particle aspects of the Cu levels has been investigated by means of stripping$^{(10)}$ and pick-up reactions in which a Cu isotope is the target or final nucleus.

The Cu^{63} (d, He^3) Ni^{62} has been measured by Hiebert et al.$^{(11)}$ and the (n, d) reaction has been measured on Cu^{63} and Zn^{64} by Wang and Winhold$^{(12)}$ and by some of us$^{(13,14)}$.

In the present paper results of the (n, d) pick-up reaction induced by 14 MeV neutrons on the isotopes Cu^{65} and $Zn^{66,68}$ are given together with an analysis of all our results, including Cu^{63} and Zu^{64}.

This reaction should permit a more straightforward extraction of the spectroscopic factors because there are no mass-three particles involved and there is no isobaric-spin multiplicity as in proton stripping reactions.

Considerable experimental difficulties are however encountered because of the use of neutral particles.

EXPERIMENTAL PROCEDURE -

Self supporting metal foils of Cu^{65} (thickness 3.4 mg/cm^2), Zn^{66} (thickness 4 mg/cm^2) and Zn^{68} (thickness 4.4 mg/cm^2) enriched to 99.7%, 96.1% and to more than 95% respectively were bombarded by 14.1 MeV neutrons. The deuterons emitted were detected by means of a dE/dx and E counter telescope. The dE/dx and E counters were two solid-state silicon detectors respectively 80 μm and 1800 μm thick. Detected deuterons passed also a gas proportional counter positioned immediately after the target and filled with 84 mm Hg of Kr and 14 mm Hg of CO_2. A coincidence was required between these three counters. A fourth proportional counter was positioned at the entrance of the counter telescope before the target and placed in anticoincidence. The use of the proportional counters is required to lower the background. The counter energy resolution was limited by the self-absorption in the isotope targets. The angular acceptance of the counter was kept at about 14° FWHM in order to maximize the counting rate. The neutron flux was held at about $5\cdot10^9$ neutrons/sec in all the solid angle: with this flux typical counting rates were about 30 counts/hr in the g. s. transition peaks.

Mass separation was checked several times during data collection by means of recoil protons and deuterons from a polyethylene and a deuterated paraffin target.

The known value of the cross section for forward (n, p) elastic scattering was used to obtain the pick-up cross section.

The absolute value of the (n, d) cross section is so derived with a precision which depends on the statistical error given in table II, and other causes such as errors in the target thickness and isotopic purity, instrumental errors and the error on the (n, p) elastic cross section$^{(15)}$. All these causes together are of the order of 10%; the last one being the most important.

RESULTS -

Deuteron energy spectra summed over forward angles are given in fig. 1.

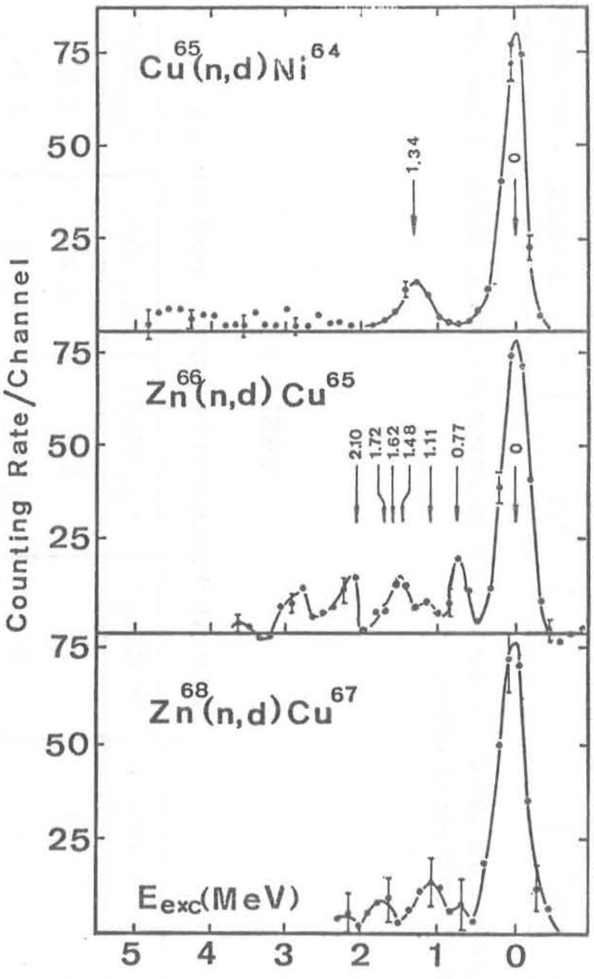

FIG. 1 - Deuteron energy spectra from $Cu^{65}(n, d)Ni^{64}$, $Zn^{66}(n, d)Cu^{65}$ and $Zn^{68}(n, d)Cu^{67}$. Data at angles between 12° and 25° have been summed. The typical errors shown at a few points are due only to counting statistics.

The transition to the ground state of the final nucleus is predominant in all the spectra. Only one peak corresponding to the first excited state of Ni^{64} has a significant intensity in the spectrum from $Cu^{65}(n, d)Ni^{64}$; higher excitation levels are weakly excited. In the deuteron spectrum from $Zn^{66}(n, d)Cu^{65}$ several peaks corresponding in some cases to unresolved levels of Cu^{65} are seen. Because of the highly negative Q-value for the (n, d) reaction on Zn^{68} only states up to 2 MeV excitation in Cu^{67} can be seen. Due to the low yield no conclusion can be drawn about Cu^{67} states although the existence of levels at about the same excitation as in Cu^{65} seems to be indicated. No previous information has been found on these levels.

Angular distributions for the prominent peaks in the spectra are given in figs. 2 to 6. The experimental data are summarized in table I.

Excitation energy, spin, adopted captured particle l-value, experimental cross section integrated in the intervals given and extracted spectroscopic factors are listed for the final nucleus levels. The errors given in the table are only those due to counting stati-

TABLE I

DATA SUMMARY

	Corresponding known level		l_p	Cross section	Spectroscopic
	E_{exc} (MeV)	J		(mb)	factor S
Cu^{63} (n, d) Ni^{62}	0	0^+	1	3.57 ± 0.40 $(0^\circ-62^\circ)^{(o)}$	$0.94 \pm 0.05^{(o)}$
	1.117	2^+	1	1.28 ± 0.17 $(0^\circ-62^\circ)$	0.40 ± 0.04
Cu^{65} (n, d) Ni^{64}	0	0^+	1	2.82 ± 0.29 $(0^\circ-90^\circ)$	1.00 ± 0.04
	1.34	2^+	1	0.70 ± 0.14 $(0^\circ-90^\circ)$	0.47 ± 0.05
Zn^{64} (n, d) Cu^{63}	0	$3/2^-$	1	3.63 ± 0.44 $(0^\circ-80^\circ)$	1.23 ± 0.08
	0.668 - 0.961	$1/2^- - 5/2^-$	1	1.48 ± 0.30 $(0^\circ-80^\circ)$	$\lesssim 0.46$
Zn^{66} (n, d) Cu^{65}	0	$3/2^-$	1	2.52 ± 0.25 $(0^\circ-80^\circ)$	1.55 ± 0.07
	0.77	$1/2^-$	1	0.48 ± 0.21 $(0^\circ-80^\circ)$	0.40 ± 0.07
	1.114	$5/2^-$	-	~ 0.40 $(0^\circ-80^\circ)$	---
	1.48 - 1.62	$7/2^- - 5/2^+$	3	1.16 ± 0.21 $(0^\circ-80^\circ)$	3.16 ± 0.47
Zn^{68} (n, d) Cu^{67}	0	$3/2^-$	1	2.15 ± 0.40 $(0^\circ-90^\circ)$	1.91 ± 0.14

(o) - The errors given are due only to counting statistics. Refer to text for a discussion of the other sources of error.

TABLE II

OPTICAL PARAMETERS USED FOR DWBA

	V (MeV)	W (MeV)	V_{so} (MeV)	r_{ov} (fm)	r_{ow} (fm)	a_v (fm)	b_w (fm)
Neutron	44	11	8.3	1.25	1.25	0.65	0.98
Deuteron	95	23	0	1.15	1.34	0.81	1.56

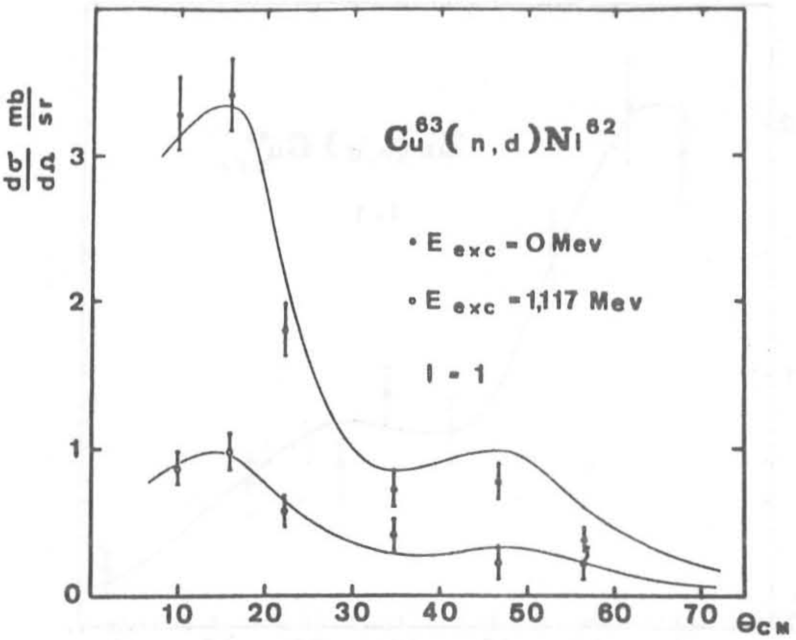

FIG. 2 - Angular distributions of deuterons from $Cu^{63}(n,d)Ni^{62}$. The curves are the result of DWBA smeared for the experimental angular resolution.

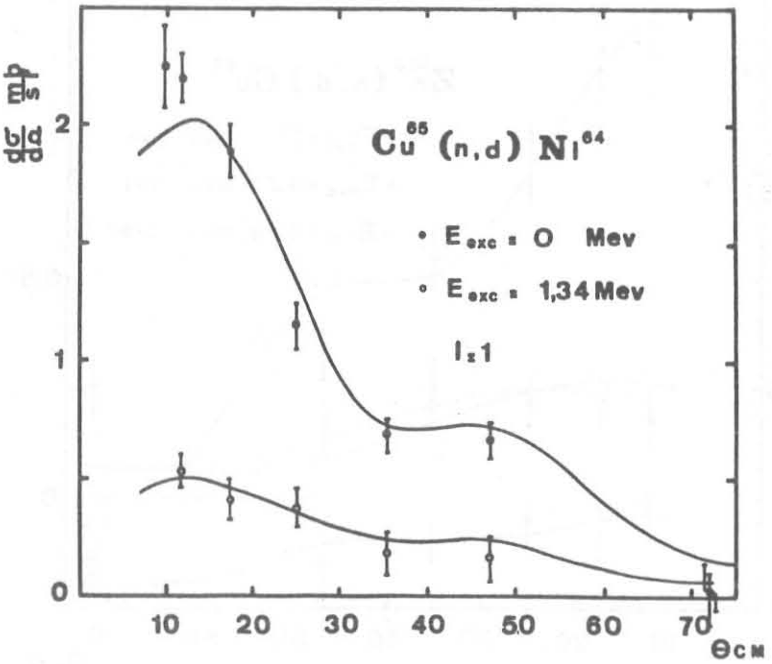

FIG. 3 - Angular distributions of deuterons from $Cu^{65}(n,d)Ni^{64}$. The curves are the result of DWBA smeared for the experimental angular resolution.

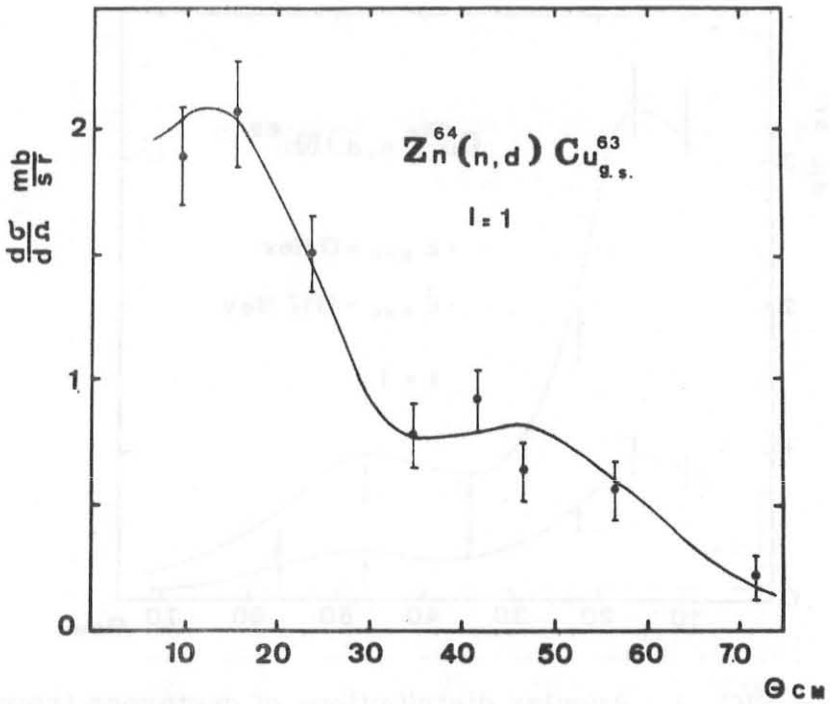

FIG. 4 - Angular distribution of deuterons from $Zn^{64}(n,d)Cu^{63}$ g.s. The curve is the result of DWBA smeared for the experimental angular resolution.

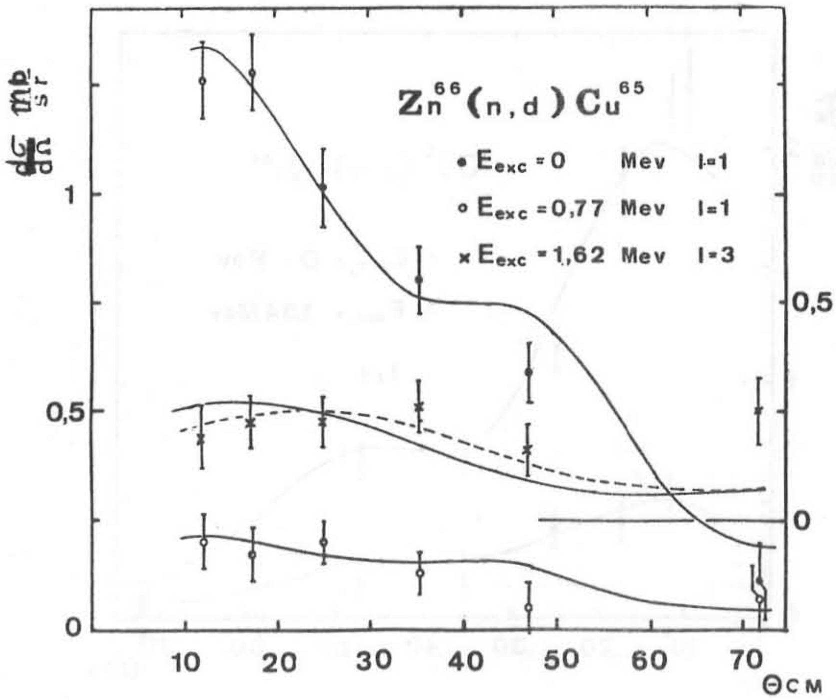

FIG. 5 - Angular distribution of deuterons from $Zn^{66}(n,d)\,Cu^{65}$. The curves are the result of DWBA smeared for the experimental angular resolution. The dashed curve is obtained with the optical parameters given in ref. (22).

stics; the errors on the integrated cross sections are larger than those on the S-values because the former are more sensitive to large angles which are affected by relatively larger statistical errors.

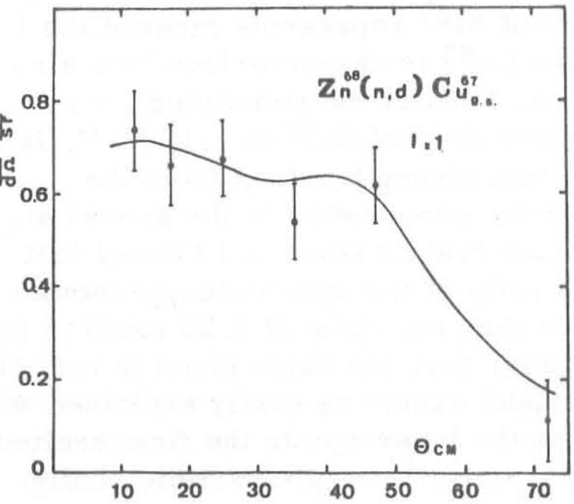

FIG. 6 - Angular distribution of deuterons from $Zn^{68}(n,d)Cu^{67}$ g.s. The curve is the result of DWBA smeared for the experimental angular resolution.

DISCUSSION -

The angular distributions have been fitted with DWBA in order to obtain l-values and spectroscopic factors.

The optical parameters used in the present calculations are given in Table II. Neutron potentials are the ones used by Biorklund and Fernbach$^{(16)}$; deuteron potentials are of the surface-interaction type, with a gaussian form factor for the imaginary part of the potential. The values used are substantially those given in set B by Perey$^{(17)}$.

Spectroscopic factors so obtained are subject to uncertainties deriving from various sources. Deformed optical potentials and coupling with inelastic channels have been considered in describing proton scattering$^{(18)}$; copper isotopes have non-zero quadrupole moments; no such calculations are, however, yet available for transfer reactions.

Core excitation in stripping processes$^{(19)}$, the choice of the binding energy of the captured nucleon$^{(20)}$ and the lack of elastic scattering data for separate isotopes, can produce significant variations in the cross section absolute value and angular dependence.

In view of these uncertainties the absolute S-values cannot be usually given to better than a factor of two$^{(21)}$. The relative values are, however, much more reliable. If the optical parameters given in ref. (22) which differ from ours for the deuteron potential (which is taken as:

$U = 100$ MeV: $W = 17.5$ MeV; $V_{SO} = 6$ MeV; $r_{OV} = 1$ fm; $r_{OW} = 1.5$ fm; $a_V = 0.9$ fm; $b_W = 1.35$ fm)

are used, absolute values which are about 2/3 times smaller are obtained while the relative values vary only by 15%.

In (n, d) pick-up the reliability of the DWBA fits is however often limited mainly by the quality of the experimental data.

It is therefore difficult to assess the presence of small higher-l components in the presence of a dominant l-value.

$Cu^{63}(n, d)\ Ni^{62}$ - The observed spectroscopic factor given in table I for the transition to the ground state of Ni^{62} represents most of the $l = 1$ transition strength expected when Cu^{63} is characterized by a single $p_{3/2}$ proton outside a closed core. Most of the remaining $l = 1$ strength is found in the 2^+ first excited state of Ni^{62} at 1.17 MeV. In the description of the unified model this strength arises from the $|2, p_{3/2}\rangle$ and $|2, p_{1/2}\rangle$ one-phonon components in the ground state of Cu^{63} and the spectroscopic factor results about 0.16 times that for the ground state transition. The ratio of the spectroscopic factors given in table I is 0.43 ± 0.05 higher than the value of 0.29 found in the Cu^{63} (dHe^3) Ni^{62} reaction$^{(11)}$ and lower than the value given in ref. (12). The disagreement with the unified model cannot be easily explained with the presence of an $l = 3$ component in the transition to the first excited state arising from a sizeable $(f_{7/2})^{-1}$ $(p_{3/2})^{+1}$ single particle configuration in the 2^+ state of Ni^{62} $^{(11 \div 13)}$. The existence of such a component is also not well verifiable because of the above difficulties in the DWBA analysis.

$Cu^{65}(n, d)\ Ni^{64}$ - As seen in table I the excitation energy of the final nucleus levels, the l-values and spectroscopic factors for the transitions are very similar to those for the reaction on the lighter Cu isotope. This fact confirms a similar structure for the two isotopes.

$Zn^{64}(n, d)Cu^{63}$ - If Zn^{64} is assumed to be described simply as two $p_{3/2}$ protons coupled to a Ni^{62} core in its 0^+ ground state and the Cu^{63} levels are correctly described by the unified model, nearly all the $l = 1$ strength should be found in the ground state transition. Although the 0.668 MeV level is not resolved, the summed cross section for the 0,668 MeV and 0,961 MeV levels gives a limit value of 0,46 for the spectroscopic factor for an $l = 1$ transition. This value is smaller than the one given in ref. (12). If the transition to the 0.961 MeV level corresponds to an $l=3$ pick-up, as indicated by the Ni^{62} (He^3, d) Cu^{63} reaction$^{(10)}$, than the spectroscopic factor for the $l = 1$ transition to the first excited level is approximatively equal to the limit value.

This fact indicated the presence of a $|0, p_{1/2}\rangle^2$ or a $|2, p_{3/2}\rangle^2$ component in the ground state configuration of Zn^{64}; if the first excited state of Cu^{63} is described by these component as in the unified model.

$Zn^{66}(n, d)Cu^{65}$ - Also in the reaction on this isotope part of the $l = 1$ strength is found in the first excited state. The spectroscopic factor for this transition is similar to the limit value given for the transition to the corresponding level in Cu^{63}. The transition to the 1,114 MeV level in Cu^{65} is not well resolved and only an approximate value for its integrated cross section is given in table I. The peak seen in the deuteron spectrum at about 1.6 MeV excitation energy may include contributions from the transitions to the 1.48, 1.62 and 1.72 MeV levels of Cu^{65}. The full curve given in fig. 5 is obtained with the parameters given in table II and $l = 3$ and does not fit well the experimental angular dependence; the dashed curve in the same figure is obtained using the optical parameters given in ref. (22).

If all the intensity of this peak is attributed to 1 = 3 transitions as found for the corresponding transitions leading to Cu^{63} levels$^{(12)}$ than the spectroscopic factor obtained with the set of optical parameters in table II is 3.16. Using the optical parameter of ref. (22) the spectroscopic factor is 2.77. These spectroscopic factors would indicate a substantial contribution from $f_{7/2}$ pick-up from the core as in the (n, d) reaction on Zn^{64} (12)

CONCLUSIONS -

As seen from table I the spectroscopic factors for transitions to corresponding final states increase going from lighter to heavier isotopes. This increase may be due to the choice of the same optical parameters for all the isotopes.

The summed strength for 1 = 1 transitions is about 2 in the (n, d) reactions on the Zn isotopes and therefore about equal to the value expected when the Zn nuclei are described as a closed core plus two protons in the p shell. The relatively large spectroscopic factors for the transitions to the first excited states of the residual Cu isotopes indicates that the ground state configurations of the Zn isotopes contain a sizeable $| 0, p_{1/2} \rangle^2$ or $| 2, p_{3/2} \rangle^2$ component. For the Cu isotopes the summed spectroscopic factors for 1 = 1 transitions is greater than one. This "o-verfilling" of the sum rule for S probably reflects a deficiency of our DWBA analysis or might indicate, as suggested also by the strong 1 = 3 peak, that a sizeable $(f_{7/2})^{-1} (p_{3/2})^2$ component is present in the Cu isotopes ground states. The transitions to the first excited 2^+ state in the final Ni nuclei are more excited than predicted by the unified model.. This large excitation indicates $| 2, p_{3/2} \rangle$ or $| 2, p_{1/2} \rangle$ components larger than predicted in Cu^{65} and Cu^{63} ground states if processes like stripping via core excitation are negligeable.

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REFERENCES -

(1) - J. Vervier, Nuovo Cimento 28, 1412 (1963).

(2) - M. Bouten and P. Van Leuven, 32, 499 (1962).

(3) - V.K. Thankappan and W.W. True, Phys. Rev. 137, B 793 (1964).

(4) - W. Beres, Phys. Letters 16, 65 (1965).

(5) - P. Doleschall and I. Lovas, Phys. Letters 21, 546 (1966).

(6) - F. Perey, R.J. Silva and G.R. Satchler, Phys. Letters 4, 25 (1963).

(7) - G. Bruge, J.C. Faivre, M. Barloutaud, H. Faraggi and J. Saudinos, Phys. Letters 7, 612 (1963).

(8) - R.L. Robinson, F.K. McGowan and Ph. Stelson, Phys. Rev. 134, 612 (1963).

(9) - N. Cindro, Nuclear Phys. 57, 542 (1964).

(10) - A.B. Blair, Phys. Letters 9, 37 (1964); Phys. Rev. 140, B 648 (1965).

(11) - J.C. Hiebert, E. Newman and R.H. Bassel, Phys. Letters 15, 160 (1965).

(12) - W.N. Wang and E. Winhold, Phys. Rev. 140, B 882 (1965).

(13) - M. Fazio, I. Iori, S. Micheletti, N. Molho and M. Pignanelli, Nuovo Cimento 38, 1938 (1965).

(14) - M. Fazio, I. Iori, S. Micheletti, N. Molho, M. Pignanelli and L. Zetta, EANDC (E) 66 U (Febr. 1966) 94.

(15) - J.L. Fowler and J.E. Brolley Jr., Revs. Mod. Phys. 28, 103 (1956).

(16) - F. Bjorklund and S. Fernbach, Phys. Rev. 109, 1295 (1958).

(17) - C.M. Perey and F.G. Perey, Phys. Rev. 132, 755 (1963).

(18) - M.P. Fricke and G.R. Satchler, Phys. Rev. 139, B 567 (1965).

(19) - B. Kozlowsky and A. De-Shalit, Nuclear Phys. 77, 215 (1966).

(20) - R. Huby and J.L. Hutton, Phys. Letters 19, 660 (1966).

(21) - W.R. Smith, Phys. Review 137, B 913 (1965).

(22) - V. Valkovic, G. Paic, I. Slaus, P. Tomas, M. Cireneo and G.R. Satchler, Phys. Rev. 139, B 331 (1965).