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Publication Date
1965

University of California

Ernest O. Lawrence Radiation Laboratory

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Berkeley, California

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UCRL-11895

Nuclear Physics

UNIVERSITY OF CALIFORNIA

Lawrence Radiation Laboratory
Berkeley, California

AEC Contract No. W-7405-eng-48

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1. Introduction

Much experimental evidence has been accumulated in recent years to show that some of the low lying levels of certain odd-A nuclei can be thought of as formed by a vector coupling of the odd nucleon to collective modes of vibration of the even-even core[1]). Thus Cu^{63}, on the basis of this model, consists of a $p_{3/2}$ odd proton coupled to Ni^{62}. The Cu^{63} ground state is therefore 3/2-, and there should be four nearly degenerate excited levels with spins 1/2, 3/2, 5/2 and 7/2 corresponding to the vector coupling of the spin of the odd nucleon to the 2+ quadrupole vibration of Ni^{62} at 1.172 MeV. Further, there should be four levels of spins 3/2, 5/2, 7/2 and 9/2+ corresponding to the coupling of the odd proton to the 3- octupole state of Ni^{62} at 3.77 MeV. The model predicts that the sum of the cross sections for formation of the members of a quartet by inelastic α-scattering will be equal to the cross section for excitation of the same core state in Ni^{62}. The cross section for each

*This work was performed under the auspices of the United States Atomic Energy Commission and BUSHIPS.

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member of the quartet will be proportional to (2J + 1). The center of gravity of the quartet (when the energies are weighted by 2J + 1) will lie just at the energy of the core state. Since the same phonon is involved in the decay of each member of a quartet, the reduced transition probabilities $B(E\lambda)\downarrow$ for decay to the ground state should be equal to each other and to the $B(E\lambda)\downarrow$ for decay of the core state in Ni^{62}.

Previous investigations by Coulomb excitation with O^{16} ions[2]) and α-particles[3]) and by inelastic α-scattering at Saclay[4]) showed that the levels in Cu^{63} at 0.668, 0.961 and 1.327 MeV were strongly excited and had $B(E2)\downarrow$ values approximately equal to that of the core state, as required by the model. Fig. 1 shows the level schemes of Cu^{63} and Ni^{62}. None of the low lying states of Cu^{63} appear to have the correct properties to be the 3/2- member of the quartet. Perey, Silva and Satchler[5]), from (p,p') studies, concluded that the 1.412-MeV level might be the missing member, but the evidence they present is not compelling.

Having available an energy-analyzed beam of helium ions at any required energy between 25 and 120 MeV at the 88" cyclotron and lithium drifted silicon counters of excellent energy resolution, we decided to look again at the spectrum of α-particles scattered from Cu^{63} to see whether we could find the missing level. The core nucleus, Ni^{62}, was also investigated.

2. Experimental

The beam-optical system, the counters and the scattering chamber have previously been described[6]).

A few spectra were measured with 25 MeV incident alphas, as well as complete angular distributions at 50 MeV. The lower energy determinations were made for the purpose of identifying levels, as the energy resolution was better at this energy. The best energy resolutions were 40 keV (FWHM) at 25 MeV and

90 keV at 50 MeV. The incident beam was responsible for most of the energy spread.

The targets were prepared from separated isotopes by rolling or by vacuum evaporation. Their thicknesses were 1.5 and 0.109 mg/cm^2 in the case of Cu^{63} and 2.4 and 0.10 mg/cm^2 for Ni^{62}. The thinner evaporated foils were used in the 25 MeV experiments.

The scattered α-particles were detected in a 0.18 cm thick lithium drifted silicon surface barrier counter. The pulses from the detector were fed into a pre-amplifier and linear amplifier system designed by F. S. Goulding and D. A. Landis[7]). The energy spectra were measured with a Nuclear Data ND-160 pulse height analyzer. The information from the analyzer was punched on paper tape and subsequently transferred to magnetic tape. This magnetic tape was used to plot accurate graphs and to serve as the input tape for the spectrum-analysis program VARMIT[8]). This program makes a least-squares fit to the experimental spectra by a series of Gaussian peaks whose heights, positions and common width are adjustable parameters. The final output of the program gives the center of mass differential cross section for each level at each of the center of mass scattering angles.

3. Experimental Results

A spectrum of 25 MeV α-particles scattered from Cu^{63} is shown in fig. 2. The levels at 0.668, 0.961 and 1.327 MeV are strongly excited. The levels at 1.412 and 1.547 MeV are weak (the latter is not even visible in fig. 2). Additional strong levels are seen at 2.51, 3.3, 3.5, 3.7 and 3.8 MeV.

With 50 MeV α-particles, it was not possible to resolve the 1.412-MeV level from the 1.327-MeV level. However, both the 1.412-MeV and 1.547-MeV levels appear to be only weakly excited. The angular distributions for scattering of 50 MeV α-particles to excite the 0.668-, 0.961- and 1.327-MeV levels of Cu^{63} are shown in fig. 3 as well as the angular distribution for excitation of the 1.172-MeV 2+ level of Ni^{62}.

Previous workers[4]) had observed a quartet of octupole levels, but the improved energy resolution in the present experiment showed that there are actually five levels that are apparently formed by an $\ell = 3$ process. They lie at 2.51, 3.32, 3.51, 3.74 and 3.83 MeV. Their angular distributions are compared with that for excitation of the 3.77-MeV octupole level of Ni^{62} in fig. 4.

4. Discussion

4.1 QUADRUPOLE LEVELS

The simple core-excitation model requires that the sum of the cross sections for excitation of the quartet of levels in Cu^{63} should be equal to the cross section for excitation of the 1.172-MeV level of Ni^{62}. Furthermore, the cross sections of the individual levels of Cu^{63}, divided by $(2J + 1)$, should be equal to the cross section for the 1.172-MeV level of Ni^{62} divided by 20. Table 1 shows the extent to which these predictions are realized. At both the 27° and 37° diffraction maxima, the sum of the cross sections for excitation of the three known quadrupole levels is slightly less than that for excitation of the 1.172-MeV level of Ni^{62}. The weighted Cu^{63} cross sections are very close to that for the 1.172-MeV level of Ni^{62}. Only the weighted cross section of the 0.668-MeV level at the 27° maximum appears to be significantly different, but inspection of the experimental results shows that the point at 27° seems to be too high. A smooth curve drawn through all the experimental points gives $\sigma(27^{\circ})$ equal to 1.3 mb and hence $\sigma/(2J + 1)$ equal to 0.65.

The last column of table 1 gives the ratio of reduced electric quadrupole transition probabilities for decay $B(E2)\downarrow$ for the Cu^{63} levels to that of the 1.172-MeV 2+ level of Ni^{62}. The averages of the values obtained at the two angles are: 0.668-MeV level, 1.0; 0.961-MeV level, 1.1; 1.327-MeV level, 0.9. The quadrupole strength of the 1.327-MeV level appears to be slightly lower than the strength of the other two levels.

Thankappan and True[9]) have made calculations of several properties of the levels of Cu^{63}. Their model permits the odd nucleon to occupy the $p_{3/2}$, $p_{1/2}$ and $f_{5/2}$ orbitals; excitation of the core is restricted to a single quadrupole phonon. The odd particle interaction with the core contains a dipole-dipole term and a quadrupole-quadrupole term. The relative strengths of these two interactions were varied to obtain best agreement with the level energies, and the ratios of the reduced electric quadrupole transition probabilities for Cu^{63} relative to that for the 2+ level of Ni^{62} were calculated. The theoretical results are compared with the results of the present experiment in table 2. The values obtained by the present authors and quoted by Thankappan and True are slightly different from the values in table 2. They were obtained by analysis of the angular distributions in the smooth cut-off approximation[10]). The reduced quadrupole transition strength for the 1.547-MeV level is about 1/10th of the values for the other levels. The 1.412-MeV level is equally weak.

In a separate experiment[11]) the scattering of α-particles by Ni^{62} was studied at several particle energies. Values of B(E2) for decay of the 1.172-MeV level were obtained by analysis with the Blair and Austern approximation[12]). The values (including the result of the present experiment at 50 MeV) are shown in table 3. The mean value—160 e^2fm^4—is in excellent agreement with values obtained by (α,α') at 43 MeV[4]) (170 e^2fm^4) and by Coulomb excitation[3]) (160 e^2fm^4), and is in excellent agreement with the theoretical values obtained by Thankappan and True[9]) for the 0.668-, 0.961- and 1.327-MeV levels of Cu^{63} (169, 166 and 153 e^2fm^4 respectively). Their calculation showed that the lowest 3/2- level of Cu^{63} should have a B(E2) for decay to the ground state that is approximately three times smaller than the 1/2-, 5/2- and 7/2- levels, and should be pushed up to an energy of 2.02 MeV. The experimentally known level at 2.012 MeV might therefore be the 3/2-level: it is certainly more weakly excited than the low-lying quadrupole levels[13]).

4.2 OCTUPOLE LEVELS

Table 4 shows the differential cross sections for excitation of the 3- level of Ni^{62} at 3.77 MeV and the five $\ell = 3$ levels of Cu^{63}. The sum of the cross sections for the Cu^{63} levels (omitting the 2.51-MeV level) is in good agreement with the cross section for excitation of the 3.77-MeV level of Ni^{62}.

Two explanations have been advanced for the appearance of five octupole levels in Cu^{63}. Since there are at least two octupole levels in Ni^{62} (at 3.77 and about 5.65 MeV), the weak coupling model would predict the appearance of two quartets of levels in Cu^{63}. Some of the observed levels might be unresolved multiplets. In the calculation of Beres and Lemmer[14]), quasi-particles were considered to be coupled to a core, and two quartets of octupole levels appeared in Cu^{63}.

Alternatively, one of the octupole levels might belong to a completely different configuration, for example an odd particle in the $g_{9/2}$ orbital coupled to the 0+ state of the core. As shown by Thankappan and True for the quadrupole levels, quite a small amount of configuration mixing can lead to a large enhancement of the transition probabilities. The 2.51-MeV level of Cu^{63} could be excited in inelastic α-particle scattering by promotion of the $p_{3/2}$ odd proton to the $g_{9/2}$ shell with a transfer of three units of angular momentum, and the transition could be enhanced. Blair has found that a level (a group of levels) with a strong $g_{9/2}$ admixture occurs at 2.51 MeV in Cu^{63} [15]).

5. Acknowledgments

We wish to thank Drs. V. K. Thankappan and W. W. True for many valuable discussions. As always we are grateful to the crew and staff of the 88-inch cyclotron for their efficient help, to C. E. Ellsworth for preparation of the targets and to Jeannette Mahoney for doing most of the reduction of the data.

Table 1

Summary of differential cross sections and weighted differential cross sections for excitation of quadrupole levels of Ni^{62} and Cu^{63} by scattering of 50 MeV α-particles.

Angle (C. of M.)	Target	Level Energy (MeV)	$\sigma(\theta)$ (mb/sr)	$\frac{\sigma(\theta)}{(2J + 1)}$	$\frac{B(E2)\downarrow\ (Cu^{63})}{B(E2)\downarrow\ (Ni^{62})}$
27^{o}	Ni^{62}	1.172	12	0.60[a]	---
	Cu^{63}	0.668	1.5	0.75	1.25 (1.1)[b]
		0.961	4.0	0.67	1.1
		1.327	4.3	0.54	0.9
		1.547	0.23	0.05[c]	0.08
	ΣCu^{63}	---	9.8[d]	0.61	---
37^{o}	Ni^{62}	1.172	5.8	0.29[a]	---
	Cu^{63}	0.668	0.55	0.27	0.93
		0.961	1.8	0.30	1.03
		1.327	2.0	0.25	0.86
		1.547	0.09	0.02[c]	0.08
	ΣCu^{63}	---	4.35[d]	0.27	---

[a] The Ni^{62} cross sections are divided by 20 to permit direct comparison with $\sigma(\theta)/(2J + 1)$ for the Cu^{63} levels.

[b] With cross section read from smooth curve (see text).

[c] Assuming a spin of 3/2 for the 1.547 MeV level.

[d] Not including the 1.547 MeV level.

Table 2

Ratios of reduced quadrupole transition probabilities for the levels of Cu^{63} relative to the 1.172 MeV-level of Ni^{62}

Level energy (MeV)	$\frac{B(E2)\downarrow}{B(E2)\downarrow\ (Ni^{62})}$ Calc (9)	Exp.
0.668	1.01	1.0
0.961	1.00	1.1
1.327	0.92	0.9

Table 3

Reduced quadrupole transition probabilities B(E2) for decay of the 1.172-MeV 2+ level of Ni^{62} measured by scattering of α-particles of various energies.

α-Particle Energy (MeV)	B(E2), e^2fm^4
33	150
50	180
85	145
100	170
Mean	160

Table 4

Differential cross sections at 22° (center of mass) for octupole levels of Ni^{62} and Cu^{63} excited by scattering of 50 MeV α-particles.

Nucleus	Level energy (MeV)	σ(θ) (mb/sr)
Ni^{62}	3.77	9.6
	5.65	~ 2.6
Σ Ni^{62}	----	12.2
Cu^{63}	2.51	4.5
	3.32	2.8
	3.51	2.5
	3.74	1.8
	3.83	1.9
Σ Cu^{63}	----	13.5
Σ Cu^{63} (omitting 2.5 MeV)		9.0

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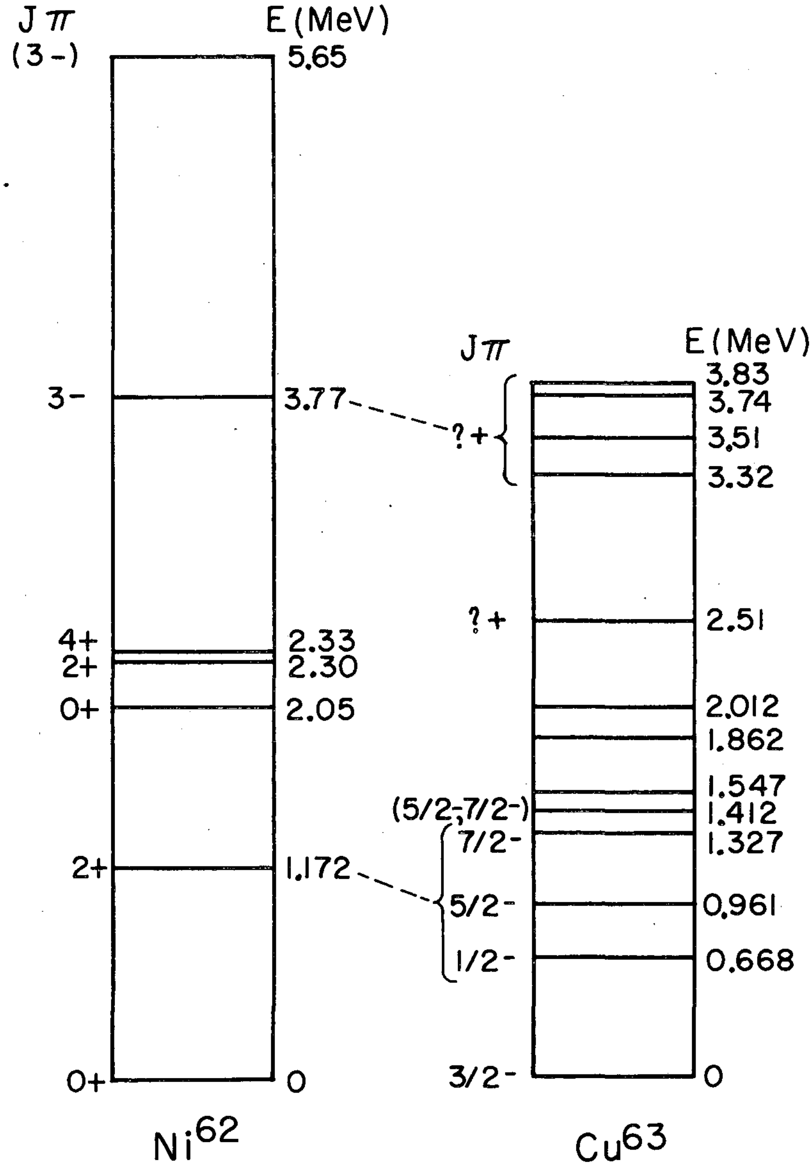
Figure Captions

Fig. 1. Experimental energy levels of Ni^{62} and Cu^{63}. Many levels in Ni^{62}, not relevant to the present work, are omitted. See ref. 9.

Fig. 2. Energy spectrum of 25 MeV α-particles scattered from Cu^{63} at an angle of 35° (lab system).

Fig. 3. Angular distributions for excitation of the 0.668-, 0.961- and 1.327-MeV levels of Cu^{63} and the 1.172-MeV level of Ni^{62} by scattering of 50 MeV α-particles.

Fig. 4. Angular distributions for excitation of the 2.51-, 3.32-, 3.51-, 3.74- and 3.84-MeV levels of Cu^{63} and the ground state and 3.77-MeV level of Ni^{62} by scattering of 50 MeV α-particles.



MUB-5160

Fig. 1

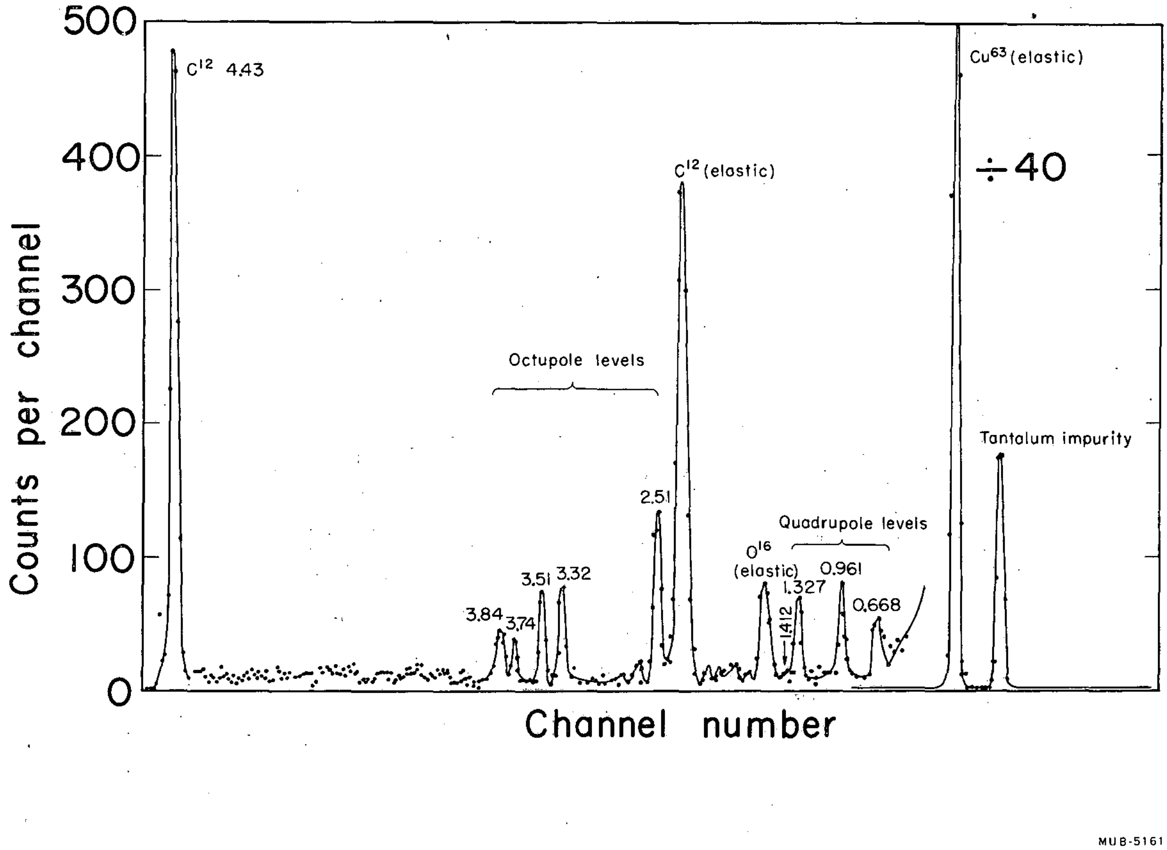

500
400
300
200
100
0
Counts per channel
Channel number
C12 4.43
C12 (elastic)
Cu63 (elastic)
÷40
Tantalum impurity
Octupole levels
Quadrupole levels
3.84
3.74
3.51
3.32
2.51
O16 (elastic)
1.412
1.327
0.961
0.668
MUB-5161

Fig. 2

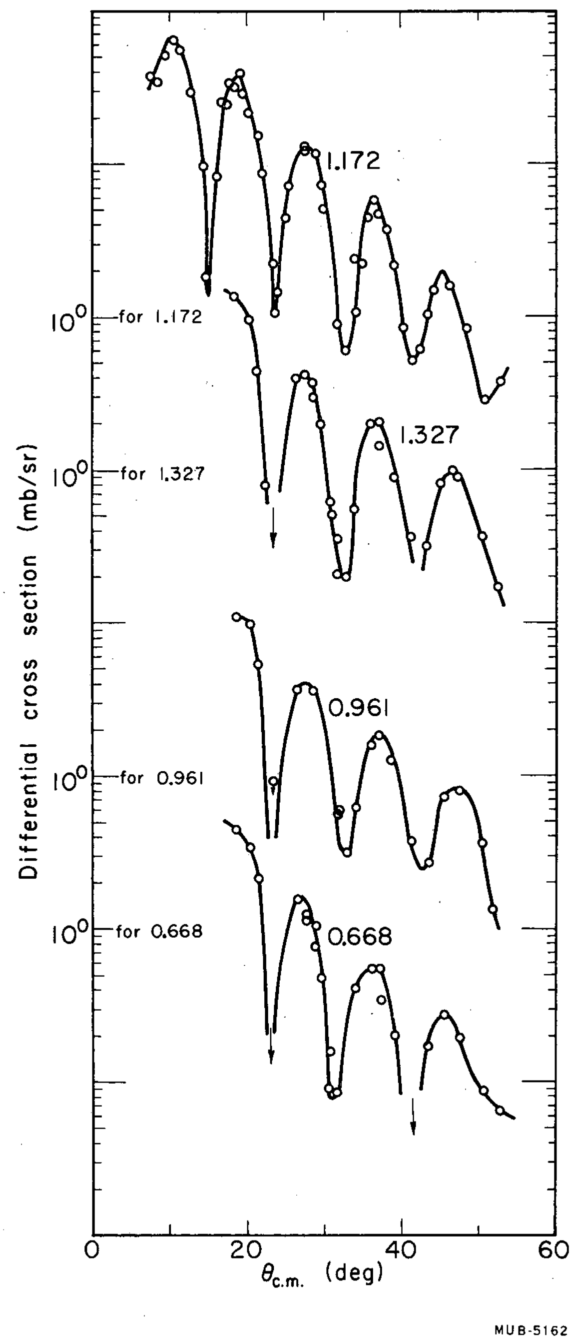
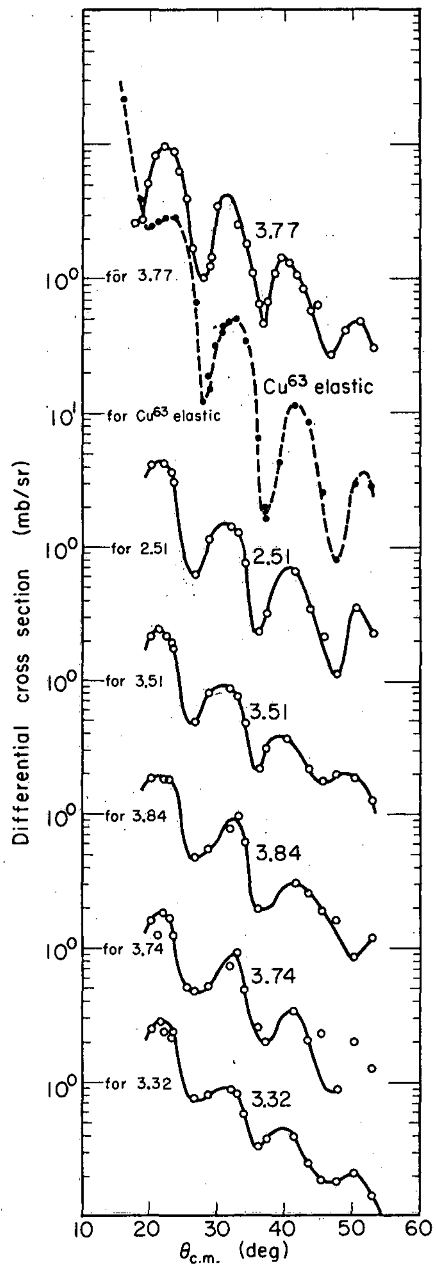

1.172
1.327
0.961
0.668
10⁰—for 1.172
10⁰—for 1.327
10⁰—for 0.961
10⁰—for 0.668
Differential cross section (mb/sr)
0
20
40
60
θc.m. (deg)
MUB-5162

Fig. 3



MUB-5159

Fig. 4