SYSTEMATIC STUDY ON NUCLEAR RESONANT SCATTERING

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ABSTRACT

~~It was observed~~ New resonent scattering effects of thermal neutron capture gamma rays from Ti and Fe on Sb, Cu, Se and Ce targets. These results together with those published by other authors are summarized and discussed in terms of a possible systematic search for new resonant scattering effects.

INTRODUCTION

The scattering of photons by nuclei is, and will be in the next future, an interesting and promissing research field in nuclear structure physics.

Specially the development of an experimental arrangement which permits the use of a reactor as a monochromatic gamma source of high intensity has improved appreciably the experimental techniques in photon scattering physics(9 18). The main physical information and insight into the structure of nuclei subject to investigation by photons can be divided into the following groups:

1) detailed structure of nuclear levels having appreciable strenght to the ground state and low excited states.
2) as a tool for the experimentalists to test nuclear models in high energy region of excitation
3) the coupling of giant multipole resonances to low energetic collective modes (collective correlations of nucleons)

While unbound nuclear levels can be populated using particle capture reactions, highy excited bound levels in stable nuclei can be conveniently reached through the electromagnetic interaction between the photons of the incident gamma beam and the nucleus.

The nuclear level spacing is usually small in the vicinity of the neutron threshold and requires an incident radiation with a narrow energy band (a few eV's) to permit the excitation of isolated levels. Such nearly monoenergetic gamma lines are obtained in the (n,γ) reaction using thermal neutrons. This method has been used extensively in the last decade to excite bound levels in a wide variety of nuclei.

Although this method is based on an accidental overlap in energy between on of the lines in the spectrum of the incident radiation and a level in the target nucleus, a large number of resonant levels have been detected so far.

Fundamentally the experimental method consists of measurements of the effective elastic cross section, angular distribution, temperature dependence of the intensity of scattered radiation and a measurement of the self absorption of the particular gamma line.

These measurements provide information for the calculation of the total and partial radioactive widths of the resonant levels, making use of the experimentally determined branching ratios of the inelastic transitions to low lying levels as seen from the spectrum of the scattered radiation

Even more, informations can be obtained also about the low-lying levels of the stable scatterer nucleus

The angular distribution of the resonant scattered radiation depends on the spins of the energy levels involved and the multipolarity of radiation So, the angular dependence of the scattering differential cross section $W(\theta,L,J_0\ J_1)$, can be calculated by using standard angular correlation procedures Here θ is the scattering angle, L is the multipolarity of the radiation, δ = (intensity of the L + 1 radiation)/(intensity of the L radiation), J_0 is the ground state spin, and J_1 the excited state spin of the nucleus

The development of experimental arrangements and the consequences from them have improved rapidly in the past decade in such a way that would be seemed to us an opportune time to review all the data obtained until now The results obtained in the present work, so as those published previously are discussed in this paper

Experimental Arrangement

The experimental facilities for resonance scattering of gamma rays at the IEAR-1 reactor have been described previously by F G Bianchini(10 11) The gamma source in this experimental arrangement is placed in the reactor core as it is shown in figure 1 since it was described in reference 50, the neutron density increases in the limits of the reactor core when graphite or water are used as reflectors

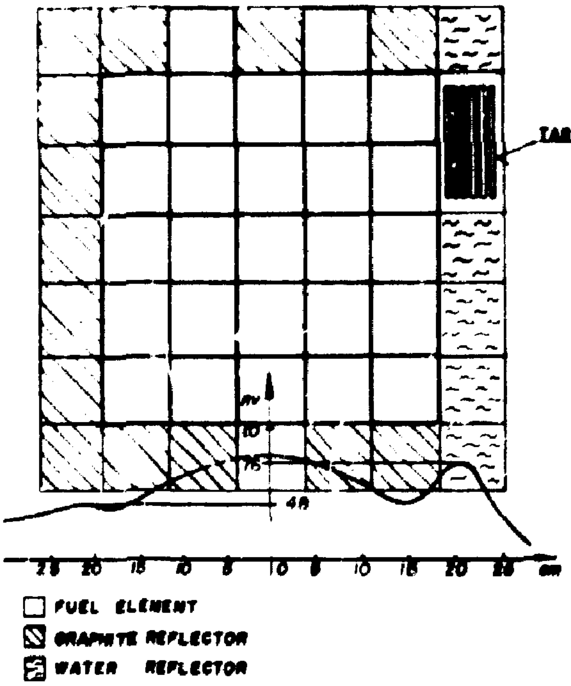

Figure 1

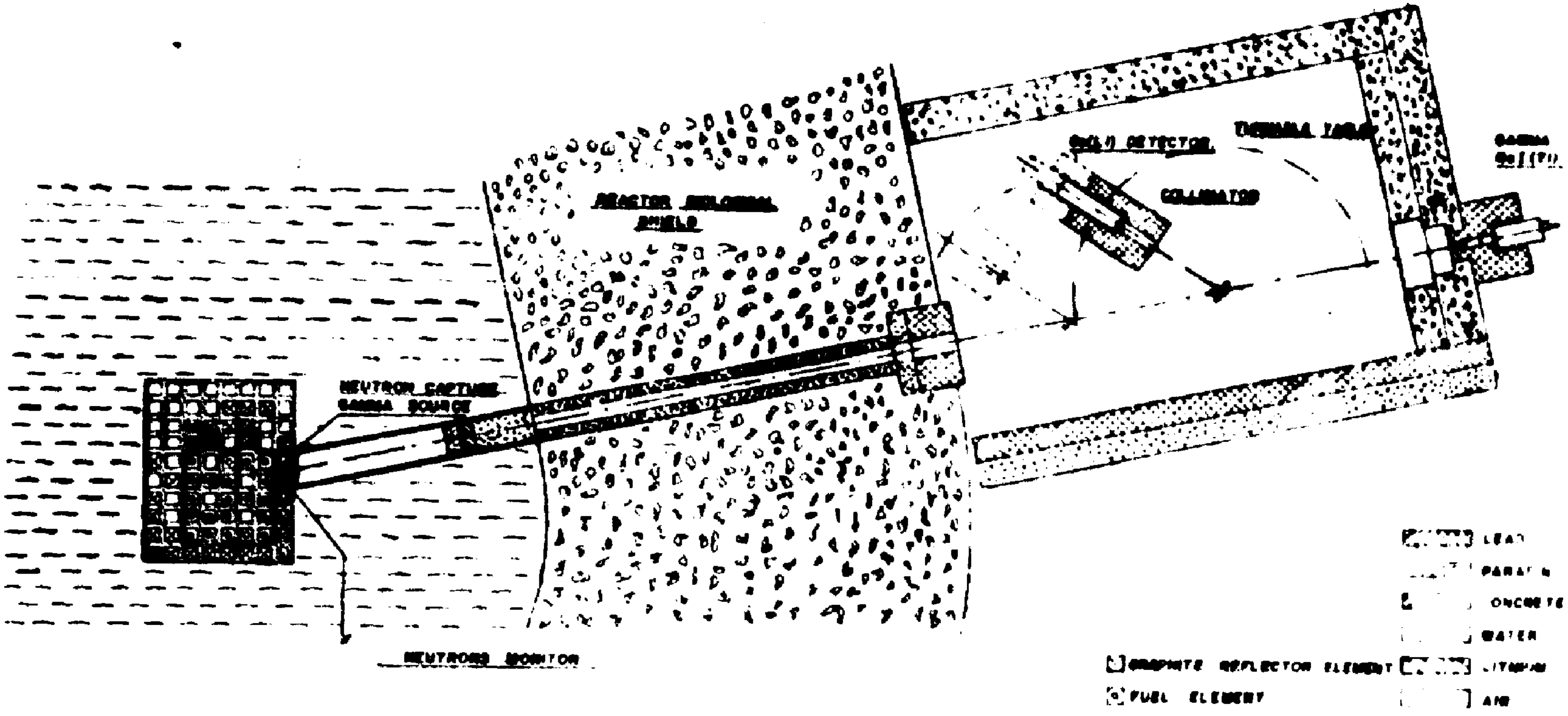
REACTOR BIOLOGICAL SHIELD
NaI(Tl) DETECTOR
THERMAL TABLE
COLLIMATOR
GAMMA MONITOR
NaI(Tl) DETECTOR
NEUTRON CAPTURE GAMMA SOURCE
NEUTRONS MONITOR
LEAD
PARAFFIN
CONCRETE
WATER
GRAPHITE REFLECTOR ELEMENT
LITHIUM
FUEL ELEMENT
AIR

Figure 2

With this arrangement a neutron density of about 5×10^{11} n/cm^3 is available in the target position. Another advantage is that the exchange of targets is made without dismount the collimator system and the handling of the very active source is made in safety conditions since it is 10 meters deep in the moderator of the reactor. A small contamination exists in the gamma beam with the 7724 KeV line of aluminium from the structural material of the reactor core. This however contributes with less than 1% of the main line of the target in the incident spectra.

This new gamma source arrangement into the reactor core as it was showed by Bianchini(11), has at least one order of magnitude higher gamma fluxes on the scatterer position than with other existing arrangements.

The resulting gammas produced in the target are collimated, as it is showed in figures 2 and 3, and filtered in a special way in order to remove fission neutrons which enter into the beam direction. The thermal neutron flux was determined to be less than 50n/cm^2 sec which is the limit of sensibility of the method utilized.

The high energy scattered spectra is measured with a 42.5 cm^3 Ge(Li) detector shielded from the room background radiation by 15 cm of lead. The spectra is obtained on a 4096 channel analyser and the data reduction of the spectra and the various calculations are done by standard computer techniques.

The Ge(Li) is fitted into a graduated rotating arm pivoted around a perpendicular axis passing through the scatterer.

The design of the system permitted the variation of the distance between the detector and the scatterer as well as the one from the scatterer to the reactor shielding wall.

Through a long run, the intensity of the incident gamma beam was monitored by detecting the neutron flux close to the target in the reactor core by using a neutron detector from the firma Reuter-Stokes (Canada) type RSW-20-2MI. The sensibility of such detector was 2.4×10^{-10} Amp/nv.

This procedure is necessary when precise intensity measurements are required such as in self absorption and angular distribution experiments.

Experimental Results

In this work some resonant levels were found in antimony, copper, selenium and cerium using sources of titanium and iron.

The gamma sources were produced by neutron capture in separated plates of natural titanium given a total weight of 4630 g and natural iron with 7300 g, placed inside a double sized fuel element container. Details of the experimental system were published previously (10). The energy resolution of the Ge(Li) was about 10 kev for the 6761 keV line of titanium.

Figure 4 shows the high energy part of the scattered spectrum from a natural copper as

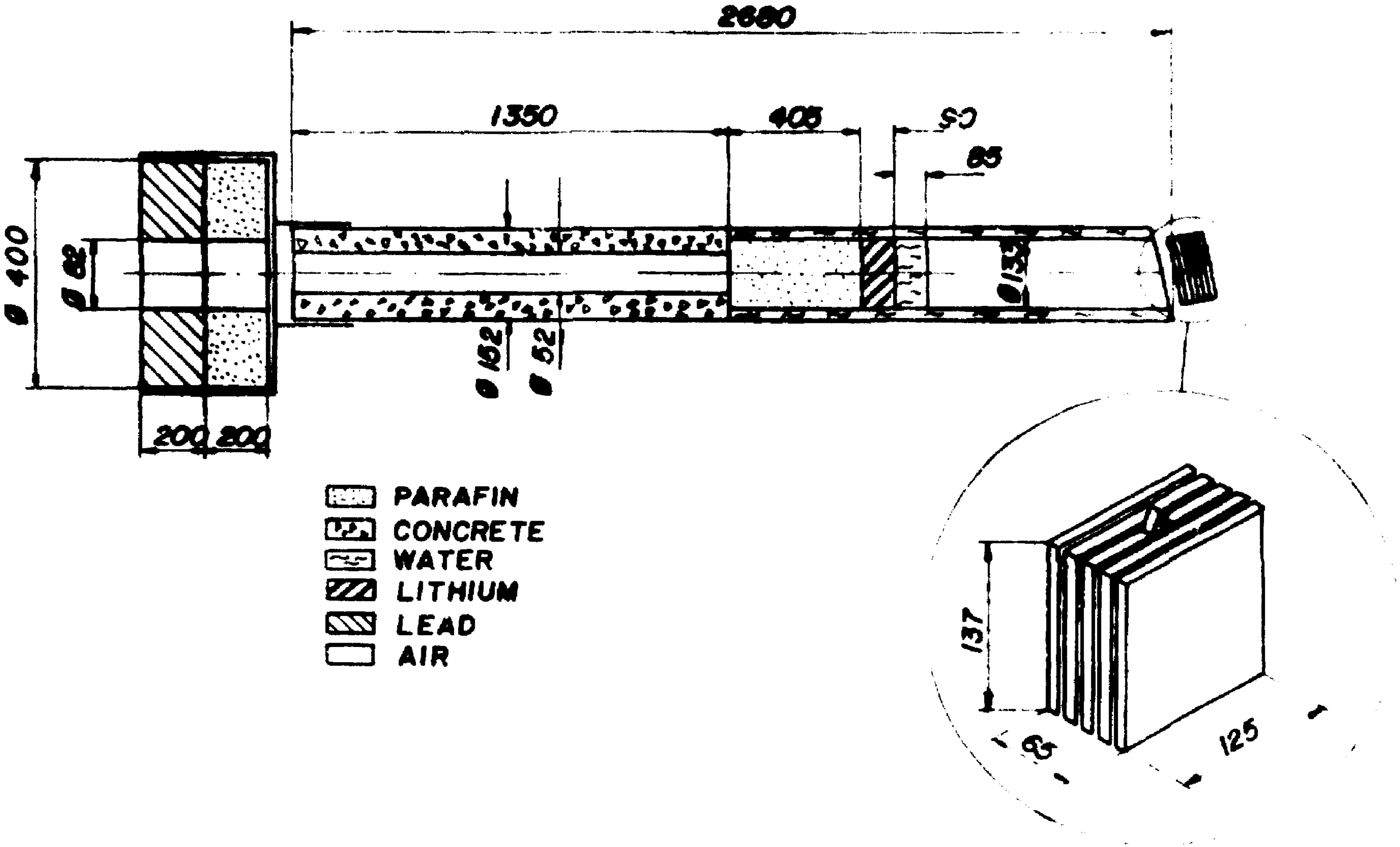
2680
1350
405
50
85
Ø 400
Ø 82
Ø 162
Ø 52
Ø 135
200
200
PARAFIN
CONCRETE
WATER
LITHIUM
LEAD
AIR
137
65
125

Figure 3

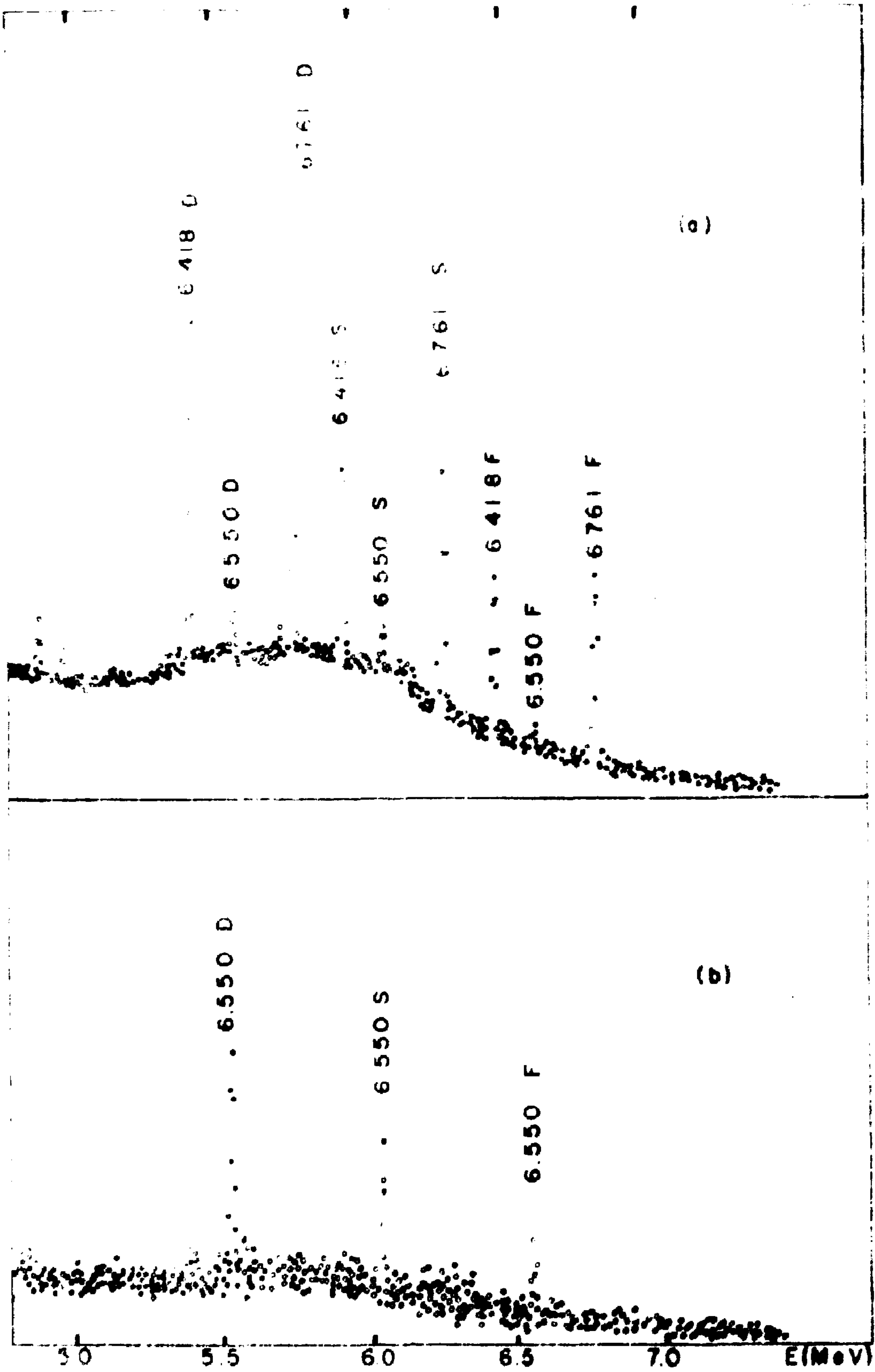
(a)
6.418 D
6.761 D
6.418 S
6.761 S
6.550 D
6.550 S
6.418 F
6.761 F
6.550 F
(b)
6.550 D
6.550 S
6.550 F
5.0
5.5
6.0
6.5
7.0
E(MeV)

Figure 4

well as the direct spectrum from the titanium target

The resonant scattering of capture gamma rays from a Ti source on copper has been observed previously by other groups (51 21 64 5) Due to the use of NaI detectors it was not possible to distinguish unambiguously from which gamma ray the resonance comes

In references (51 21 and 5) it was supposed to be the week 6 07 MeV transition from Ti the responsible for the resonance scattering observed on ^{63}Cu and ^{65}Cu with a calculated cross section around 220 mb and 440 mb respectively Toumbev(64), still using a NaI detector supposed to be the strong 6 41 MeV transition the origin of this resonance and calculated a cross section of 18 6 mb Due to the fact that such calculations are so dependent of the hypothesis from which gamma ray the resonance comes, we perfomed an experiment in the gamma scattering facility of the IEAR-1 reactor of S Paulo using a Ge-Li detector From figure 4 it is possible to observe that the resonant energy is the weak 6 557 MeV line instead of the 6 07 or 6 417 MeV lines

It was observed some lines in the spectrum of gamma rays scattered elastically and inelastically from a target of Sb when we were using a titanium gamma source.

The proposed decay scheme for the 6761 KeV level of ^{123}Sb is shown in figure 5 together with the schemes of Cu and Se The partial decay scheme of Sb is based on few lines which fits immediately to the known levels of Sb

In figure 6 it is showed the angular distribution from the gamma rays scattered elastic and inelasticaly by Sb where it was possible to identify the isotope responsible for the resonance scattering

In table I is aimed to be displayed all results obtained until now since the first paper on resonance scattering of capture gamma rays made by Fleischman(18) appeared or at least the most important papers were related in this table Small fluctuations on the energies of some gamma ray sources were permited without any correction by us since we cannot be held the responsability for discrepancies other than our own contributions

If we take a close look into the literature, the amount of papers which makes a complete study of the nuclides in question is negligible Many of those previous papers were done by using NaI detectors or were done only in order to search for new resonances without any intention to make a deeply study of the scatterer nuclide So, much work has to be done until a deeply systematic of the data can be made It also happens sometimes that not all of the measurable resonance have enough intensity to permit accurate studies of level schemes and resonance level parameters Much of the experimental difficulty is due also to the high level of background caused mainly by multiple electronic scattering from the intense gamma rays belonging to the source material As it has been observed by Y Kawarasaki(27) the application of week lines as a monochromatic beam of neutron-capture gamma rays would provide more information on highly excited levels near neutron threshold, because there remain many untried emitters and, hence, many monochromatic lines.

For instance we could use Cd as a gamma source since it is plenty of lines and, by proper choosing of the geometry a large amount of Cd could be put in the source position.

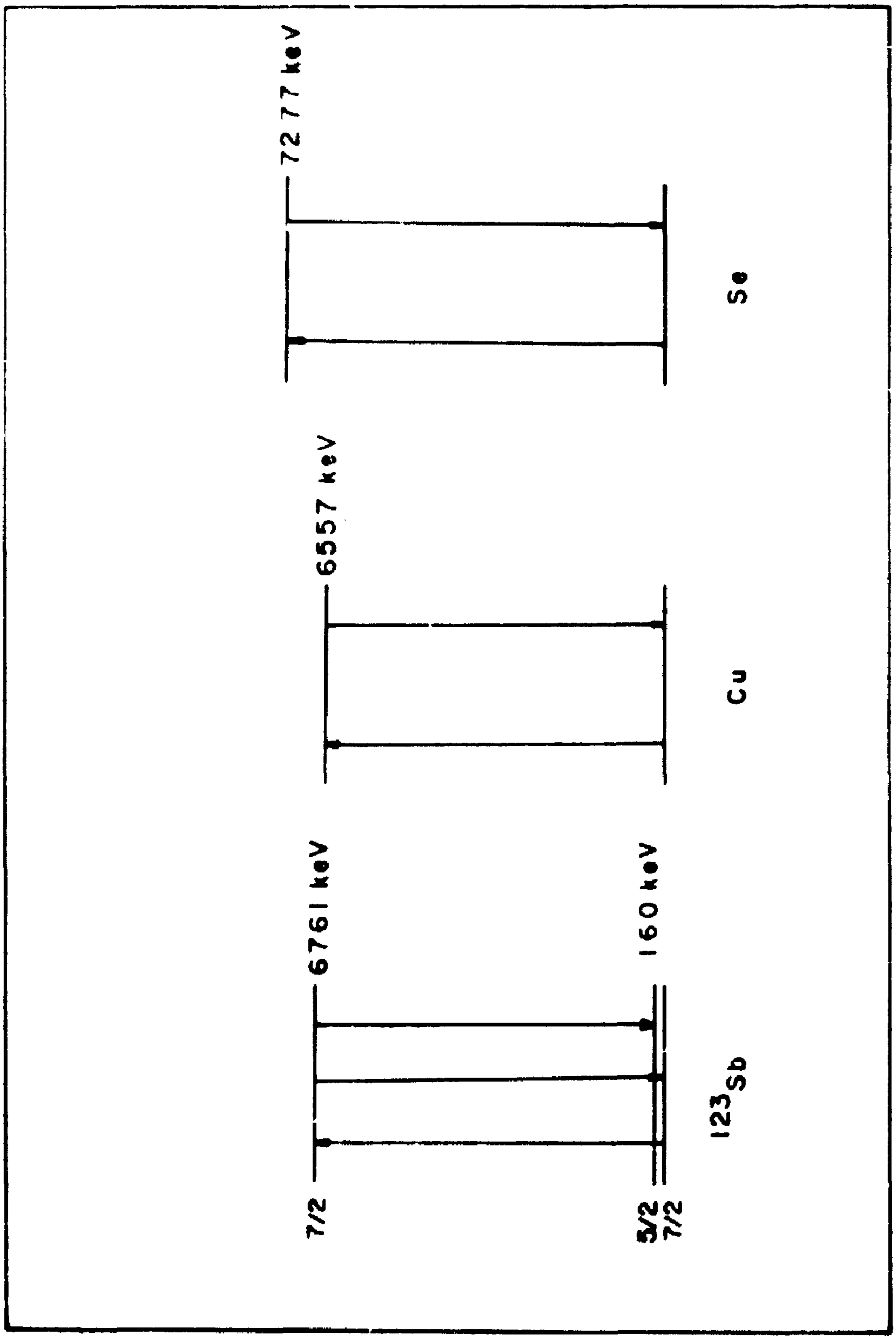

Figure 5

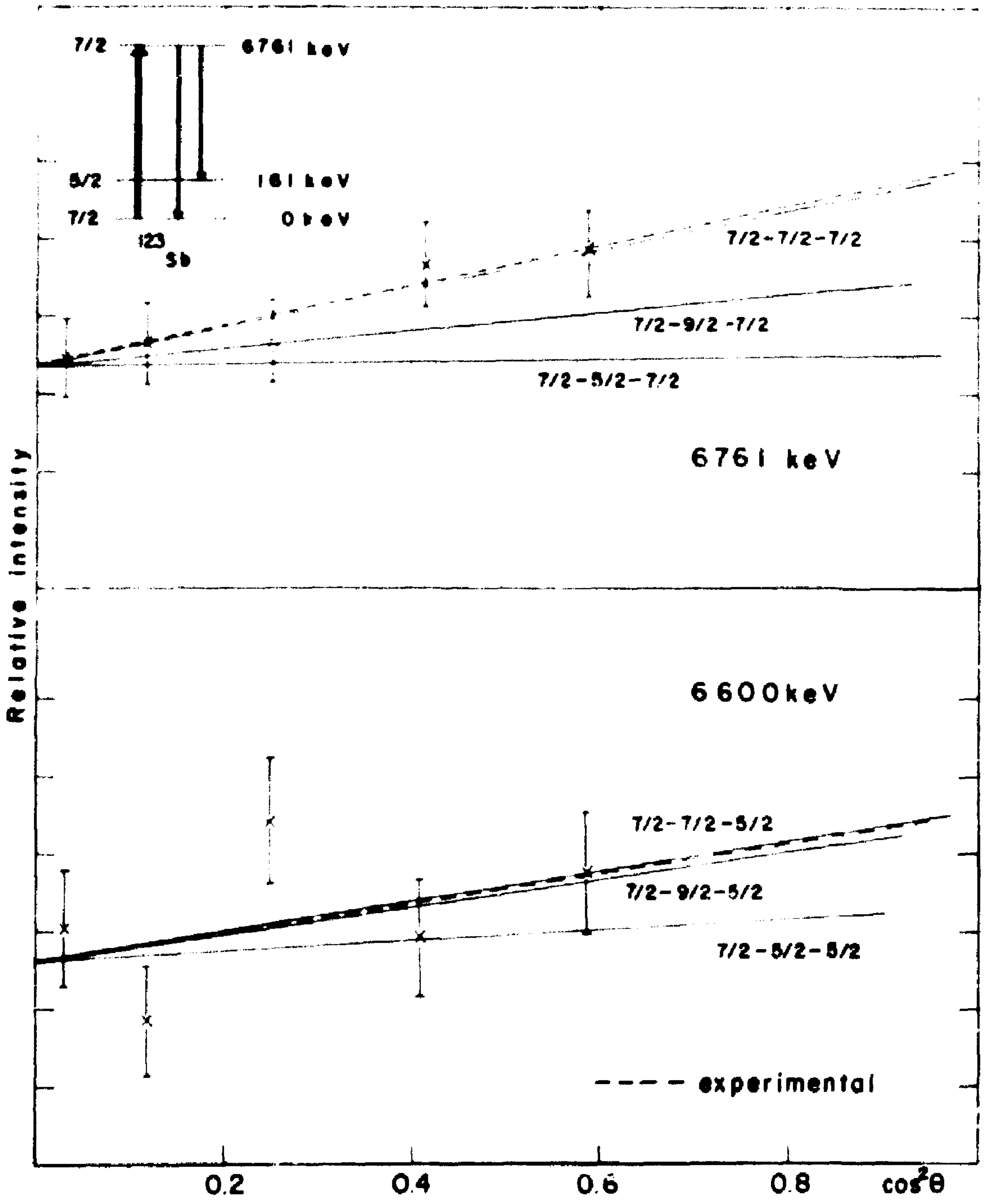
7/2
6761 keV
5/2
161 keV
7/2
0 keV
123
Sb
7/2-7/2-7/2
7/2-9/2-7/2
7/2-5/2-7/2
6761 keV
Relative intensity
6600keV
7/2-7/2-5/2
7/2-9/2-5/2
7/2-5/2-5/2
---- experimental
0.2
0.4
0.6
0.8
cos²θ

Figure 6

Special attention should also be devoted to the methods utilized in the calculations since much of the discrepancies come from the criterium utilized in the approximations. Only in a very few cases the nuclear level can be approximated by a pure Doppler form and so in the most of the cases the Doppler broadened shape of a gamma line has to be calculated accurately for quantitative analysis.

In figure 7 it is shown the average branching ratio versus the resonant energy for those nuclides of table I where it was possible to identify the resonant isotope. As it can be seen, the branching ratio seems to decrease slowly as the excitation energy increases.

In figure 8 it is displayed the number of resonances observed in each element and we can observe clearly the magic number structure. This picture serves also as a suggestion to find new resonant elements. We can see clearly in it that is highly probable to find new resonant levels in the region of 20, 28 and 50 neutron closed shells as in the 28 proton closed shell. Also, Indium is a high probable candidate to display new resonances effects.

As was explained by Ben-David[8] the low density of low-lying levels in the region of closed shells reduces the probability of a dipole transition to an excited state, thus giving a ground state branching ratio Γ_0/Γ close to unit for highly excited states below the neutron emission threshold. For nuclei far from closed shells this branching ratio is usually much less than unity, which greatly reduces the scattering cross section, and therefore the probability of observing resonant scattering from these nuclei.

In figure 9 it is shown the elements which presents some resonant effect against the gamma sources. What is curious from this figure is that in spite of the rather small amount of data collected exist the aglomerate of resonances observed involving the magic numbers either from the scatterer element or the gamma source.

RESUMO

Foram observados novos efeitos de espalhamento ressonante de raios gama de captura de neutron térmicos do Ti e Fe em alvos de Sb, Cu, Se e Ce. Estes resultados juntamente com aqueles publicados por outros autores são relacionados e discutidos em termos de uma possível pesquisa sistemática de novos efeitos de espalhamento ressonante.

RÉSUMÉ

On a observé d'effets nouveaux de la diffusion par résonance des rayons gamma de capture des neutrons lents de Ti et Fe en cibles de Sb, Cu, Se et Ce. Ces résultats, em même temps que ceux publiés par d'autres auteurs sont rapportés et débatis en termes d'une possible recherche systématique d'effets nouveaux de la diffusion par résonance.

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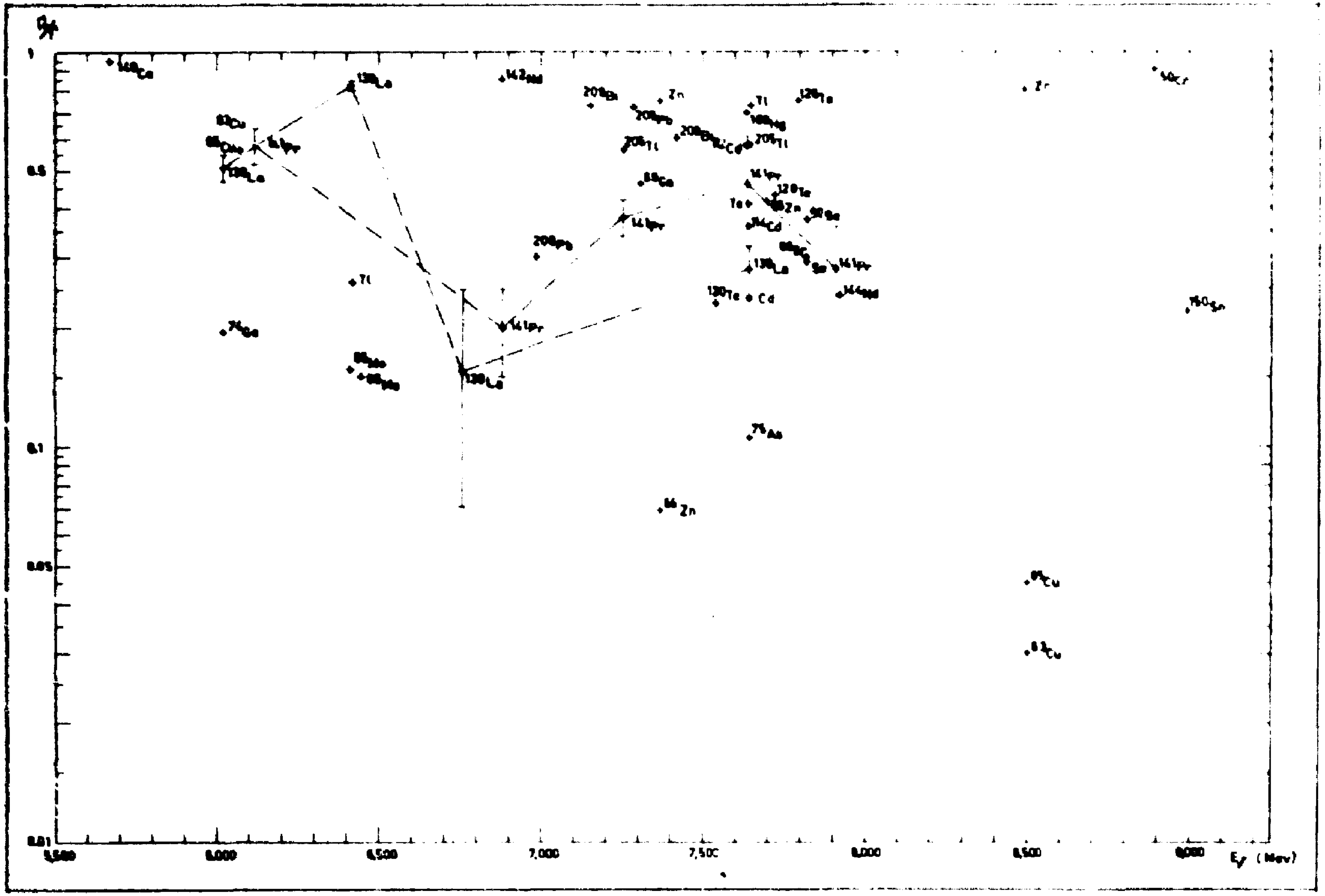
Γ/A
1
0.5
0.1
0.05
0.01
5,500
6,000
6,500
7,000
7,500
8,000
8,500
9,000
Eγ (Mev)
140Ce
63Cu
65Cu
141Pr
139La
139La
142Nd
74Ge
Tl
85Mo
86Mo
139La
141Pr
208Pb
208Bi
Zn
208Pb
206Tl
208Bi
Cd
Tl
160Hg
206Tl
88Ce
141Pr
141Pr
120Te
Te
Zn
90Se
114Cd
139La
Sn
141Pr
130Te
Cd
144Nd
75As
66Zn
Zr
150Sn
Cr
65Cu
63Cu

Figure 7

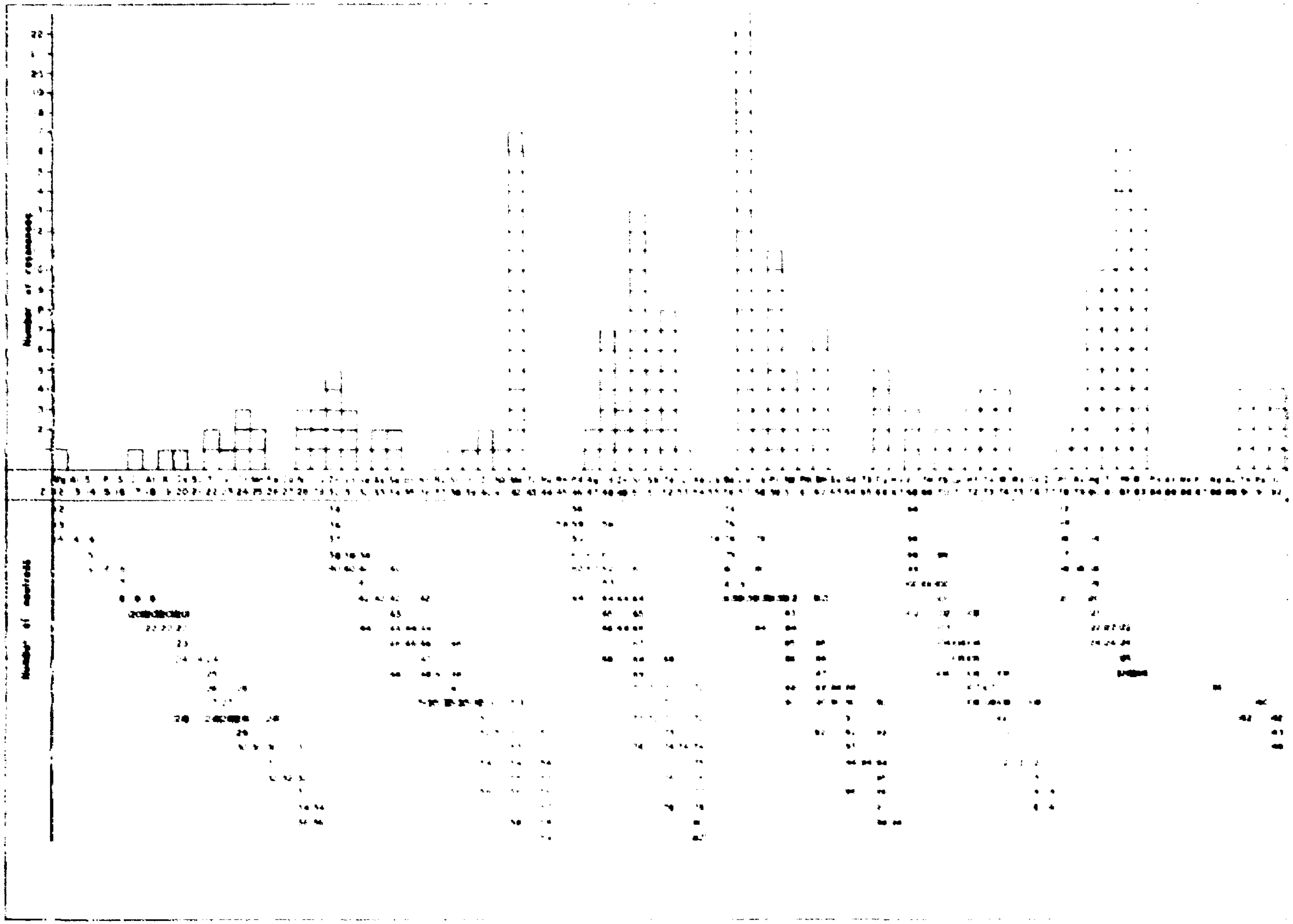

Figure 8

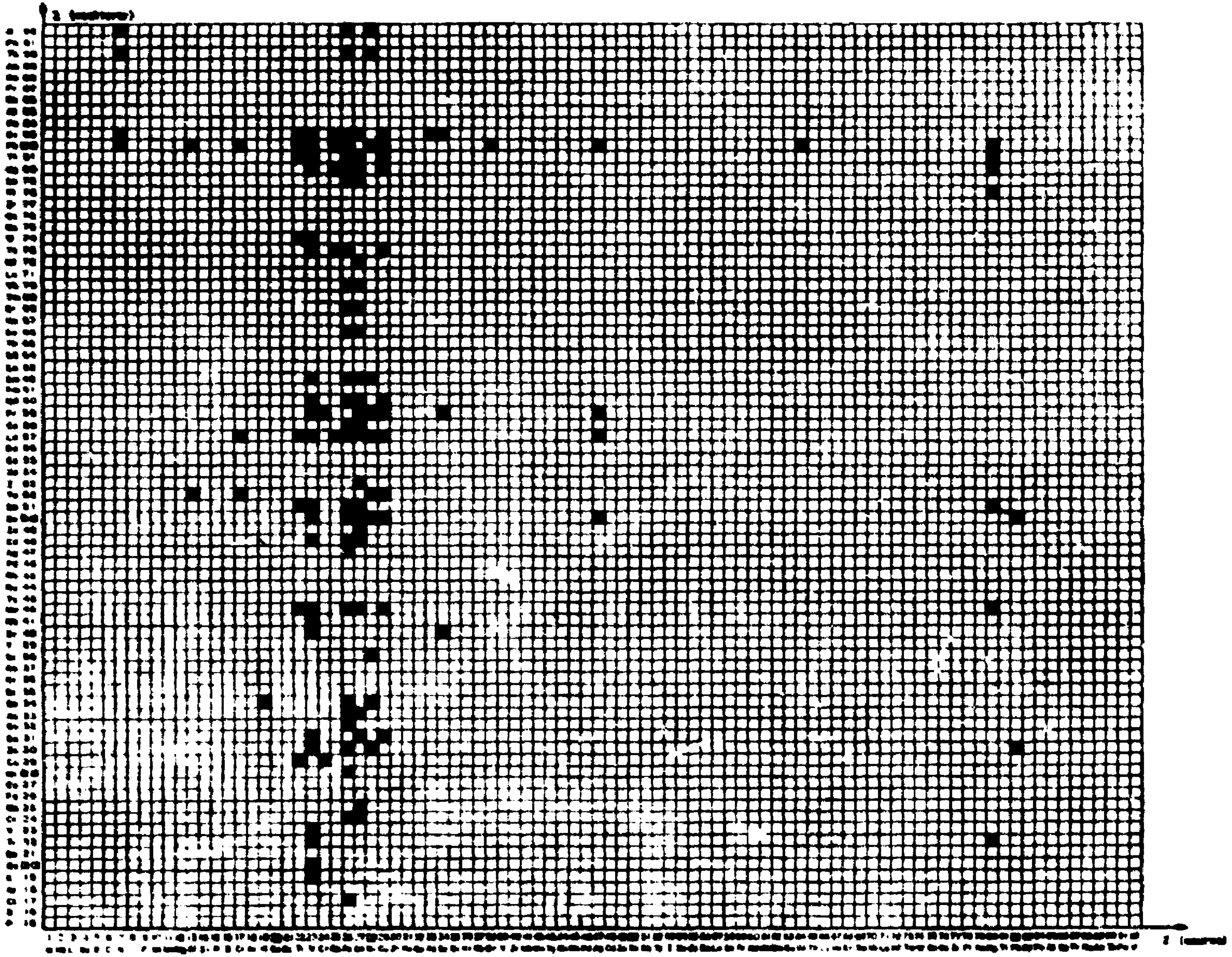

Figure 9

rays Phys Rev B. New York, 133 684 700 1964

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Table 1

Z	Scatterer	A	Gamma Source	E_γ(MeV)	Γ_0(eV)	Γ_0/Γ	ϵ(eV)	$\sigma_{\gamma\gamma}$(mb)	Comments	Ref
17	Cl		Fe	7.285				34		8
22	Ti		Hg	6.31				2		8
24	Cr		Co	7.214						63
24	Cr	50	Fe	8.888	0.675 ± 0.180	0.90	18 ± 1	905		33
24	Cr		Fe	7.646						33
25	Mn	55	Co	7.491	0.080 ± 0.040	0.24	17 ± 1	6 ± 2		63
28	Ni	62	Fe	7.646	0.307 ± 0.032	0.64	14 ± 1	569		33
28	Ni		Fe	7.646						12
28	Ni		Fe	7.646			12 ± 1	10.5	C	2
28	Ni		Fe	7.646	0.31	0.65				23
28	Ni		Fe	7.64 ± 0.05	0.074	0.69 ± 0.08	11	190 ± 40	B.N	17
28	Ni		Fe	7.64				1.5	N	9
28	Ni	62	^{57}Fe	7.64	0.15 ± 0.02	0.71 ± 0.07	11.0 ± 0.5	375 ± 6	N	19
28	Ni		^{57}Fe	7.64	0.63 ± 0.17	0.21 ± 0.14	12.5 ± 0.14	375 ± 6	N	20
28	Ni	62	Fe	7.64	~ 0.2		11 ± 0.5	370 ± 110	N	51
28	Ni	62	Fe	7.64	1 ± 0.1	0.185	12.5 ± 0.5	530 ± 20	N	60
28	Ni		Fe	7.64				7	N	8
28	Ni	62	Fe	7.64					N	11
28	Ni	62	Fe	7.64	1 ± 0.1	0.185 ± 0.058		530 ± 20	N	5
28	Ni		Fe	6.977					D	12
28	Ni		Fe	6.266					D	12
29	Cu		Cr	8.500	0.94 ± 0.29	0.08 ± 0.04	9.4 ± 0.7	42 ± 13		21
29	Cu	65	Cr	8.500	0.47 ± 0.10	0.045 ± 0.031		36 ± 9		5,6

Table 1 - Continuation

Z	Scatterer	A	Gamma Source	E_γ(MeV)	Γ_0(eV)	Γ_0/Γ	ε(eV)	$\sigma_{\gamma\gamma}$(mb)	Comments	Ref
29	Cu	63	Cr	8.500	0.26 ± 0.08	0.30 ± 0.021		22 ± 7	-	5,6
29	Cu	63	Cr	8.500	0.28 ± 0.09		8.6 ± 0.4	19 ± 6		51
29	Cu	65	Cr	8.500	0.94 ± 0.29		9.4 ± 0.7	42 ± 13		51
29	Cu		Cr	8.499				24		8
29	Cu	63	Cr	8.499				36	E	2
29	Cu	65	Cr	8.499				80	E	2
29	Cu	65	Cr	8.484						13
29	Cu	-	Cr	8.449				15		9
29	Cu	-	Cr	7.939						13
29	Cu	-	Ti	6.550	-					present work
29	Cu	-	Ti	6.41	-		-	16.6 ± 3.4	F	64
29	Cu	63	Ti	6.07	0.16 ± 0.03	-	9.2 ± 0.8	200 ± 60	F	51
29	Cu	65	Ti	6.07	0.36 ± 0.07		9.3 ± 0.8	440 ± 130	F	51
29	Cu	65	Ti	6.07					F	4
29	Cu	63	Ti	6.07	0.18 ± 0.04	0.62 ± 0.37		215 ± 71	F	5,6
29	Cu	65	Ti	6.07	0.34 ± 0.06	0.58 ± 0.34	-	423 ± 108	F	5,6
29	Cu	65	Ti	6.07	0.16 ± 0.03	0.51 ± 0.18	9.2 ± 0.8	200 ± 60	F	21
29	Cu	65	Ti	6.07	0.36 ± 0.07	0.54 ± 0.19	9.3 ± 0.8	440 ± 130	F	21
30	Zn	-	Fe	7.279		-	-	-	-	33
30	Zn	-	Ni	8.119	-	-	-	13	-	8
30	Zn		Ni	7.696	-	-	-	-	-	53
30	Zn	66	Ni	7.696		0.360 ± 0.048	-		-	56
30	Zn	66	Ni	7.696	0.10 ± 0.02	0.47 ± 0.13	-		-	54

Tabela 1 - Continuation

Z	Scatterer	A	Gamma Source	E_γ(MeV)	Γ_o(eV)	Γ_o/Γ	ε(eV)	$\sigma_{\gamma\gamma}$(mb)	Comments	Ref
30	Zn	-	Pb	7.38			9 – 15	33 ± 4.5		7
30	Zn	64	Pb	7.38	0.58 ± 0.12			33 ± 4.5		6
30	Zn		Pb	7.368		0.78				59
30	Zn		Pb	7.368	0.22 ± 0.02	0.71	8.5 ± $^{0.7}_{0.5}$			58
30	Zn	66	Pb	7.368	0.58 ± 0.12	0.069 ± 0.040		33 ± 4.5		5
31	Ga		Co	5.976						62
31	Ga	69	Cu	7.306	0.048 ± 0.027	0.46 ± 0.06	6.2 ± 0.5	80 ± 5		35
31	Ga	71	V	7.310					P	36
31	Ga	69	V	6.874						35
32	Ge	74	Fe	6.018	0.023 ± 0.003	0.19	4.5 ± 0.5	61		33
32	Ge	74	Fe	6.018	0.023	0.19	4.5	61		43
32	Ge	74	Fe	6.018						38
33	As	-	Co	6.948						63
33	As	75	Fe	7.646	0.040 ± 0.011	0.11	7.4 ± 0.3	4.4		33
33	As	75	Fe	7.646	0.041 ± 0.011	0.11	7.4 ± 0.3	4.4		46
33	As	75	Fe	7.646	0.041 ± 0.011	0.11 ± 0.05	-			54
34	Se	-	K	7.76	-		-	90		8
34	Se	-	Fe	7.277	-	-	-	-		present work
34	Se	78	Ni	7.820	-	-				52
34	Se	80	Ni	7.820	-	0.425 ± 0.070	-			56
34	Se	80	Ni	7.820	0.030 ± 0.007	0.33 ± 0.09	-	-	-	54
34	Se	-	Ni	7.819	-	-			-	61
34	Se	-	Ni	7.817	-	-	-	50	-	8

Table 1 Continuation

Z	Scatterer	A	Gamma Source	E_γ(MeV)	Γ_0(eV)	Γ_0/Γ	ϵ(eV)	$\sigma_{\gamma\gamma}$(mb)	Comments	Ref
38	Sr	86	Ni	7.820	0.030 ± 0.015	0.3 ± 0.2			-	54
38	Sr	-	Ni	7.820		0.292 ± 0.033		-		56
40	Zr	-	Se	8.496	1.68 ± 0.02	0.8 ± 0.2	5.60 ± 0.15		-	52
40	Zr		Se	3.496	-	-				30
40	Zr		Se	8.496				3060		8 37
42	Mo		Co	5.976			-		-	63
42	Mo	-	Co	5.660					-	63
42	Mo	100	Cu	7.637	0.040 ± 0.005	0.28 ± 0.09	4.5 ± 0.5	98 ± 15		48
42	Mo		Cu	7.634				11		8
42	Mo	100	Cu	5.451				-		48
42	Mo	100	Cu	5.187					-	48
42	Mo	100	Cu	5.045		-			-	48
42	Mo	100	Cu	4.902		-	-	-	-	48
42	Mo	100	Cu	4.732	-			-	-	48
42	Mo	-	Fe	7.632		-		-	-	33
42	Mo	-	Hg	6.44	-	-	-	25	K	8
42	Mo	96	Hg	6.44	0.12 ± 0.04	0.15 ± 0.10		201 ± 37	-	5,6
42	Mo	100	Ti	7.168	-	-	-		-	48
42	Mo	100	Ti	6.760	-	-	-	-	-	48
42	Mo	94	Ti	6.558	-		-		-	48
42	Mo	100	Ti	6.418	0.025 ± 0.008	0.50 ± 0.38	4.3 ± 0.3	150 ± 15	-	48
42	Mo	100	Ti	6.418	-	-	-	-	-	38
42	Mo	-	Ti	6.413	-		-	10	-	8
42	Mo	96	Ti	6.413	0.11 ± 0.02	0.162 ± 0.097	-	11.2 ± 1.4	-	5,6
42	Mo	96	Ti	6.41	-		-	-	-	4

Table 1 - Continuation

Z	Scatterer	A	Gamma Source	E_γ(MeV)	Γ_o(eV)	Γ_o/Γ	ϵ(eV)	$\sigma_{\gamma\gamma}$(mb)	Comments	Ref
42	Mo	100	V	7.162	–	–	–	–	–	48
42	Mo	100	V	6.517	$0.072 \pm^{0.068}_{0.048}$	$0.40 \pm^{0.44}_{0.35}$	12.8 ± 1.2	110 ± 30	–	48
42	Mo	100	V	6.465	–	–	–	–	–	48
47	Ag	109	Fe	7.632	0.0014 ± 0.0008	0.7	9 ± 1	3 5	–	33
47	Ag	–	Fe	6.018	–	–	–	–	–	33
48	Cd	–	Co	6.990	–	–	–	–	–	30
48	Cd	–	Co	6.985	–	–	–	–	–	63
48	Cd	–	Co	6.490	–	–	–	–	–	30
48	Cd	110	Co	6.486	–	–	–	–	–	63
48	Cd	–	Co	6.485	–	–	–	–	–	52
48	Cd	–	Co	6.474	–	–	–	110	–	8,37
48	Cd	–	Co	6.279	–	–	–	–	–	63
48	Cd	–	Co	5.860	–	–	–	–	–	63
48	Cd	114	Fe	7.64	0.20 ± 0.05	0.36 ± 0.12	–	–	G N	60
48	Cd	–	Fe	7.64	–	–	–	–	N	16
48	Cd	–	Fe	7.64	–	–	–	40	N	8,37
48	Cd	–	Fe	7.64	$0.6 \pm^{0.2}_{0.1}$	0 46 ± 0.06	$16 \pm^{3}_{1}$	170 ± 30	–	31
48	Cd	–	Fe	7.64	0.22 ± 0.02	0.11 ± 0.06	≤ 1	287 ± 6	–	19
48	Cd	–	Fe	7.64	0.22 ± 0.05	0.14 ± 0.06	≤ 1	287 ± 6	–	20
48	Cd	114	Fe	7.64	0.20 ± 0.05	0.36 ± 0 12	–	180 ± 10	G	5
48	Cd	114	Fe	7.64	0.37 ± 0.11	–	≤ 2	300 ± 100	G	51
48	Cd	112	Fe	7.632	–	–	–	–	–	38
48	Cd	112	Fe	7.632	0.06	0.5	–	–	–	40
48	Cd	112	Fe	7.632	–	–	–	–	–	12
48	Cd	112	Fe	7.632	0.047 ± 0.008	0.55	–	198	–	41

Table . Continuation

Z	Scatterer	A	Gamma Source	E_γ(MeV)	Γ_0(eV)	Γ_0/Γ	ϵ(eV)	$\sigma_{\gamma\gamma}$(mb)	Comments	Ref
48	Cd	112	Fe	7.632	0.047 ± 0.001	0.55	4.8 ± 0.4	198		33
48	Cd	112	Fe	7.632	0.06	0.45				23
48	Cd	112	Fe	7.632						13
48	Cd	112	Fe	7.629		$<0.574 \pm 0.011$				30
49	In		Co	6.877						63
49	In	-	Co	6.275						63
49	In		Co	5.039						63
50	Sn	-	Ag	6.27				75		8
50	Sn		Co	7.491						63
50	Sn	-	Co	7.214						63
50	Sn	117	Cu	7.01	0.15 ± 0.04	0.20 ± 0.13		1150 ± 240		5,6
50	Sn	117	Cu	7.01				1000		2
50	Sn	117	Cu	7.01	0.3 ± 0.3	0.6	3.6 ± 0.7	1200 ± 400		21
50	Sn	117	Cu	7.01		$<0.802 \pm 0.042$				30
50	Sn		Cu	7.01				110		8,37
50	Sn	-	Cu	6.988						52
50	Sn	118	Cu	6.988						12
50	Sn		Cu	6.322						12
50	Sn		Cu	4.604						12
50	Sn		Fe	7.646						33
50	Sn		Fe	7.279						33
50	Sn	-	Ni	8.998		$0.096 \pm^{0.020}_{0.045}$				56
50	Sn	-	Ni	7.82				5		9

Table 1 Continuation

Z	Scatterer	A	Gamma Source	E_γ(MeV)	Γ_0(eV)	Γ_0/Γ	ε(eV)	$\sigma_{\gamma\gamma}$(mb)	Comments	Ref
50	Sn		Ni	7.696		$0.596 \pm^{0.043}_{0.102}$				56
50	Sn		Ni	7.698	0.07 ± 0.02	0.58 ± 0.22				54
50	Sn	120	^{204}Pb	6.730	0.03 ± 0.01	0.88 ± 0.08	1.0 ± 0.3	480 ± 60		27,57
50	Sn		V	6.508				14		2
51	Sb	-	Co	5.357						63
51	Sb		Fe	7.646						23
51	Sb	-	Fe	7.643						present work
51	Sb		Fe	7.632						33
51	Sb		Fe	7.629						present work
51	Sb	-	Hg	6.31				6	0	8
51	Sb	-	Ti	6.418						present work
51	Sb	-	Ti	6.761						present work
51	Sb	-	V	7.67					A	8
52	Te		Al	7.727	0.10 ± 0.01	0.35 ± 0.01	17 ± 2	5 ± 1		10
52	Te	-	Al	7.724		0.51 ± 0.07				56
52	Te	-	Cl	7.791						23
52	Te	126	Cl	7.791		0.75 ± 0.09				56
52	Te	-	Cu	7.637		0.41 ± 0.07				56
52	Te	130	Ni	8.539						53
52	Te		Ni	8.535						10
52	Te	130	Ni	8.536				12		10
52	Te	-	Ni	8.532				3	A	8
52	Te	130	Ni	7.540						53

Table 1 Continuation

Z	Scatterer	A	Gamma Source	E_γ(MeV)	Γ_0(eV)	Γ_0/Γ	ϵ(eV)	$\sigma_{\gamma\gamma}$(mb)	Comments	Ref
52	Te	-	Ni	7.639	0.31 ± 0.06	0.28 ± 0.02	6.5 ± 1.3	602 ± 90		10
52	Te	130	Ni	7.538						23
52	Te	130	Ni	7.638				190		56
52	Te	130	Ni	7.538	0.06 ± 0.01	0.20 ± 0.06				54
52	Te	-	Ni	7.628				66	H	8
52	Te	130	Ni	8.838						10
52	Te	130	Ni	6.838				10		56
52	Te		Ni	6.7						8
52	Te		Ni	5.8					I	8
53	I	127	Co	6.985						63
57	La	139	Ag	6.540						23
57	La	-	Ag	6.54				12		8
57	La	139	Cl	8.583						23
57	La	139	Cl	8.582				5		62
57	La	139	Cl	6.12						53
57	La		Cl	6.12				35		8,24
57	La	139	Cl	6.118	0.022 ± 0.011	0.044 ± 0.022				54
57	La	139	Cl	6.115	0.009 ± 0.003	0.43 ± 0.01	10 ± 1			62
57	La	139	Cl	6.112						23
57	La	139	Co	7.214						63
57	La	-	Cu	7.637						23
57	La	139	Cu	7.637	0.047 ± 0.006	0.28 ± 0.04				68
57	La	139	Cu	7.637						62
57	La	-	Cu	7.634				7		8
57	La	-	Cu	7.170						23

Table 1 Continuation

Z	Scatterer	A	Gamma Source	E_γ(MeV)	Γ_0(eV)	Γ_0/Γ	ϵ(eV)	$\sigma_{\gamma\gamma}$(mb)	Comments	Ref
57	La	139	Fe	7.632		-			-	33,42.45
57	La	139	Fe	7.279						33 42.45
57	La	139	Fe	6.018	$0.026 \pm^{0.007}_{0.003}$	0.60	8.2 ± 0.6	39		2.46
57	La	139	Fe	6.018	0.025 ± 0.008	0.50 ± 0.06		-		56
57	La	139	Fe	6.018	0.04 ± 0.01	0.52 ± 0.05			-	42
57	La	139	Mn	8.535						23
57	La	139	Mn	7.278	-		-	-		62
57	La	139	Mn	7.166			-		-	62
57	La		Mn	7.15				50	-	8
57	La	139	Mn	6.797	-	-	-			62
57	La	139	Mn	6.429	-		-	-	-	62
57	La	139	Mn	6.112	-	-	-		-	62
57	La	139	Mn	6.020	-	-	-	-	-	62
57	La	139	Mn	5.951		-	-	-		62
57	La	139	Mn	5.537	-	-	-	-		62
57	La	139	Mn	5.445	-	-	-	-	-	62
57	La	139	Ni	8.536	-	-	-	-	-	23
57	La	-	Ni	8.532		-	-	6	-	8
57	La	139	Ni	8.527	-	-	-	-		62
57	La	139	Ni	6.584	-	-	-	-	-	23
57	La	139	Ti	6.760	-	-	-	-	-	45
57	La	139	Ti	6.760	-		<8	7	-	62
57	La	139	Ti	6.760	0.011 ± 0.006	0.16 ± 0.09	-		-	54
57	La	139	Ti	6.754	-	-	-		-	23

Table 1 Continuation

Z	Scatterer	A	Gamma Source	E_γ(MeV)	Γ_0(eV)	Γ_0/Γ	ϵ(eV)	$\sigma_{\gamma\gamma}$(mb)	Comments	Ref
57	La	139	Ti	6.418	$0.063 \pm^{0.010}_{0.005}$	0.78	9.5 ± 0.5	142		45
57	La	139	Ti	6.418			8.7 ± 0.8	65		62
57	La	139	Ti	6.418	0.063 ± 0.008	0.78 ± 0.08			-	66
57	La	139	Ti	6.413				72		8
57	La	139	Ti	6.413					-	23
57	La	139	Ti	6.413	0.28 ± 0.05	0.08 ± 0.04		16.04 ± 2.10		5,6
57	La	139	Ti	6.41	-					4
58	Ce	140	Co	5.660	0.011 ± 0.003	0.95 ± 0.06			-	66
58	Ce	140	Co	5.660	0.012 ± 0.002	0.93 ± 0.14	4.7 ± 0.3	190 ± 50		63
58	Ce		Co	5.640			-	17	-	8
58	Ce		Fe	7.646				-	-	present work
59	Pr	141	Cl	6.12	-		-	-	-	53
59	Pr	141	Cl	6.12				103	K	2
59	Pr	141	Cl	6.12	-	-		-		24
59	Pr	141	Cl	6.12	-	<0.600 ± 0.032	-	-	-	30
59	Pr	141	Cl	6.12	-	-	-	230	-	9
59	Pr	141	Cl	6.12	-		-	110	-	8,37
59	Pr	141	Cl	6.115	0.028 ± 0.008	0.56 ± 0.18	-	-		54
59	Pr	141	Cl	6.115	0.029 ± 0.005	0.567 ± 0.010	4.5 ± 1.0	110	-	49
59	Pr	141	Co	6.877	0.018 ± 0.009	0.20 ± 0.009	0.20 ± 0.05		-	63,66
59	Pr	141	Co	6.817	-	-		3	-	8
59	Pr	141	Co	6.690	-			27	K	2
59	Pr	141	Co	6.111	-	-		-	J	49
59	Pr	141	Cr	8.883	-	-	-	-	-	49

Table 1 Continuation

Z	Scatterer	A	Gamma Source	E_γ(MeV)	Γ_o(eV)	Γ_o/Γ	ϵ(eV)	$\sigma_{\gamma\gamma}$(mb)	Comments	Ref
59	Pr	141	Cr	8.881				9.3		26
59	Pr	141	Cr	8.881				1		9
59	Pr	141	Cr	8.881				9		8
59	Pr	141	Cu	7.915	0.002 ± 0.001	0.28 ± 0.08				66
59	Pr	141	Cu	7.256						49
59	Pr	141	Cu	7.252	0.110 ± 0.010	0.38 ± 0.04				66
59	Pr	141	Fe	7.64				12	N	8
59	Pr	141	Fe	7.64				4.0	N	9
59	Pr	141	Fe	7.639				10	C	2
59	Pr	141	Fe	7.632	0.035 ± 0.010	0.46 ± 0.15				66
59	Pr	141	Fe	7.632	0.063 ± 0.011	0.48	10.3 ± 0.3	20		44
59	Pr	141	Fe	7.632	$0.234 \pm^{0.006}_{0.002}$	0.46	$11.4 \pm^{0.3}_{0.9}$			33
59	Pr	141	Fe	7.632						23
59	Pr	141	Fe	7.629						30
59	Pr	141	Ni	8.997				0.4		9
59	Pr	141	Se	7.188						49
59	Pr	141	Se	7.185				80		8
60	Nd	142	Co	6.877	0.275 ± 0.060	0.85 ± 0.10				66
60	Nd	142	Co	6.877	0.270 ± 0.020	0.84 ± 0.13	12.4 ± 0.3	720 ± 130		63
60	Nd		Co	6.867				22		2
60	Nd		Co	6.867				30		8.37
60	Nd		Co	4.944						63
60	Nd	144	Cu	7.915	0.008 ± 0.003	0.24 ± 0.06				66
60	Nd		Fe	7.632						33
62	Sm		Co	6.706						63

Table 1 Continuation

Z	Scatterer	A	Gamma Source	E_γ(MeV)	Γ_0(eV)	Γ_c/Γ	ϵ(eV)	$\sigma_{\gamma\gamma}$(mb)	Comments	Ref
62	Sm		Co	5.703						63
62	Sm	-	Co	5.660						63
62	Sm	144	Fe	7.646						33
62	Sm	144	Fe	7.632						33
62	Sm	150	Ni	8.998	1.43 ± 0.30	0 22 ± 0.05				54
62	Sm		Ni	8.997				2 8		2
62	Sm	144	Ni	8.997				100		8
62	Sm	-	Ni	8.997				1		9
62	Dy	-	Co	7 214						63
62	Dy	160	Co	6.486						63
66	Dy		Co	5.660						63
66	Dy	-	Fe	7.646						33
66	Dy	-	Fe	7.632						33
68	Er		Co	6.706						63
68	Er	-	Co	6.110						63
68	Er		Fe	7.646						33
72	Hf	-	Co	7.066						63
72	Hf	-	Co	6.985						63
72	Hf	-	Co	5.850				< 0.2		65
73	Ta		Fe	7.64				0 7 ± 0 4		66
73	Ta	-	Mn	7.26				< 0 3		66
74	W	184	Ti	6.760						39
74	W	184	Ti	6.556						39
74	W	-	Ti	6.418						38
74	W	186	Ti	6.418						39

Table 1 Continuation

Z	Scatterer	A	Gamma Source	E_γ(MeV)	Γ_0(eV)	Γ_0/Γ	ϵ(eV)	$\sigma_{\gamma\gamma}$(mb)	Comments	Ref
74	Pt		Ti	~6.3	-	-	-		-	8
78	Pt	-	Hg	5.99	-	-		40	K	8
79	Au	197	Co	5.926				-	-	63
79	Au	—	Fe	7.646			-		-	33
79	Au	—	Fe	7.632	-		-			33
80	Hg	-	Co	4.924				-	-	29
80	Hg	202	Co	4.922	0.260 ± 0.020	0.99 ± 0.15	4.2 ± 0.5	5800 ± 1200		63
80	Hg	-	Co	4.906	-	-	-	-	-	52
80	Hg	-	Co	4.903	-	-		385	-	8,37
80	Hg	-	Cu	4.378	-		-		-	63
80	Hg	-	Cu	7.91	-	-	-	20 4	-	65
80	Hg	-	Fe	7.646	-	-	-	-	-	33
80	Hg	-	Fe	7.64	-		-	2 4 ± 1.3	N	65
80	Hg	-	Fe	7.632			-	-	-	33
80	Hg	-	Hg	5.44	-	-	-	56	-	9
80	Hg	-	Hg	5.44	-	-	-	128	-	2
80	Hg	-	Hg	5.44	-	-	-	75	K	8
80	Hg	-	Mn	7.26	-	-	-	0.5 ± 0.3	-	65
81	Tl	205	Cu	7.252	0.025 ± 0.006	0.56 ± 0.06	-	-		66
81	Tl	-	Cu	7.16		-	-	120	-	8,37
81	Tl	-	Co	7.214	-	-	-	-	-	63
81	Tl	-	Co	6.985	-	-	-	-	-	63
81	Tl	-	Co	5.743	-	-	-	-	-	63
81	Tl	-	Co	5.070	-		-	-	-	63
81	Tl	-	Fe	7.647	1.0	0.85 ± 0.17	11.5 ± 0.2	-	-	52

Table 1 Continuation

Z	Scatterer	A	Gamma Source	E_γ(MeV)	Γ_o(eV)	Γ_o/Γ	ϵ(eV)	$\sigma_{\gamma\gamma}$(mb)	Comments	Ref
81	Tl		Fe	7.646	0.57 ± 0.05	0.58	9.3 ± 0.3	574		8
81	Tl	-	Fe	7.646		0.617 ± 0.092				14
81	Tl	205	Fe	7.646	0.57 ± 0.06	0.581	9.3 ± 0.3		-	47
81	Tl	205	Fe	7.646	0.56	0.59				23
81	Tl	-	Fe	7.646						38
81	Tl	205	Fe	7.646	0.57 ± 0.03	0.58 ± 0.06				68
81	Tl	-	Fe	7.646	2.45	0.69	11.6			34
81	Tl	-	Fe	7.646						13
81	Tl	-	Fe	7.64				370	N	8.37
81	Tl	-	Fe	5.62						52
81	Tl	-	Hg	5.99				5	K	8
81	Tl	-	Tl	6.418	0.083 ± 0.015	0.26 ± 0.03				56
81	Tl	203	Tl	6.418	0.083 ± 0.015	0.26	0.5 ± 0.5	100		36
81	Tl	203	Tl	6.418	-					39
81	Tl	-	Tl	6.413				26		8
82	Pb	-	Ag	5.53				70		8
82	Pb	208	Al	6.98			10 ± 1	1300 ± 400		51
82	Pb	208	Al	6.98	-			2900		2
82	Pb	208	Al	6.98	0.86 ± 0.10	0.30 ± 0.07	11.5 ± 2.5	1290 ± 60		19
82	Pb	208	Al	6.98	0.95 ± 0.10	0.27 ± 0.03		1290 ± 60		20
82	Pb	-	Cl	6.98	-	-	-	346		2
82	Pb	-	Co	7.149				1000		2
82	Pb	-	Cu	7.91	-		-	< 0.2		65
82	Pb	208	Fe	7.64	-	-	-	126 ± 20	N	66

Table 1 Continuation

Z	Scatterer	A	Gamma Source	E_γ(MeV)	Γ_o(eV)	Γ_o/Γ	ϵ(eV)	$\sigma_{\gamma\gamma}$(mb)	Comments	Ref
82	Pb	208	Fe	7.285	0.77	1.0	7.3	–	–	34
82	Pb	208	Fe	7.285	0.80 ± 0.03	~ 1	8.5 ± 0.5	4100	–	2
82	Pb	208	Fe	7.285	–	–	8.1 ± 1	–	–	1
82	Pb	208	Fe	7.285	0.84 ± 0.03	–	3.9 ± 0.3	5200 ± 1600	–	51
82	Pb	–	Fe	7.285	–	–	–	4100	–	8,37
82	Pb	–	Fe	7.28	–	–	–	800	–	9
82	Pb	–	Fe	7.28	0.70 ± 0.20	–	–	1000	–	28
82	Pb	208	Fe	7.28	0.73 ± 0.05	0.84 ± 0.08	4.8 ± 0.3	5620 ± 150	–	19
82	Pb	208	Fe	7.28	0.86 ± 0.06	0.72 ± 0.13	5.0 ± 0.5	5620 ± 150	–	20
82	Pb	208	Fe	7.28	0.78 ± 0.03	0.62 ± 0.03	–	4640 ± 180	–	5,60
82	Pb	208	Fe	7.279	–	–	–	–	–	11
82	Pb	208	Fe	7.279	0.78 ± 0.06	1.0	–	–	–	66
82	Pb	208	Fe	7.277	–	–	–	–	–	30
82	Pb	208	Fe	7.277	0.68 ± 0.03	$0.95 \pm^{0.06}_{0.17}$	8.00 ± 0.14	–	–	52
82	Pb	206	Gd	6.15	–	–	–	–	M	8
82	Pb	–	Hg	7.32	–	–	–	5600	–	2
82	Pb	–	Mn	7.261	–	–	–	25	–	9
82	Pb	–	Mn	7.26	–	–	–	0.9 ± 0.5	–	65
82	Pb	–	N	10.83	–	–	–	–	–	25
82	Pb	208	N	7.297	1.30 ± 0.25	~ 1	–	–	–	15
82	Pb	–	Ni	8.998	–	–	–	–	–	32
82	Pb	206	Sr	5.9	–	–	–	–	–	8
82	Pb	–	Ti	6.41	–	–	–	0.6 ± 0.4	–	65
82	Pb	208	V	7.305	–	–	–	12.5	–	2
83	Bi	209	As	7.300	–	–	–	80	–	8

Table 1 - Continuation

Z	Scatterer	A	Gamma Source	E_γ(Mev)	Γ_0(eV)	Γ_0/Γ	ϵ(eV)	$\sigma_{\gamma\gamma}$(mb)	Comments	Ref
83	Bi	209	Co	5.646	–	–	–	55	–	8
83	Bi	209	Co	5.609	–	–	–	348 ± 69	–	29
83	Bi	209	Co	5.603	0.95 ± 0.03	1.0	–	–	–	66
83	Bi	209	Co	5.603	0.95 ± 0.02	1.00 ± 0.15	13 ± 1	1050 ± 250	–	63
83	Bi	–	Cu	7.91	–	–	–	$<$ 0.2	–	65
83	Bi	–	Cu	7.637	–	–	–	–	–	12
83	Bi	209	Cu	7.634	–	–	–	4	–	8
83	Bi	–	Cu	7.172	–	–	–	–	–	12
83	Bi	–	Cu	6.392	–	–	–	–	–	12
83	Bi	–	Fe	7.64	–	–	–	2.0 ± 1.1	–	65
83	Bi	–	Mn	7.26	–	–	–	0.8 ± 0.4	–	66
83	Bi	–	N	10.83	–	–	–	$\leq$ 1	–	26
83	Bi	209	Se	7.416	–	–	–	100	–	8
83	Bi	209	Se	7.416	0.14 ± 0.09	0.6 ± 0.2	3.4 ± 1.6	–	–	52
83	Bi	209	Ti	7.168	0.82 ± 0.04	1.0	–	–	–	66
83	Bi	205	Ti	7.15	0.32 ± 0.07	–	–	1200 ± 230	–	5,6
83	Bi	209	Ti	7.15	0.42 ± 0.14	$>$ 0.68	$<$ 2	2600 ± 800	–	21
83	Bi	209	Ti	7.15	–	–	–	–	–	4
83	Bi	209	Ti	7.149	–	–	–	2000	–	8,37
83	Bi	209	Ti	7.149	–	–	–	–	–	52
83	Bi	209	Ti	7.00	0.42 ± 0.14	–	$<$ 2	2600 ± 700	–	51
83	Bi	209	Ti	6.996	–	–	–	1560	–	2
90	Th	232	Fe	9.298	–	–	–	–	–	22
90	Th	–	N	10.83	–	–	–	–	–	26

Table 1 - Continuation

Z	Scatterer	A	Gama Source	E_γ(MeV)	Γ_0(eV)	Γ_0/Γ	ε(eV)	$\sigma_{\gamma\gamma}$(mb)	Comments	Ref
90	Th	232	Ni	8.998	–	–	–	–	–	22
90	Th	232	Ni	8.533	–	–	–	–	–	22
92	U	238	Fe	9.298	–	–	–	–	–	22
92	U	238	N	10.83	–	–	–	–	–	26
92	U	–	Ni	8.998	–	–	–	–	–	32
92	U	–	Ni	8.998	–	–	–	–	–	22
92	U	–	Ni	8.533	–	–	–	–	–	22

Comments

- A) High energy component of a complex spectrum
- B) The value of Γ_0 is obtained by using the value of ϵ given in ref 6
- C) In the present reference it was not decided which line of iron (7 639 or 7 646 MeV) is responsible for the resonance observed
- D) The lines of 6 266 and 6 977 MeV were supposed to be elastic only in this reference
- E) The rough estimate of Γ_0 and Γ_0/Γ were proposed without confirmation
- F) The correct resonance energy is 6 550 MeV
- G) The mass number given in this reference is 114 instead of 112 as proposed by others authors
- H) Is probably an independent level in the complex spectrum of Ni gamma rays on Te
- I) May be an inelastic component from 7 528 MeV level in Te
- J) Probably a spurious resonance originated from a compound of chlorine in the vicinity of the gamma source A Wolf et alii ref 39
- K) The value of the cross section may be in error due to discrepancies of the γ ray intensities reported by Bartholomew and Groshev ref 63
- L) Unbound levels
- M) The relative line intensities in this case are due to Groshev and co workers
- N) The cross section value was not corrected for the presence of two lines of 7 629 and 7 643 MeV of equal intensities in spectrum of iron (Groshev ref 63)
- O) Rough estimate
- P) Probably the 7 310 MeV line corresponds to a resonance in ^{71}Ga

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