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WORKSHOP ON NUCLEAR MODEL COMPUTER CODES

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REPORT ON THE INTERNATIONAL NUCLEAR MODEL CODE INTERCOMPARISON SPHERICAL OPTICAL AND STATISTICAL MODEL STUDY

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Report on the

International Nuclear Model Code Intercomparison

Spherical Optical and Statistical Model Study

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"The will is infinite and the execution confined, the desire is boundless and the act a slave to limit"

E. Cesàro

1. INTRODUCTION

International Code Intercomparisons have been carried out during the last decade on different topics: Radiation Shielding, Reactor Safety, Reactor Dynamics, Reactor Noise and also Nuclear Models. They follow a rather regular pattern.

After a first comparison, which normally shows rather discrepant results, the exercise is repeated with some additional specifications, which are intended to limit the use of personal judgement in the choice of some parameters. The new results agree better, but to obtain good agreement, some codes have to be modified. It is interesting to observe that this happens also when everybody is using the "same" program.

To use computer codes, i.e. to translate a physical or mathematical problem into a program input, requires a certain craftsmanship that can only be acquired with experience. The "turn the handle" approach often leads to erroneous results.

It is also with this in mind that such benchmark exercises are carried out. The different iterations needed to obtain "convergence" of the results given by the different participants provide much insight for both participants and later users about how to use the different codes, their fine qualities and deficiencies as well as the limitations in the way a physical process in the code is modelled.

[illegible] Cross Section Evaluation Working Group (USA) under the chairmanship of A. Prince (BNL). This study resulted in a significant improvement in agreement for calculations of total, elastic, inelastic, capture and threshold reaction cross sections for the six codes of US origin considered.

Prince then suggested an extension of this comparative study to include codes of European and Japanese origin, with the collaboration of the Nuclear Energy Agency Nuclear Data Committee and the Nuclear Energy Agency Data Bank. He suggested using the same cross section calculation for 59-Co as already carried out in the frame of CSEWG NMCS.

Thus the present study is an intercomparison of cross section calculations made with various nuclear model codes. We do not aim to achieve agreement with experimental data, but to pin-point errors and deficiencies in codes and to create confidence in code calculations where experimental data is non-existent.

The parameter specification of the exercise is given in Appendix I.

Each participant was asked to use the same:

- set of parameters (e.g. optical model parameters, level density parameters, level schemes, mass excesses);
- giant resonance parameters;
- normalization for the radiative width;
- level density formulation;
- spin and parity distribution laws;
- optical model and statistical model formalisms.

Due to the special features and limitations of some of the codes used, input and model differences were introduced by some participants with respect to the original formulation of the exercise. These cases are pointed out in the tables and discussed in the section dealing with the analysis of the results.

At energies above about 14 MeV, pre-equilibrium processes contribute appreciably to the cross sections. These may be calculated in several different ways, and a detailed comparison of these will be made in a later report.

The results are presented in comparative tables and graphs. The computed quantities are shown for each incident energy and each code and for each reaction separately.

In this exercise the participants went through two iterations. Better convergence of the results have been achieved in this way because some of the participants have tried, in the second iteration, to comply as stricly as possible with the parameter specifications.

[illegible] computer codes [illegible] codes against the results provided by "experienced" codes used in this exercise.

This study should also prove useful to those who are just starting on neutron cross section calculations.

The results included in this report also show the present state of the art in the statistical model calculations and indicate the degree of confidence one can place in the cross sections derived from them. It is hoped that authors of codes used in this study will be willing to make them available, preferably with reasonably full documentation, for distribution through NEA Data Bank.

Codes are normally requested from authors and tested for inclusion in our master files when a specific user request is received. However, some of these are already available: SCAT-2, ELIESE-3, HAUSER-5, CERBERO, ERINNI, SASSI and the latest version of ABACUS called A-THREE (from the CPC library in Belfast, U.K.).

2. PARTICIPANTS AND COMPUTER CODES USED IN THIS EXERCISE

Program		User and Author	Establishment	Country
1. SCAT-2	(Ref. 1)	O. Bersillon	CEA Bruyères-le-Chatel	France
2. ABACUS-2	(Ref. 2)	E. Correa de Oliveria	IEACTA Sao José dos Campos	Brazil
3. OPTICAL	(Ref. 3)	T.W. Phillips	LLNL, Livermore	USA
4. ABACUS-NEARREX	(Ref. 4)	E. Ramstroem	SSRL, Nykoeping	Sweden
5. NGROGI	(Ref. 5)	Y. Harima M. Kawai	RLNR-TIT, Tokyo NAIG-NRL, Tokyo	Japan
6. EMPIRE	(Ref. 6)	M. Herman	IBJ, Warsaw	Poland
7. ELIESE-3	(Ref. 7)	G. Vasiliu, S. Mateescu S.B. Garg, V.K. Shukla Amar Sinha	INPR, Bucharest BARC, Bombay	Rumania India
8. HAUSER-5	(Ref. 8)	S.B. Garg, V.K. Shukla Amar Sinha	BARC, Bombay	India
9. CERBERO	(Ref. 9)	H.A.J. Van der Kamp H. Gruppelaar G. Reffo	ECN, Petten ENEA, Bologna	Netherlands
10. ERINNI	(Ref.10)	H.A.J. Van der Kamp H. Gruppelaar G. Reffo	ECN, Petten ENEA, Bologna	Netherlands
11. SASSI-ECN	(Ref.11)	H.A.J. Van der Kamp H. Gruppelaar	ECN, Petten	Netherlands
12. IDA	(Ref.12)	G. Reffo, F. Fabbri	ENEA, Bologna	Italy
13. ABAREX	(Ref.13)	P.A. Moldauer	ANL, Argonne	USA

The description of these codes, their special features when compared to others and their limitations with respect to this exercise are given in Appendix II.

3. PRESENTATION OF THE RESULTS

The results received have been arranged in such a way as to make a fast comparison possible, that is:

i) optical model cross sections (Tables 1 to 17);

ii) integrated cross sections below the threshold of second-particle emission (Tables 1 to 9);

iii) integrated cross sections for multiple particle emissions (Tables 9 to 17);

iv) graphical presentation of each reaction cross section (Graphs 1-32).

4. COMPARISON OF RESULTS

4.1 Optical Model Cross Sections

Only the codes OPTICAL, POLIFEMO, NAUSIKAA and ABACUS-2 used the optional energy dependence of the nucleon radii in the neutron optical potential real and imaginary well depths; we can therefore divide the code responses into two code groups. Within each group an agreement within a few per cent at all energies among all the codes was found.

The use of the energy dependent radii produced higher cross sections with differences that increase with incident energy up to 6% at En = 14 MeV. This effect is shown clearly by T. Phillips who gave results for both parametrizations. However, on the whole good agreement (within a few per mil) was observed among the codes using each option, and these are shown in the graphs by different curves (Figs. 1-12).

The calculations with HAUSER-5 do not include the spin-orbit potential; this accounts for the somewhat higher values of the compound nucleus cross section (Figs. 11, 12). The program EMPIRE sets the spin-orbit radius $r_{SO} = r_I$, and interpolates the incoming neutron transmission coefficients from a precomputed table, and this may account for the somewhat different values obtained for the compound nucleus cross section.

As far as the matching radius is concerned, some participants have used the built-in values of their program instead of the one proposed in the exercise. However, no significant discrepancies could be found which were attributable to such differences.

4.2 Results for the Hauser-Feshbach Theory Calculation Comparison

The following differences were found that may influence the present comparison in all or in part of the energy range.

i) Mr. Vasiliu used an older Moldauer theory with inclusion of an interference term in the elastic channel which is not any longer in use.

ii) No indication was given in the exercise as to how the spin distribution between E_{cut} and U_x should be taken. This was linearly interpolated between $\sigma^2(U_x)$ at U_x and σ^2_{LEV} at E_{cut} by Reffo, Van der Kamp and Herman. (σ^2_{LEV} being the spin cut off derived from fitting the proposed spin distribution law to the discrete level spin distribution with the maximum likelihood method.) The other participants did not specify their assumptions. Some code users are accustomed to extrapolate $\sigma^2(U_x)$ down to E_{cut}; this procedure is probably wrong and makes this comparison less exact.

iii) The width fluctuation correction used by Herman is that of Hoffman, Richert, Tepel and Weidenmüller (Ref. 14). His approach is different from all the other participants who used the usual width fluctuation integral formulae. In addition Moldauer, Reffo and Van der Kamp used an effective number of degrees of freedom greater than one for the χ^2 width distribution law, according to the latest Moldauer theory (Ref. 13), whereas the remaining participants used a Porter-Thomas distribution law. In SASSI-ECN the width fluctuation correction method of Hoffman et al. was used above E = 1.09 MeV (first excited state of Co-59). Below that energy the usual width fluctuation integral was used with Porter-Thomas distribution law.

4.2.1 Neutron Radiative Capture (Figs. 15, 16)

For neutron radiative capture, we observed good agreement (see Tables 1 to 17) between the results of CERBERO-ERINNI on the one hand and IDA system on the other. Discrepancies start increasing at neutron energies above ~ 14 MeV. This may be due to numerical differences in the integration procedures which influence very low capture values. The capture cross sections given by SASSI-ECN appear to be some 40% higher; this being interpreted by the author as due to a different normalization in total radiative widths. In fact in SASSI-ECN the gamma-decay width of the neutron resonances is taken (as requested) Γ_γ = 500 for any ℓ whereas in CERBERO, ERINNI, POLIFEMO, NAUSIKAA it is spin and parity dependent; the normalization adopted is indicated in the table below:

J	π = +	π = -
3	507. MeV	262 MeV
4	493. MeV	224 MeV

The results given by EMPIRE and HAUSER-5 differ from each other up to 25% in the region below 6 MeV. Above 6 MeV no (n,γ) values were available from the EMPIRE code.

The values about 40% lower given by the EMPIRE and HAUSER-5 codes, with respect to the ENEA codes, cannot be due to different width fluctuation corrections because discrepancies are observed in the whole considered energy range; the effect is most probably due to a different or no normalization of Γ_γ. This assumption can be verified by examining the Γ_γ normalization for all J$^\pi$. At higher energies other types of discrepancies appear between the above mentioned codes. These are probably attributable to numerical integration differences with respect to both neutron and gamma-ray channels. Differences in the adopted spin distributions of continuum levels may also be responsible in part for these discrepancies.

In ABAREX only one giant resonance can be specified; the one at 19.12 MeV was chosen in this exercise; however, the s-wave neutron-gamma widths over spacings have been correctly normalized according to the exercise specifications.

Also in SASSI-ECN only one giant dipole resonance was assumed at E = 19.5 MeV with a width of 6 MeV. The reason for the high values of the radiative capture cross section above 14 MeV of SASSI-ECN is due to the inclusion of a direct and collective component.

4.2.2 Neutron Inelastic Scattering (Figs. 13, 14)

The inelastic cross sections given by some participants could not be compared because they provided the compound elastic and inelastic neutron scattering cross sections added together. The (n,n') results agree within approximately 10% in the region of the maximum. Again Vasiliu's values appear to be higher because he used an earlier Moldauer theory for the width fluctuation correction with the inclusion of the resonance interference contribution.

The cross sections obtained with HAUSER-5 are appreciably higher; this can be attributed to the use of a potential without a spin-orbit term as mentioned previously. The results provided by the ENEA set of codes are consistent with each other over the whole energy range.

4.2.3 Results for (n,2n) (Figs. 25, 26)

Good agreement (within 5%) is observed at all energies between the NGROGI code and the ENEA codes. Exception is made for 12 MeV where the NGROGI results are 20% lower.

4.2.4 Results for (n,p) (n,α) (Figs. 17-20)

While the set of ENEA codes agree well with each other up to 8 MeV, the energy around which the (n,pn) reaction has its threshold, NGROGI and EMPIRE disagree with them. The neglection of the discrete inelastic scattering in NGROGI might enhance the proton emission. Above 8 MeV there is reasonable agreement in the trend and in the values between ERINNI, PENELOPE and NGROGI. Note that above 12 MeV the proton volume potential changes from W_V = 0.22E - 2.7 to W_V = 0.

In the case of the (n,α) reaction there is a reasonable agreement between the different codes at energies above 12 MeV. The results of NGROGI are discrepant with those provided by the other codes for energies above 12 MeV.

4.2.5 Results for Two Particle Emission Processes

Comparison of the following reactions show substantial discrepancies:

$$\sigma(n,\alpha n),\ \sigma(n,n\alpha),\ \sigma(n,pn),\ \sigma(n,np)$$

However, the values for $\sigma(n,\alpha x) = \sigma(n,\alpha) + \sigma(n,\alpha n)$ are in quite good agreement apart from the results of NGROGI at lower energies.

5. CONCLUSIONS

From the short comparative analysis outlined above for the results from the different codes one may conclude that the optical model cross sections are in reasonable agreement. The statistical model cross sections are more or less discrepant.

In particular:

i) The optical model quantities σ_γ, and σ_R for neutrons are in good agreement. We are unable to compare the proton and alpha optical model calculations involved as only a few users have provided results for it. We therefore cannot say to what extent the observed discrepancies in particle emissions are due to differences in the calculated transmission coefficients.

ii) Large discrepancies in $\sigma(n,2n)$ and in $\sigma(n,2n) + \sigma(n,n')$ which represent the dominant competition, give even larger discrepencies for weak and very weak competitions which share what is left over of the compound nucleus cross section. In some cases one observes differences of one order of magnitude between the results of different codes for the single and multiple particle emissions involving charged particles. Also these differences tend to increase with energy. Discrepancies seem to explode above 12 MeV where the $(n,2n)$, (n,pn), $(n,\alpha n)$, (n,np), $(n,n\alpha)$ competitions start rising fast.

iii) According to the conclusions in (i) such discrepancies can hardly be attributed to the optical model calculations for the neutron, so one has to look for other possible explanations such as:

a) Differences in accuracy of the numerical integration techniques (e.g. integration method, number of steps, etc.).

b) Differences in the level density formulae used which result in different weights for channel reactions involved.

c) Discrepancies in the charged particle optical model transmission coefficients.

d) As far as discrepancies in $\sigma(n,\gamma)$ are concerned these might be due to different Γ_γ normalization for different J and π and differences in the treatment of gamma-ray competition.

vi) It is highly desirable that authors examine their codes to identify the sources of the discrepancies noted under paragraph (iii). Until this is done, it is not possible to make reliable statistical model calculations of many of the reaction channels studied in this exercise.

6. FUTURE PROGRAMME

This series of program intercomparisons is being extended by exercises on:

i) coupled channel calculations;

ii) pre-equilibrium reactions;

iii) charged particle optical model calculations.

The specifications for these intercomparisons are available on request.

7. ACKNOWLEDGEMENTS

NEA Data Bank wishes to thank all the participants who have made the present program comparison possible and who have contributed their comments to this report. Several of them have, in addition, made comparison runs of their programs with modified input parameters that conform better with the exercise specifications. The work of Dr. P. Hodgson in checking and suggesting modifications to this report has been particularly valuable.

Data Bank staff who have joined in this project and in the preparation of the report are Ms. S. Greenstreet, P. Johnston, P. Nagel, Ms. R. Posca and N. Tubbs.

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CODE(S) USER mb SIGMA	SCAT2 BERSILLON	ABACUS2 E DE OLIVEIRA	OPTICAL PHILLIPS	ABACUS-NEARREX RAMSTROEM	NGROGI HARIMA-KAWAI	EMPIRE HERMAN	ELIESE3* HAUSER 5 CARG	ELIESE3 VASILIU	CERBERO3 L GRUPPELAAR	SASSI ECN L GRUPPELAAR	IDA EL REFFO	AGAREX MOLDAUER
TOTAL	4857	4856	4854 4871E	4859	4857		4858*	4858	4858	4859	4877	4859
COMP.NUCL.	2500		2497 2499E	2502	2499	2543	2499* 2534	2499	2496	2499	2499	2503
ELASTIC: HF HF+WFC	2357S	2363S	2357S 2373SE	4854 4824	2357S		4858M*	4849 4849M	4850 4851	4847	4868 4869	2356S 4849
n n HF												
n n HF+WFC												
n γ HF									8.17		8.16	
n γ HF+WFC						7.02	5.41		7.86	11.66	7.84	9.54
n nγ HF											.001	
n nγ HF+WFC											.001	0.00
n p HF												
n p HF+WFC												
n α HF												

S = shape elastic

M = modified transmission coefficients $(t_{lj} = \Theta_{lj} - .25\Theta_{lj}\Theta^2_{lj})^{J\pi}$ are used according to Moldauer's theory

L = linear interpolation of spin cut-off in the intermediate continuum region

E = energy dependence of the nucleon radii in the neutron optical potential

Table 1 En = 0.5 MeV

Table 2 En = 1.0 MeV

CODE(S) USER mb SIGMA	SCAT2 BERSILLON	ABACUS2 E DE OLIVEIRA	OPTICAL PHILLIPS	ABACUS-NEARREX RAMSTROEM	NGROGI HARIMA-KAWAI	EMPIRE HERMAN	ELIESE3* HAUSER 5 CARG	ELIESE3 VASILIU	CERBERO3 L GRUPPELAAR	SASSI ECN L GRUPPELAAR	IDA EL REFFO	AGAREX MOLDAUER
TOTAL	3825	3825	3819 3835E	3829	3825		3826*	3826	3827	3828	3843	3828
COMP.NUCL.	2381		2377 2384E	2383	2380	2404	2380* 2399	2380	2379	2381	2388	2384
ELASTIC: HF HF+WFC	1444S	1446S	1443S 1451SE	3824 3794	1444S		3826*	3818 3818M	3819 3820	3817	3835 3836	1444S 3820
n n HF												
n n HF+WFC												
n γ HF									7.41		7.44	
n γ HF+WFC						6.26	4.75		7.11	11.08	7.12	8.05
n nγ HF											.02	.01
n nγ HF+WFC											.02	
n p HF												
n p HF+WFC												
n α HF												

S = shape elastic

M = modified transmission coefficients $(t_{lj} = \Theta_{lj} - .25\Theta_{lj}\Theta^2_{lj})^{J\pi}$ are used according to Moldauer's theory

L = linear interpolation of spin cut-off in the intermediate continuum region

E = energy dependence of the nucleon radii in the neutron optical potential

Table 2 En = 1.0 MeV

Table 3 En = 1.5 MeV

CODE(S) USER mb SIGMA	SCAT2 BERSILLON	ABACUS2 E DE OLIVEIRA	OPTICAL PHILLIPS	ABACUS-NEARREX RAMSTROEM	NORDGI HARIMA-KAWAI	EMPIRE HERMAN	ELIESE3* HAUSER 5 GARG	ELIESE3 VASILIU	CERBERO3 L GRUPPELAAR	SASSI ECN L GRUPPELAAR	IDA EL REFFO	ABAREX MOLDAUER
TOTAL	3503	3498	3498 3498E	3506	3502		3502*	3502	3507	3505	3502	3506
COMP.NUCL.	2239		2236 2243E	2241	2238	2264	2238* 2193	2238	2237	2240	2245	2241
ELASTIC: HF HF+WFC	1264S	1260S	1262S 1255SE	2763 2976	1264S		2763*	2759 2926M	2760 2936	2945	2759 2936	1265S 2935
n n HF				739				738	737		738	
n n HF+WFC				497			504	571M	560	552	561	546
n γ HF									5.35		5.21	
n γ HF+WFC						4.17	3.09		4.91	8.2	4.96	5.12
n nγ HF											.06	
n nγ HF+WFC											.06	[illegible]
n p HF												
n p HF+WFC												
n α HF												

S = shape elastic

M = modified transmission coefficients $(t_{lj} = \Theta_{lj} - .25\Theta_{lj}\Theta_{lj}^2)^{J\pi}$ are used according to Moldauer's theory

L = linear interpolation of spin cut-off in the intermediate continuum region

E = energy dependence of the nucleon radii in the neutron optical potential

Table 3 En = 1.5 MeV

Table 4 En = 2.0 MeV

CODE(S) USER mb SIGMA	SCAT2 BERSILLON	ABACUS2 E DE OLIVEIRA	OPTICAL PHILLIPS	ABACUS-NEARREX RAMSTROEM	NORDGI HARIMA-KAWAI	EMPIRE HERMAN	ELIESE3* HAUSER 5 GARG	ELIESE3 VASILIU	CERBERO3 L GRUPPELAAR	SASSI ECN L GRUPPELAAR	IDA EL REFFO	ABAREX MOLDAUER
TOTAL	3370	3328	3367 3353E	3371	3369		3369*	3369	3366	3369	3352	3372
COMP.NUCL.	[illegible]		2047 2055E	2049	2048	2070	2047* 2110	2047	2046	2045	2055	2049
ELASTIC: HF HF+WFC	1322S	1276S	1320S 1298SE	2091 2369	1322S		2091*	2089 2277M	2088 2301	2293	2089 2294	1322S 2291
n n HF				1277			1278	1276	1275		1280	
n n HF+WFC				970		1097		1089M	1061	1071	1065	1078
n γ HF							2.06		3.23		3.27	
n γ HF+WFC						2.72			3.24	[illegible].74	3.29	3.22
n nγ HF											.11	
n nγ HF+WFC											.11	.07
n p HF							.003					
n p HF+WFC												
n α HF												

S = shape elastic

M = modified transmission coefficients $(t_{lj} = \Theta_{lj} - .25\Theta_{lj}\Theta_{lj}^2)^{J\pi}$ are used according to Moldauer's theory

L = linear interpolation of spin cut-off in the intermediate continuum region

E = energy dependence of the nucleon radii in the neutron optical potential

Table 4 En = 2.0 MeV

Table 5 En = 2.5 MeV

CODE(S) / USER / mb SIGMA	SCAT2 / BERSILLON	ABACUS2 E / DE OLIVEIRA	OPTICAL / PHILLIPS	ABACUS-NEARREX / RAMSTROEM	NGROGI / HARIMA-KAWAI	EMPIRE / HERMAN	ELIESE3* HAUSER 5 / GARG	ELIESE3 / VASILIU	CERBERO3 L / GRUPPELAAR	SASSI ECN L / GRUPPELAAR	IDA EL / REFFO	ABAREX / MOLDAUER
TOTAL	3343	3300	3342 .3323E	3341	3342		3341*	3341	3337	3340	3318	3342
COMP.NUCL.	1888		1890 1903E	1888	1888	1901	1888* 1866	1888	1887	1888	1900	1888
ELASTIC: HF HF+WFC	1454S	1399S	1453S 1421SE	1865 2080	1454S		1978*	1865 1999M	1862 2020	2005	1834 2001	1454S 2010
n n HF				1473			1314	1473	1472		1481	
n n HF+WFC				1231		1342		1339M	1307	1330	1314	1329
n γ HF							1.69		2.49		2.55	
n γ HF+WFC						2.10			2.50	4.44	2.56	2.38
n nγ HF											.18	
n nγ HF+WFC											.18	.13
n p HF							.07	.038	.07		.071	
n p HF+WFC								.038M	.07		.070	
n α HF												

S = shape elastic

M = modified transmission coefficients $(t_{lj} = \Theta_{lj} - .25\Theta_{lj}\Theta_{lj}^2)^{J\pi}$ are used according to Moldauer's theory

L = linear interpolation of spin cut-off in the intermediate continuum region

E = energy dependence of the nucleon radii in the neutron optical potential

Table 5 En = 2.5 MeV

Table 6 En = 3.0 MeV

CODE(S) / USER / mb SIGMA	SCAT2 / BERSILLON	ABACUS2 E / DE OLIVEIRA	OPTICAL / PHILLIPS	ABACUS-NEARREX / RAMSTROEM	NGROGI / HARIMA-KAWAI	EMPIRE / HERMAN	ELIESE3* HAUSER 5 / GARG	ELIESE3 / VASILIU	CERBERO3 L / GRUPPELAAR	SASSI ECN L / GRUPPELAAR	IDA EL / REFFO	ABAREX / MOLDAUER
TOTAL	3387	3360	3388 3378E	3382	3386		3385*	3385	3379	3382	3367	3383
COMP.NUCL.	1782		1785 1807E	1780	1782	1786	1782* 1859	1782	1781	1781	1802	1781
ELASTIC: HF HF+WFC	1605S	1555S	1604S 1571SE	1857 2012	1604S		1891*	1858 1952M	1854 1970	1953	1826 1944	1958
n n HF				1523			1600	1524	1522		1539	
n n HF+WFC				1341		1443		1430M	1406	1424	1420	1423
n γ HF							1.41		2.23		2.30	
n γ HF+WFC						1.83			2.26	4.06	2.33	2.05
n nγ HF											.30	
n nγ HF+WFC											.30	.20
n p HF					.043		.49	.274	.56		.55	
n p HF+WFC								.273M	.55		.55	
n α HF												

S = shape elastic

M = modified transmission coefficients $(t_{lj} = \Theta_{lj} - .25\Theta_{lj}\Theta_{lj}^2)^{J\pi}$ are used according to Moldauer's theory

L = linear interpolation of spin cut-off in the intermediate continuum region

E = energy dependence of the nucleon radii in the neutron optical potential

Table 6 En = 3.0 MeV

Table 7 En = 4.0 MeV

CODE(S) USER mb SIGMA	SCAT2 BERSILLON	ABACUS2 E DE OLIVEIRA	OPTICAL PHILLIPS	ABACUS-NEARREX RAMSTROEM	NGROGI HARIMA-KAWAI	EMPIRE HERMAN	ELIESE3* HAUSER 5 GARG	ELIESE3 VASILIU	CERBERO3 L GRUPPELAAR	SASSI ECN L GRUPPELAAR	IDA EL REFFO	ABAREX MOLDAUER
TOTAL	3556	3576	3562 3595E		3556		3556*	3556	3549	3547	3580	3548
COMP.NUCL.	1683		1686 1729E		1683	1671	1683* 1814	1683	1682	1680	1724	1682
ELASTIC: HF HF+WFC	1873S	1856S	1875S 1866SE		1872S		2043*	1992 2107M	1990 2055	2040	1994 2054	1866S 2002
$n\ n$ HF							1675	1559	1547		1582	1543
$n\ n$ HF+WFC						1512		1443M	1479	1499	1511	
$n\ \gamma$ HF							1.33		2.02		2.13	
$n\ \gamma$ HF+WFC						1.48			2.02	3.331	2.14	1.35
$n\ n\gamma$ HF											.66	
$n\ n\gamma$ HF+WFC											.66	.29
$n\ p$ HF					.67	5.36	4.33	3.05	5.43		5.38	
$n\ p$ HF+WFC								4.05M	5.38		5.32	
$n\ \alpha$ HF						0.13	.005					

S = shape elastic

M = modified transmission coefficients $(t_{lj} = \Theta_{lj} - .25\Theta_{lj}\Theta^2_{lj})^{J\pi}$ are used according to Moldauer's theory

L = linear interpolation of spin cut-off in the intermediate continuum region

E = energy dependence of the nucleon radii in the neutron optical potential

Table 7 En = 4.0 MeV

Table 8 En = 6.0 MeV

CODE(S) USER mb SIGMA	SCAT2 BERSILLON	ABACUS2 E DE OLIVEIRA	OPTICAL PHILLIPS	ABACUS-NEARREX RAMSTROEM	NGROGI HARIMA-KAWAI	EMPIRE HERMAN	ELIESE3* HAUSER 5 GARG	ELIESE3 VASILIU	CERBERO3 L GRUPPELAAR	SASSI ECN L GRUPPELAAR	IDA EL REFFO	ABAREX MOLDAUER
TOTAL	3635	3758	3639 3740E		3635		3638*		3635	3672	3734	3625
COMP.NUCL.	1594		1594 1640E		1594	1583	1594* 1737		1595	1593	1640	1595
ELASTIC: HF HF+WFC	2042S	2108S	2045S 2101SE		2042S		2063*		2068	2092	2123	205.
$n\ n$ HF						1500	1643		1541		1585	1573
$n\ n$ HF+WFC										1514		
$n\ \gamma$ HF						0.83	0.76				1.35	.7
$n\ \gamma$ HF+WFC									1.23	2.0		
$n\ n\gamma$ HF											1.24	
$n\ n\gamma$ HF+WFC												
$n\ p$ HF					7.4	17.9	17.55		22.56		22.55	
$n\ p$ HF+WFC												
$n\ \alpha$ HF					.21	1.29	0.91		1.25		1.30	

S = shape elastic

M = modified transmission coefficients $(t_{lj} = \Theta_{lj} - .25\Theta_{lj}\Theta^2_{lj})^{J\pi}$ are used according to Moldauer's theory

L = linear interpolation of spin cut-off in the intermediate continuum region

E = energy dependence of the nucleon radii in the neutron optical potential

Table 8 En = 6.0 MeV

Table 9 — En = 8.0 MeV

CODE(S) / USER / mb SIGMA	SCAT2 / BERSILLON	ABACUS2 E / DE OLIVEIRA	OPTICAL / PHILLIPS	ABACUS-NEARREX / RAMSTROEM	NGROGI / HARIMA-KAWAI	EMPIRE / HERMAN	ELIESE3* HAUSER 5 / GARG	ELIESE3 / VASILIU	CERBERO3 L / GRUPPELAAR	SASSI ECN L / GRUPPELAAR	IDA EL / REFFO	ABAREX / MOLDAUER
TOTAL	3377	3509	3379 352CE		3377		3382*		3381	3355	3522	3367
COMP.NUCL.	1534		1533 1575E		1534	1529	1534* 1667		1535	1539	1577	1536
ELASTIC: HF / HF+WFC	1843S	1937S	1846S 1946SE		1843S		1851*		1851	1826	1950	1834
n n HF						1500	1614		1497		1539	1533
n n HF+WFC										1498		
n γ HF							.48				.703	
n γ HF+WFC									.622	.94		
n nγ HF											1.36	
n nγ HF+WFC												
n p HF					17.3	18.7	39.3		22.9		22.59	
n p HF+WFC												
n α HF					2.2	6.63	5.78		7.88		8.08	

S = shape elastic

M = modified transmission coefficients $(t_{lj} = \Theta_{lj} - .25\Theta_{lj}\Theta^2_{lj})^{J\pi}$ are used according to Moldauer's theory

L = linear interpolation of spin cut-off in the intermediate continuum region

E = energy dependence of the nucleon radii in the neutron optical potential

Table 9 En = 8.0 MeV

Table 10 — En = 6 MeV

CODE(S) / USER / mb SIGMA	SCAT2 / BERSILLON	ABACUS2 E / DE OLIVEIRA	OPTICAL / PHILLIPS	NGROGI / HARIMA-KAWAI	EMPIRE * / HERMAN	HAUSER5 / GARG	ERINNI L / GRUPPELAAR	SASSI ECN L / GRUPPELAAR	IDA EL / REFFO	ABAREX / MOLDAUER
TOTAL	3635	3757	3639 3740E	3635			3635	3632	3734	3625
COMP.NUCL.	1594		1594 164CE	1594	1583	1737	1595	1593	1640	1595
ELASTIC: HF	2042S	2108S	2045S 2101SE	2042S			2068	2092	2123	2051
n n					1500	1643	1541	1514	1585	1573
n nn										
n np										
n nα										
n nαn										
n nnn										
n nnp										
n p				7.4	17.9	17.6	22.6		22.1	
n pn										
n pp										
n pγ										
n α				.21	1.29	.91	1.25		1.3	
n αn										
n γ					.83	.76	1.2	2.0	1.35 1.24	
n γn										
n γp										
n d										
n t										

S = shape elastic

L = linear interpolation of spin cut-off in the intermediate continuum region

E = energy dependence of the nucleon radii in the neutron optical potential

* $\sigma(n,\alpha) = \sigma(n,\alpha) + \sigma(n,\alpha n)$

Table 10 En = 6 MeV

Table 11 En = 8 MeV

CODE(S) USER / ED SIGMA	SCAT2 BERSILLON	ABACUS2 E DE OLIVEIRA	OPTICAL PHILLIPS	NGROGI HARIMA-KAWAI	EMPIRE * HERMAN	HAUSERS GARG	ERINNI L GRUPPELAAR	SASSI ECN L GRUPPELAAR	IDA EL REFFO	ABAREX HOLDAUER
TOTAL	3377	3509	3379 3520E	3377			3381	3355	3522	3367
COMP.NUCL.	1534		1533 1575E	1534	1529	1667	1535	1539	1577	1535
ELASTIC: PE	1843S	1937S	1846S 1946SE	1843S			1851	1826	1950	1834
n n					1500	1614	1497	1496	1539	1533
n nn										
n np										
n nα										
n nαn										
n nnn										
n nnp										
n p				17.3	18.7	39.3	22.9		22.6	
n pn										
n pp										
n pγ										
n α				2.2	6.63	5.8	7.8		8.1	
n αn										
n γ						.48	.62	.94	.7	
n γn										
n γp										
n d						.008				
n t										

S = shape elastic

L = linear interpolation of spin cut-off in the intermediate continuum region

E = energy dependence of the nucleon radii in the neutron optical potential

* $\sigma(n,\alpha) \equiv \sigma(n,\alpha) + \sigma(n,\alpha n)$

Table 11 En = 8 MeV

Table 12 En = 10 MeV

CODE(S) USER / ED SIGMA	SCAT2 BERSILLON	ABACUS2 E DE OLIVEIRA	OPTICAL PHILLIPS	NGROGI HARIMA-KAWAI	EMPIRE * HERMAN	HAUSERS GARG	ERINNI L GRUPPELAAR	SASSI ECN L GRUPPELAAR	IDA EL REFFO	ABAREX HOLDAUER
TOTAL	[illegible]	3240	3051 3219E	3051			3059	3050	3224	3044
COMP.NUCL.	1497		1495 1538E	1497	1495	1619	1498	1515	1541	1500
ELASTIC: HF	1554S	1695S	1557S 1680SE	1554S			1562	1537	1684	1545
n n							1450	1468	1504	
n nn				0			0		0	
n np				0.31						
n nα										
n nαn										
n nnn										
n nnp										
n p				24.9			23.5		25.2	
n pn				.013			.13			
n pp										
n pγ										
n α				5.5	7.86		8.6		9.1	
n αn										
n γ							.30	[illegible]	.32	
n γn									1.3	
n γp										
n d										
n t									0.	

S = shape elastic

L = linear interpolation of spin cut-off in the intermediate continuum region

E = energy dependence of the nucleon radii in the neutron optical potential

* $\sigma(n,\alpha) \equiv \sigma(n,\alpha) + \sigma(n,\alpha n)$

Table 12 En = 10 MeV

Table 13 En = 12 MeV

CODE(S) USER σb SIGMA	SCAT2 BERSILLON	ABACUS2 E DE OLIVEIRA	OPTICAL PHILLIPS	NORDGI HARIMA-KAWAI	EMPIRE * HERMAN	HAUSER5 GARG	ERINNI L GRUPPELAAR	SASSI ECN L GRUPPELAAR	IDA EL REFFO	ABAREX MOLDAUER
TOTAL	2759	2924	2760 2936E	2760			2767	2769	2942	2758
COMP.NUCL.	1463		1461 1511E	1463	1462	1573	1464	1483	1513	1467
ELASTIC: HF	1297S	1416S	1299S 1425SE	1297S			1305	1286	1430	1291
n n							904	930	890	
n nn				323			422	427	420	
n np				19			81		151	
n nα				.003			0		0	
n nαn										
n nnn										
n nnp										
n p				31.0			28.6		25	
n pn				3.7			6.2		9.6	
n pp							0.		0	
n pγ							0.		0	
n α				8.6	9.17		9.6		8.8	
n αn				.002			0		0	
n γ							.23	.29	.23	
n γn									.4	
n γp							0		0	
n d									.54	
n t									0.	

S = shape elastic

L = linear interpolation of spin cut-off in the intermediate continuum region

E = energy dependence of the nucleon radii in the neutron optical potential

* $\sigma(n,\alpha) \equiv \sigma(n,\alpha) + \sigma(n,\alpha n)$

Table 13 En = 12 MeV

Table 14 En = 14 MeV

CODE(S) USER σb SIGMA	SCAT2 BERSILLON	ABACUS2 E DE OLIVEIRA	OPTICAL PHILLIPS	NORDGI HARIMA-KAWAI	EMPIRE * HERMAN	HAUSER5 GARG	ERINNI L GRUPPELAAR	SASSI ECN L GRUPPELAAR	IDA EL REFFO	ABAREX MOLDAUER
TOTAL	2544	2727	2545 2713E	2544			2553	2546	2718	2547
COMP.NUCL.	1433		1432 1489E	1433	1432	1524	1434	1441	1489	1438
ELASTIC: HF	1111S	1234S	1113S 1224SE	1112S			1119	1105	1229	1109
n n							329	346	316	
n nn				933			977	971	1005	
n np				23.3			64		98	
n nα				.12			.01		1.45	
n nαn										
n nnn										
n nnp										
n p				24.0			23		17	
n pn				23.8			25		32.8	
n pp							0		0	
n pγ							0		0	
n α				11.4	11.7		11.7		11.3	
n αn				.44			.48		1.35	
n γ							.17	.52	0.134	
n γn									0.3	
n γp							0		0	
n d									.56	
n t									.08	

S = shape elastic

L = linear interpolation of spin cut-off in the intermediate continuum region

E = energy dependence of the nucleon radii in the neutron optical potential

* $\sigma(n,\alpha) \equiv \sigma(n,\alpha) + \sigma(n,\alpha n)$

Table 14 En = 14 MeV

Table 15 En = 16 MeV

CODE(S) USER mb SIGMA	SCAT2 BERSILLON	ABACUS2 E DE OLIVEIRA	OPTICAL PHILLIPS	NGROGI HARIMA-KAWAI	EMPIRE * HERMAN	HAUSER5 GARG	ERINNI L GRUPPELAAR	SASSI ECN L GRUPPELAAR	IDA EL REFFO	ABAREX MOLDAUER
TOTAL	2406	2580	2407 2549E	2406			2413	2404	2553	2411
COMP.NUCL.	1405		1405 1465E	1405	1404	1483	1406	1405	1465	1411
ELASTIC: HF	1001S	1106S	1002S 1083SE	1001S			1007	999	1088	1000
n n					111		118	112	108	
n nn				1115	1097		1131	1135	1165	
n np				58	116		76		90	
n nα				1.51			.51		11.1	
n nαn					8.2					
n nnn										
n nnp										
n p				11.7	7.9		13.3		8.1	
n pn				51.3	49.4		50		59	
n pp					.0001		0		0	
n pγ							0		0	
n α				10.3	14.9		10.1		9.4	
n αn				4.8			5.3		6.9	
n γ							.1	1.31	.057	
n γn									.24	
n γp									0	
n d									.64	
n t									.12	

S = shape elastic

L = linear interpolation of spin cut-off in the intermediate continuum region

E = energy dependence of the nucleon radii in the neutron optical potential

* $\sigma(n,\alpha) \equiv \sigma(n,\alpha) + \sigma(n,\alpha n)$

Table 15 En = 16 MeV

Table 16 En = 18 MeV

CODE(S) USER mb SIGMA	SCAT2 BERSILLON	ABACUS2 E DE OLIVEIRA	OPTICAL PHILLIPS	NGROGI HARIMA-KAWAI	EMPIRE * HERMAN	HAUSER5 GARG	ERINNI L GRUPPELAAR	SASSI ECN L GRUPPELAAR	IDA EL REFFO	ABAREX MOLDAUER
TOTAL	2329	2441	2328 2433E	2329			2333	2332	2438	2334
COMP.NUCL.	1375		1375 1436E	1375	1375	1441	1376	1375	1436	1384
ELASTIC: HF	953S	1005S	953S 997SE	953S			957	958	1002	951
n'n							39	35	37	
n nn				1134			1150	1153	1172	
n np				82.2			82		92	
n nα				6.1			3.3		21.6	
n nαn										
n nnn										
n nnp										
n p				4.6			6.0		2.9	
n pn				74.2			74		83	
n pp				.001			0		0	
n pγ				.01			0		0	
n α				5.8	10.1		5.4		4.4	
n αn							13.3		15.6	
n γ							.05	1.78	.01	
n γn									.2	
n γp									0	
n d									1.0	
n t									.13	

S = shape elastic

L = linear interpolation of spin cut-off in the intermediate continuum region

E = energy dependence of the nucleon radii in the neutron optical potential

* $\sigma(n,\alpha) \equiv \sigma(n,\alpha) + \sigma(n,\alpha n)$

Table 16 En = 18 MeV

Table 17

En = 20 MeV

CODE(S)	SCAT2	ABACUS2 E	OPTICAL	NGROGI	EMPIRE *	HAUSER5	ERINNI L	SASSI ECN L	IDA EL	ABAREX
USER	BERSILLON	DE OLIVEIRA	PHILLIPS	HARIMA-KAWAI	HERMAN	GARG	GRUPPELAAR	GRUPPELAAR	REFFO	MOLDAUER
mb SIGMA										
TOTAL	2300	2389	2299 2370E	2300			2301	2307	2372	2303
COMP.NUCL.	1345		1345 1409E	1345	1347	1399	1346	1344	1409	1357
ELASTIC: HF	954S	974S	954S 960SE	954S			955	963	963	946
n n							14.8	10.0	13.0	
n nn				1092			1107	1110	1128	
n np				101			94		103	
n nα				12.9			9.9		26.4	
n αn									.6	
n nnn				.93					16.6	
n nnp				.065					3.2	
n npn				.006					.21	
n p				1.97			2.4		1.0	
n pn				92.7			94		104	
n pp				.027			0		0.	
n pγ				.17			0		0.	
n α				2.6	20.9		2.3		1.6	
n αn				18.5			19.3		21.5	
n γ							.01	1.68	0.0	
n γn									.22	
n γp									0.	
n d										
n t										

S = shape elastic

L = linear interpolation of spin cut-off in the intermediate continuum region

E = energy dependence of the nucleon radii in the neutron optical potential

* $\sigma(n,\alpha) \equiv \sigma(n,\alpha) + \sigma(n,\alpha n)$

Table 17

En = 20 MeV

GRAPHS

Abbreviations used:

AX	(n,α) + (n,αn) cross section
TOT	total cross section
COM	compound nucleus cross section
SHE	shape elastic cross section
ELA	elastic cross section
N	total inelastic cross section
G	(n,γ)cross section
P	(n,p) cross section
A	(n,α) cross section
NN	(n,2n) cross section
NP	(n,np) cross section
NA	(n,nα) cross section
PN	(n,pn) cross section
PP	(n,2p) cross section
AN	(n,αn) cross section
HF or H	Hauser-Feshbach
WF or W	Hauser-Feshbach + width fluctuation correction
E	energy dependence option

Abbreviations for the computer codes:

ABA	ABACUS-2
ABN	ABACUS-NEARREX
ABX	ABAREX
CER	CERBERO-3
ELI	ELIESE-3, ELV=ELI run by Vasiliu
EMP	EMPIRE
ERI	ERINNI
HAU	HAUSER*5
IDA	IDA
NGR	NGROGI
OPT	OPTICAL
SAS	SASSI-ECN
SCA	SCAT-2

....	line drawn through cross section values for which an energy independent nucleon radius was used in the neutron optical potential
-------	line drawn through cross section values for which an energy dependent nucleon radius was used in the neutron optical potential

Fig. 1 Total Cross-section log-log

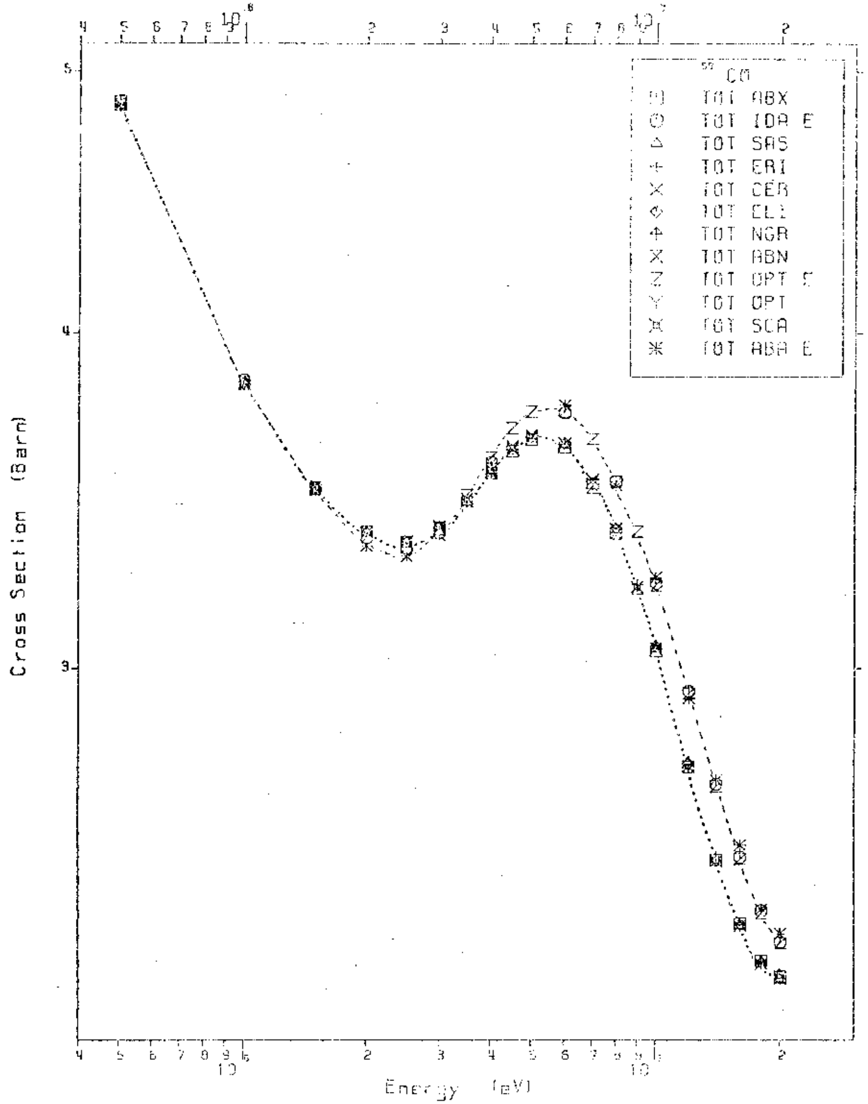


Fig. 2 Total Cross-section lin-lin

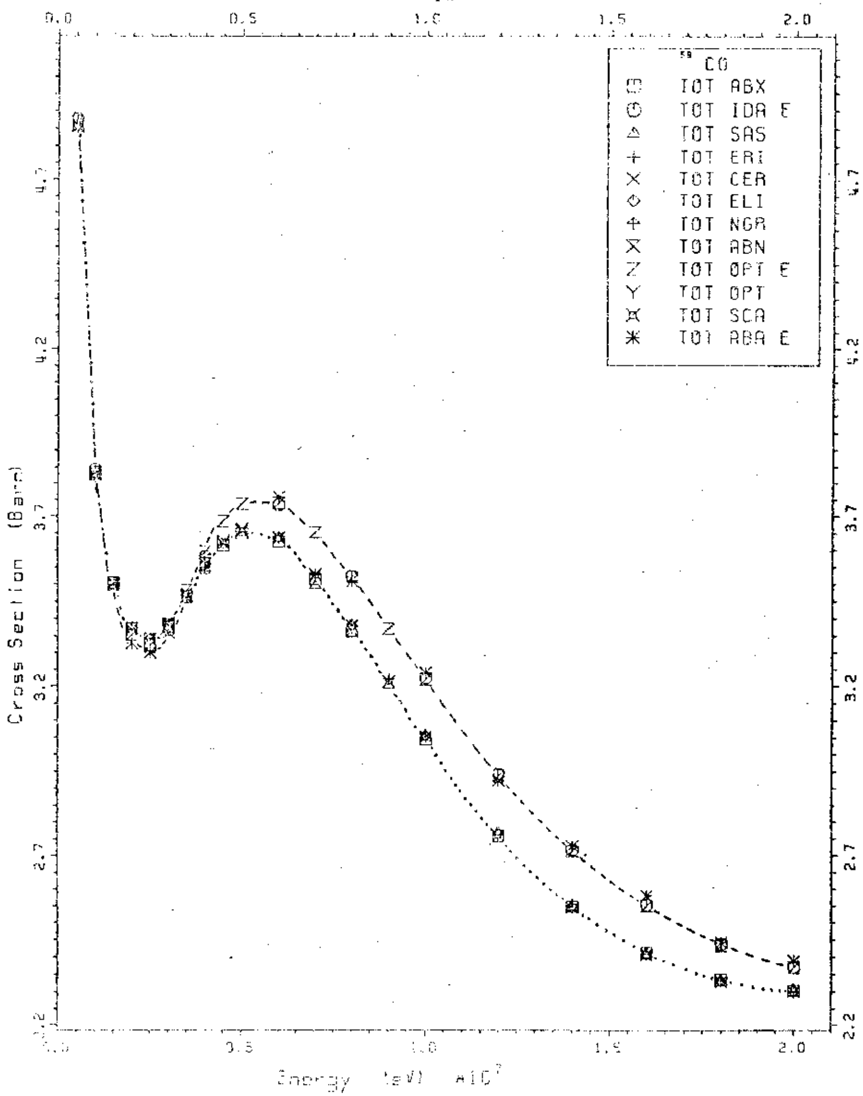


Fig. 3 Shape-elatic Cross-section log-log

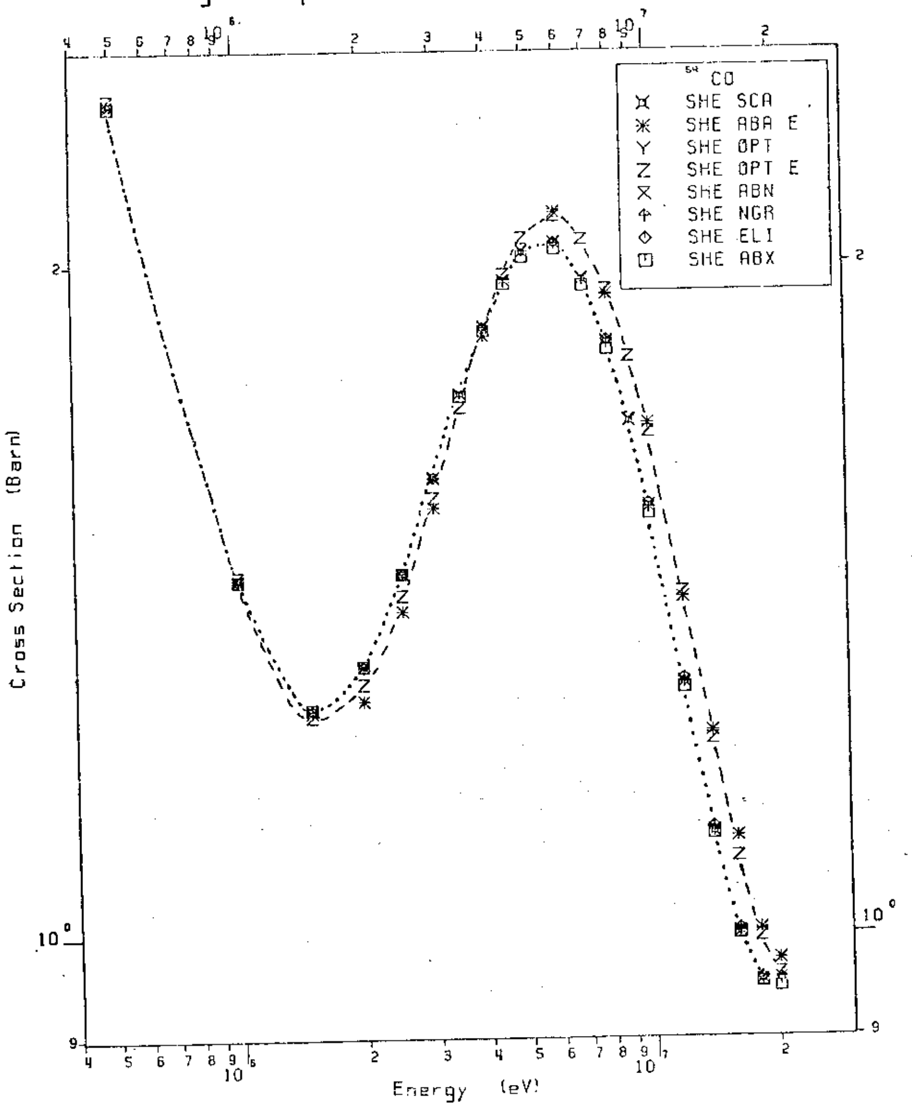


Fig. 4 Shape-elastic Cross-section lin-lin

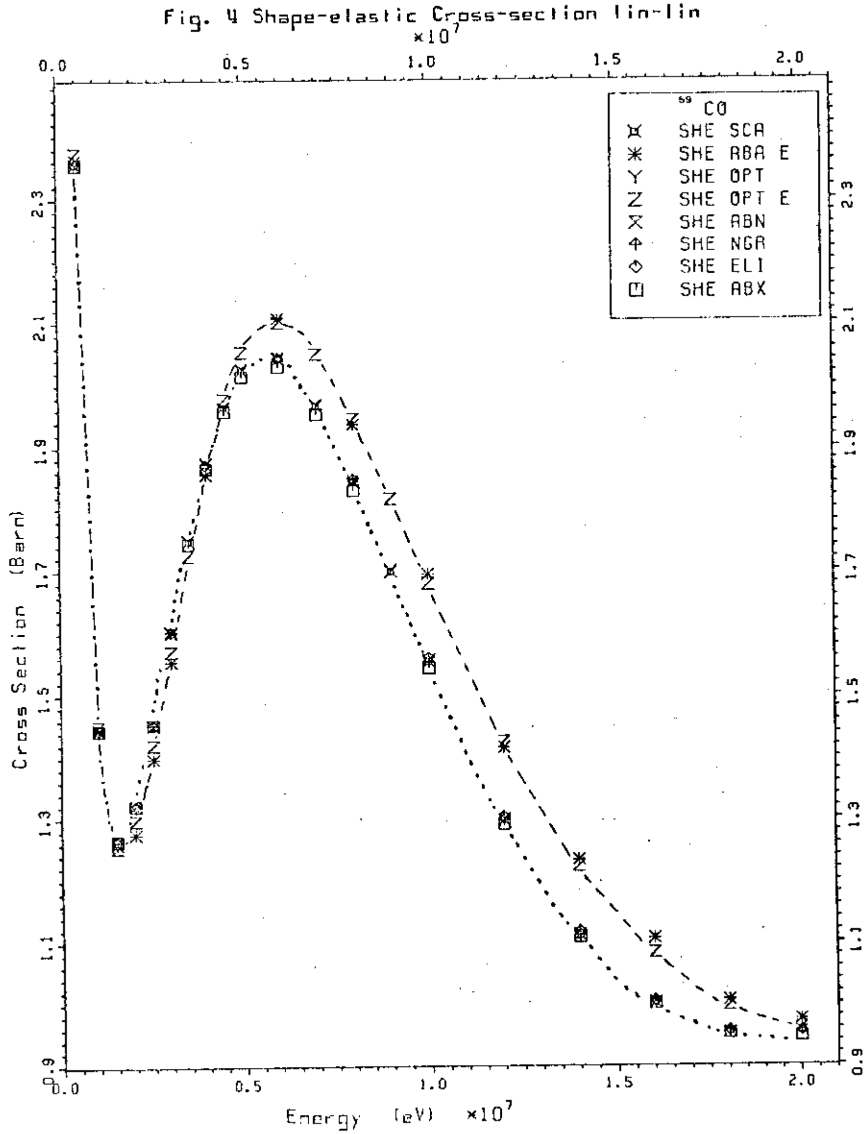


Fig. 5 Elastic Cross-section (HF) log-log

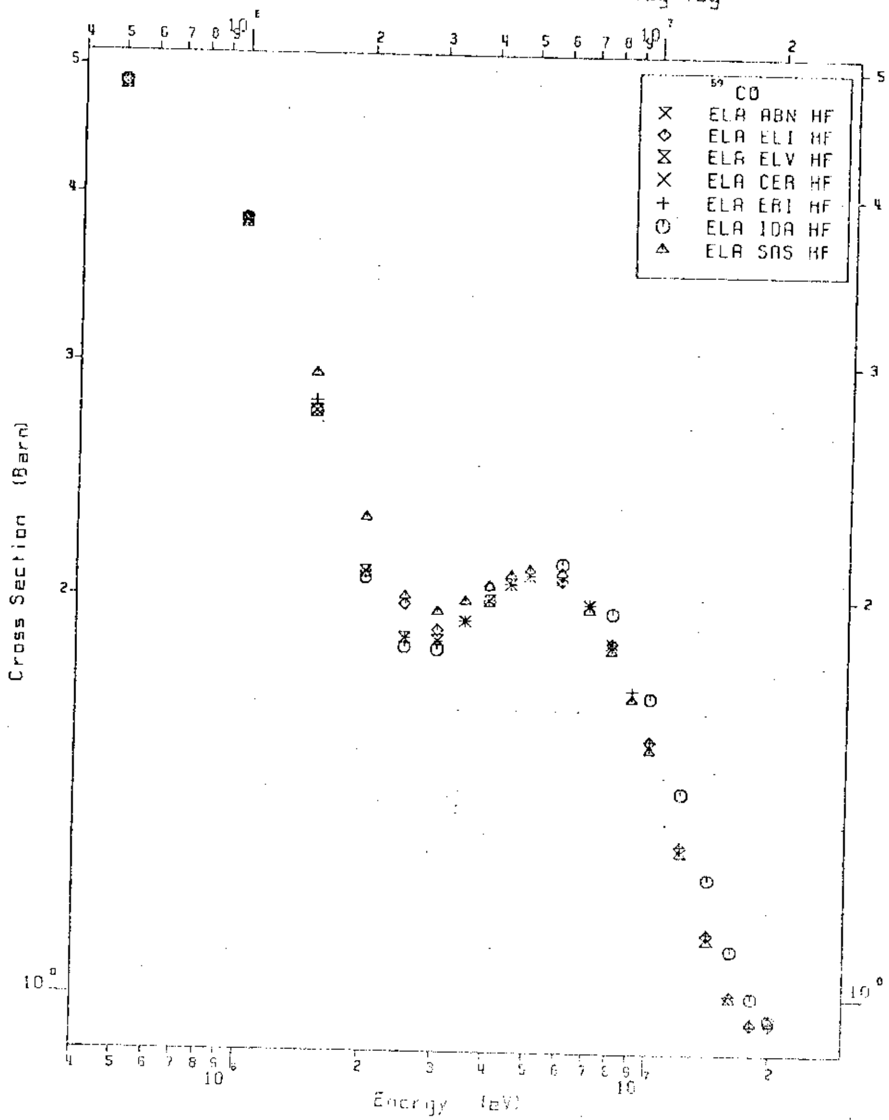


Fig. 6 Elastic Cross-section (HF) lin-lin

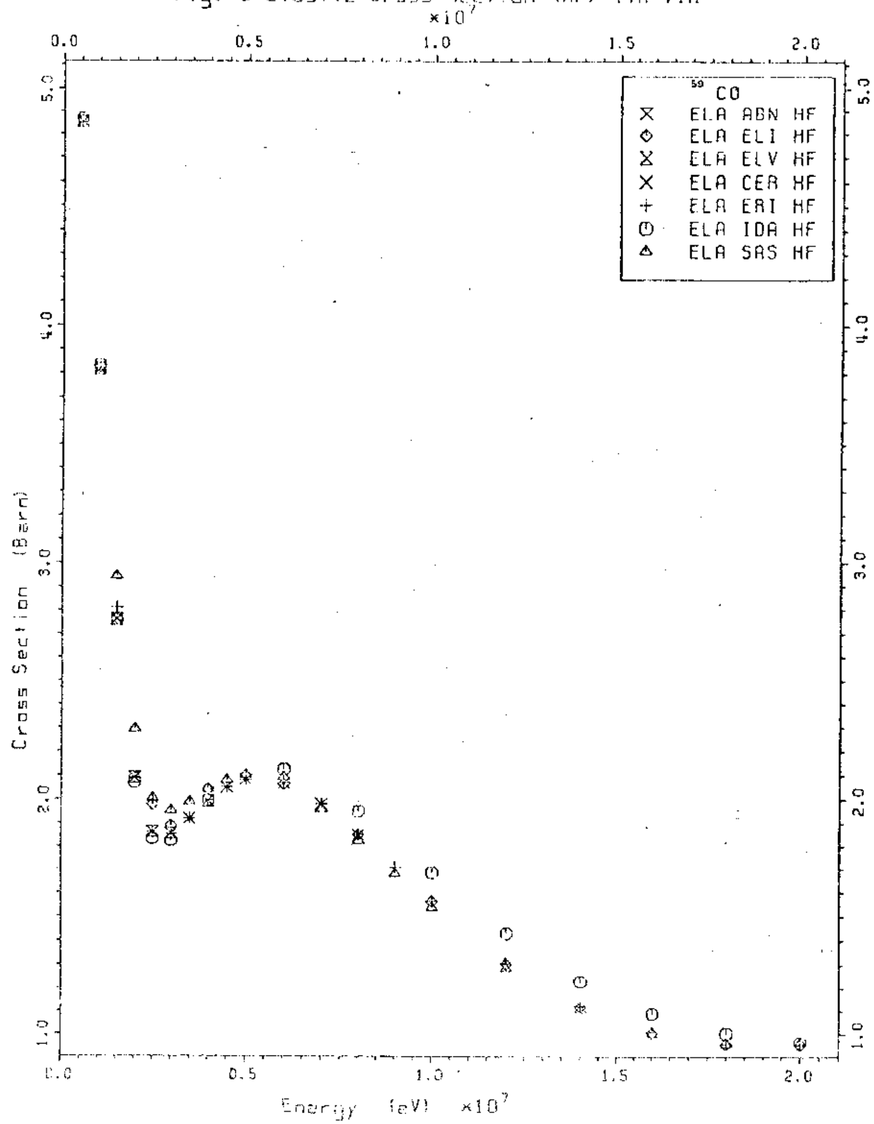


Fig. 7 Elastic Cross-section (WFC) log-log

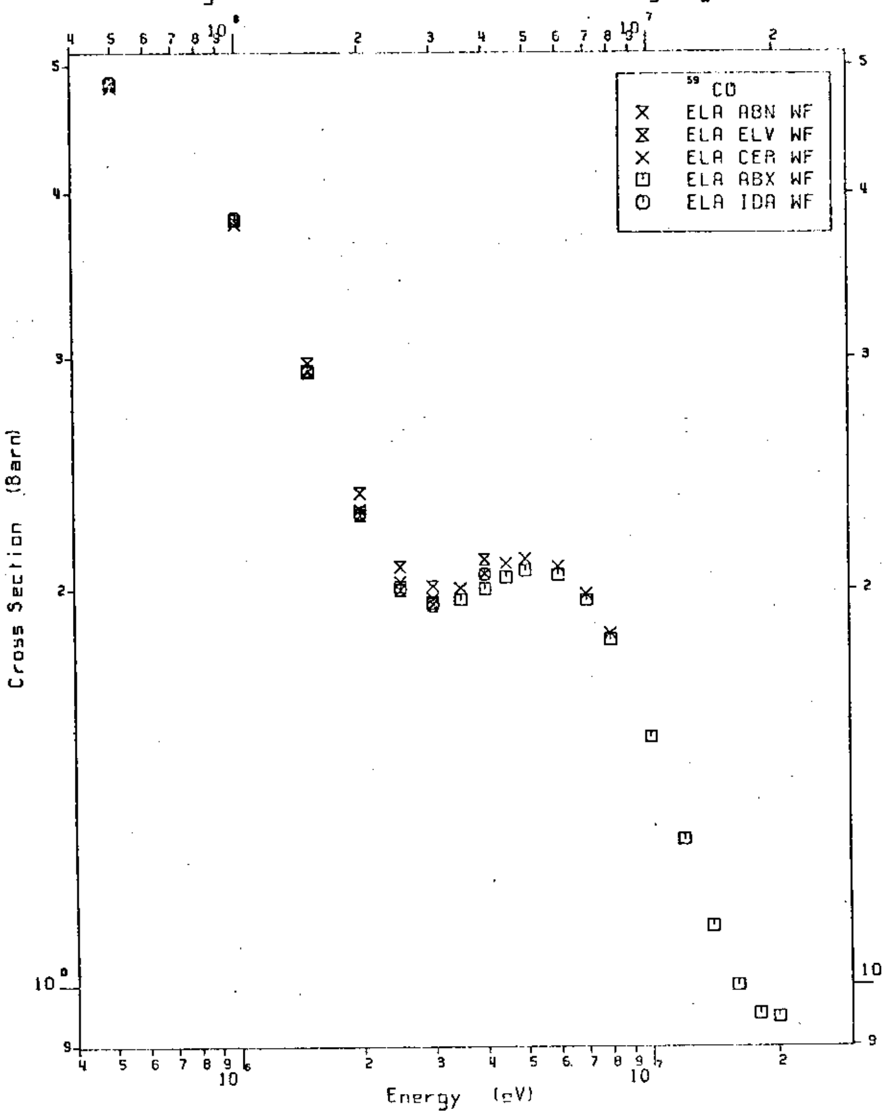


Fig. 8 Elastic Cross-section (WFC) lin-lin

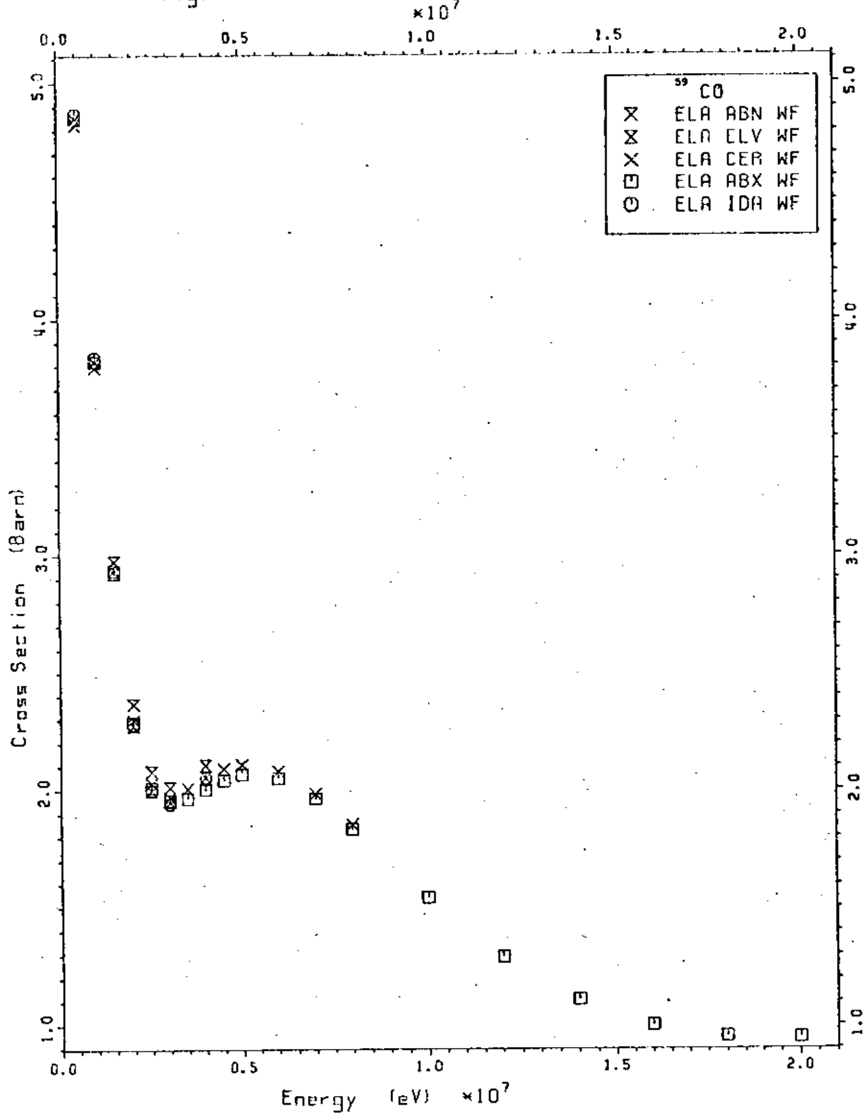


Fig. 9 Elastic Cross-section (HF&WFC) log-log

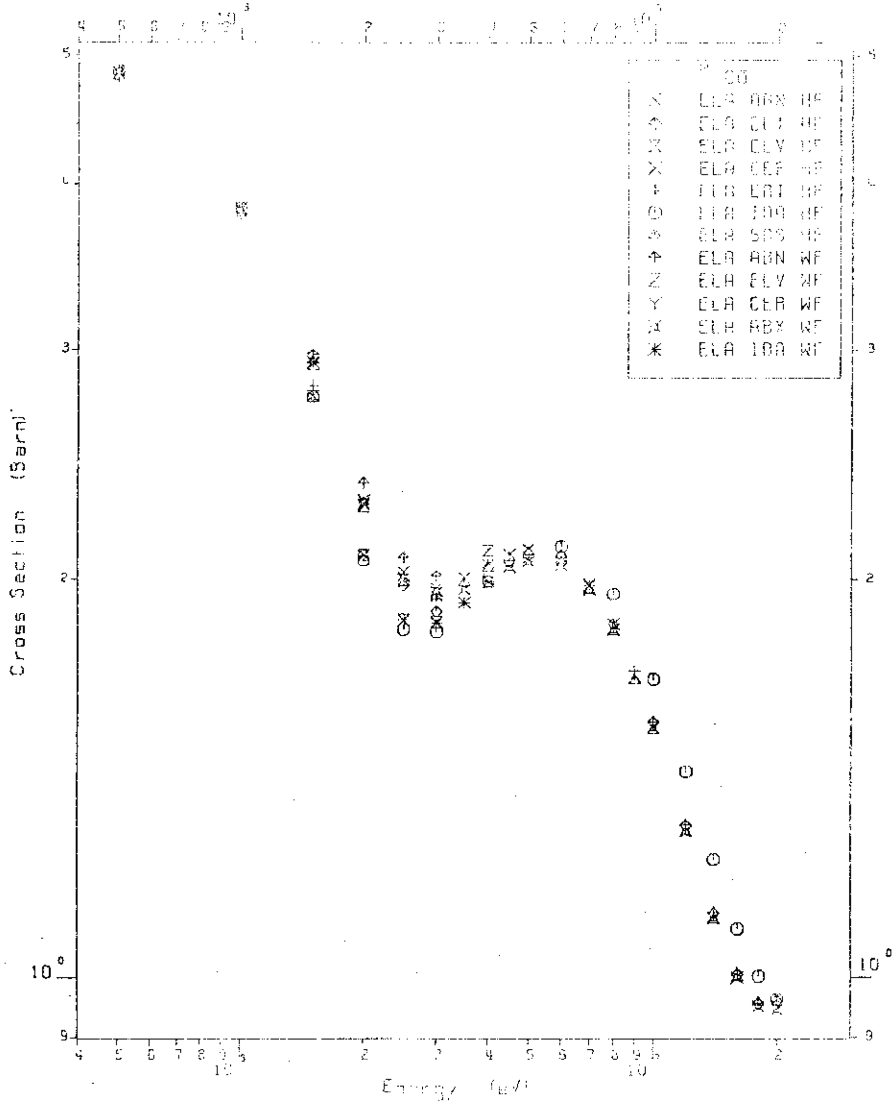


Fig. 10 Elastic Cross-section (HF&WFC) lin-lin

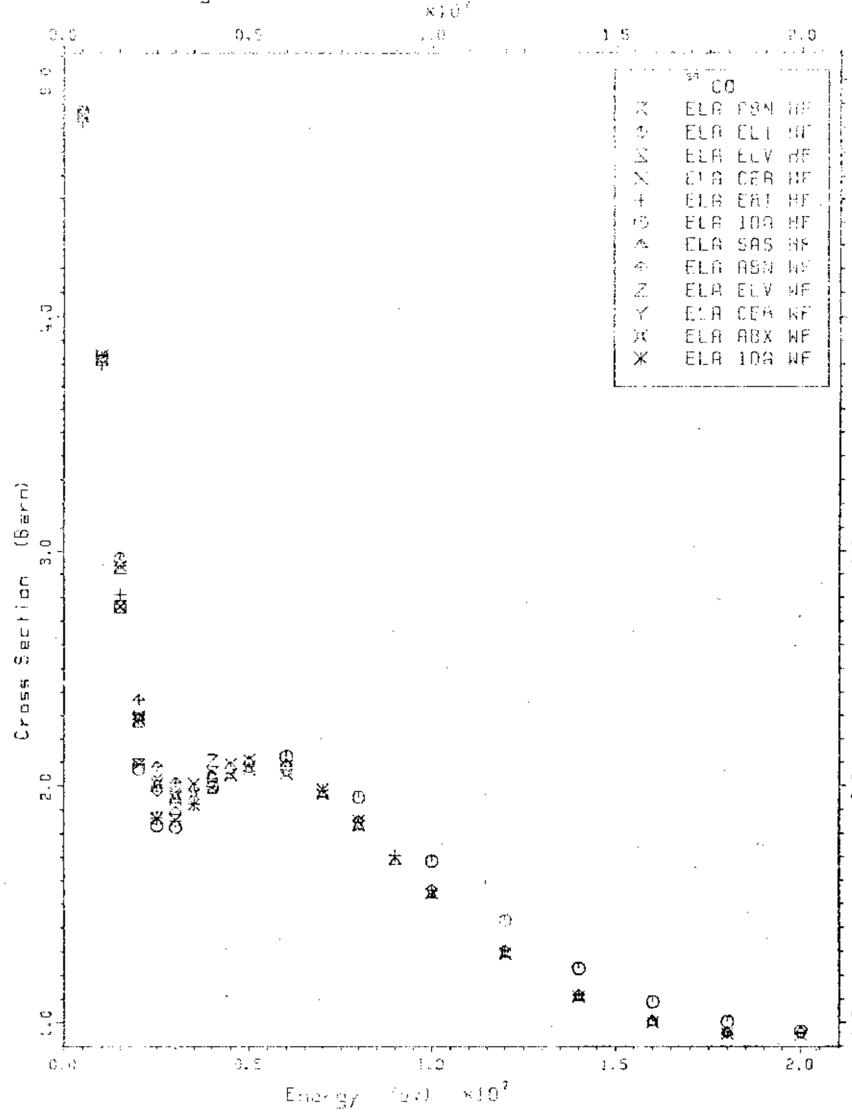


Fig. 11 Compound-nucleus Cross-section log-log

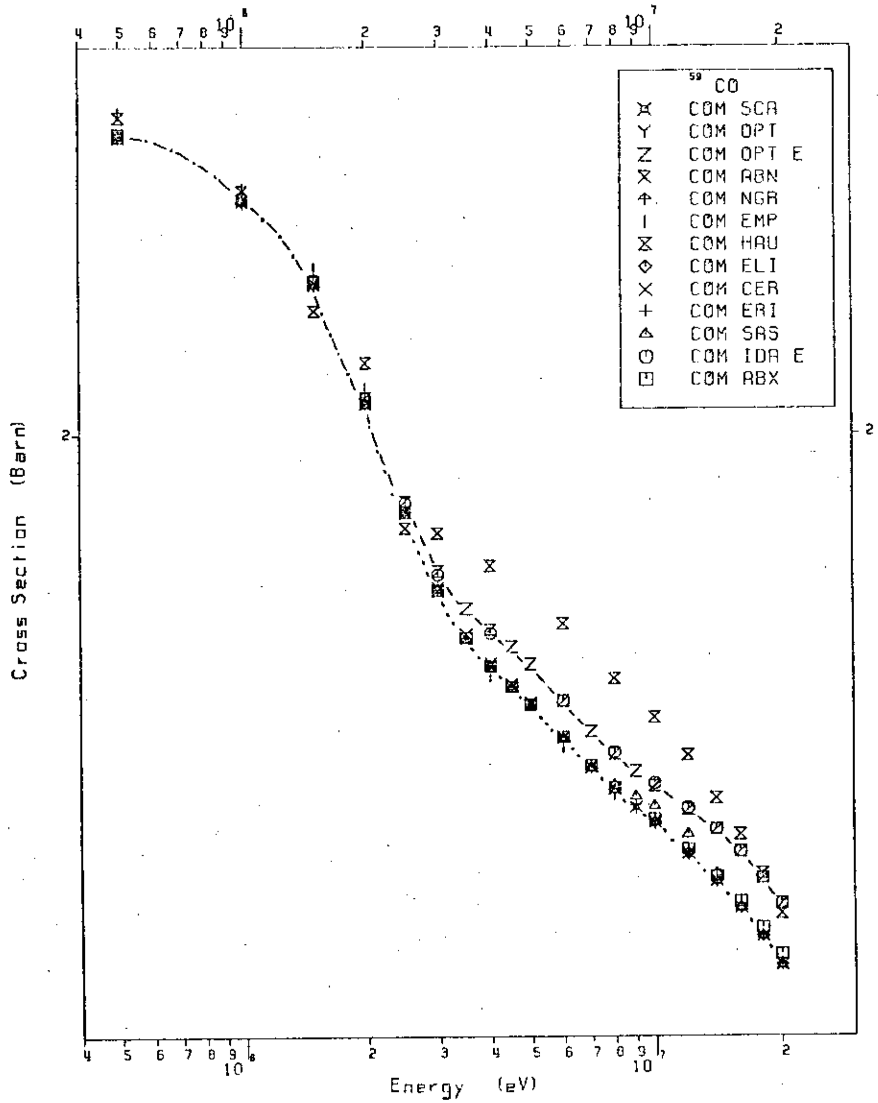


Fig. 12 Compound-nucleus Cross-section lin-lin

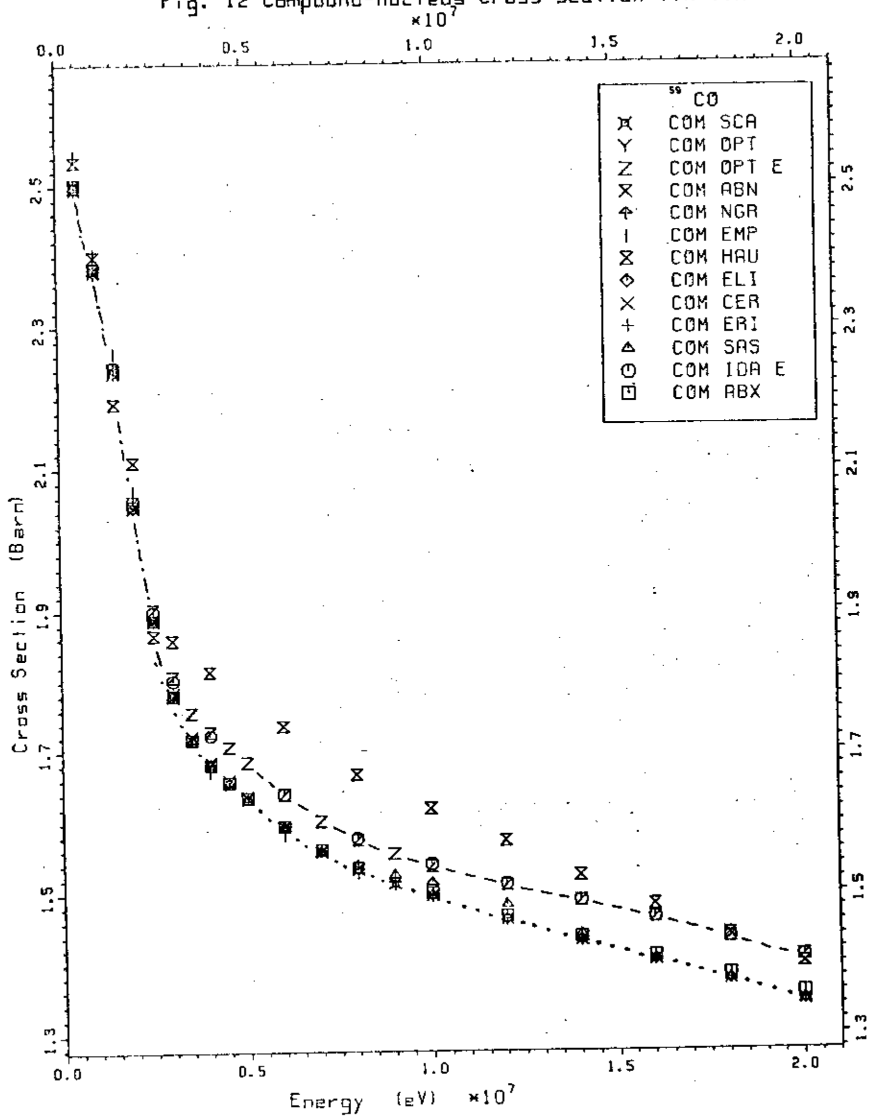


Fig. 13 Inelastic (n,n') Cross-section log-log

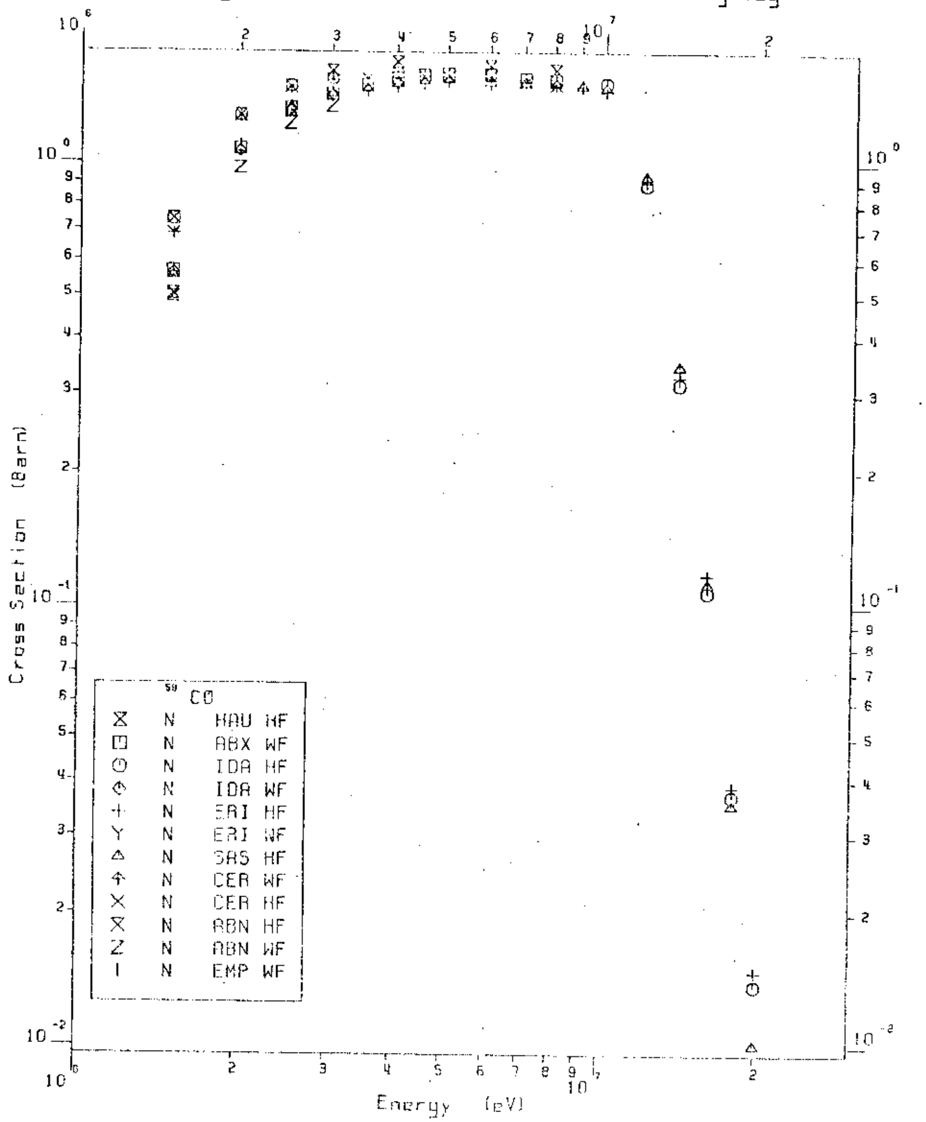
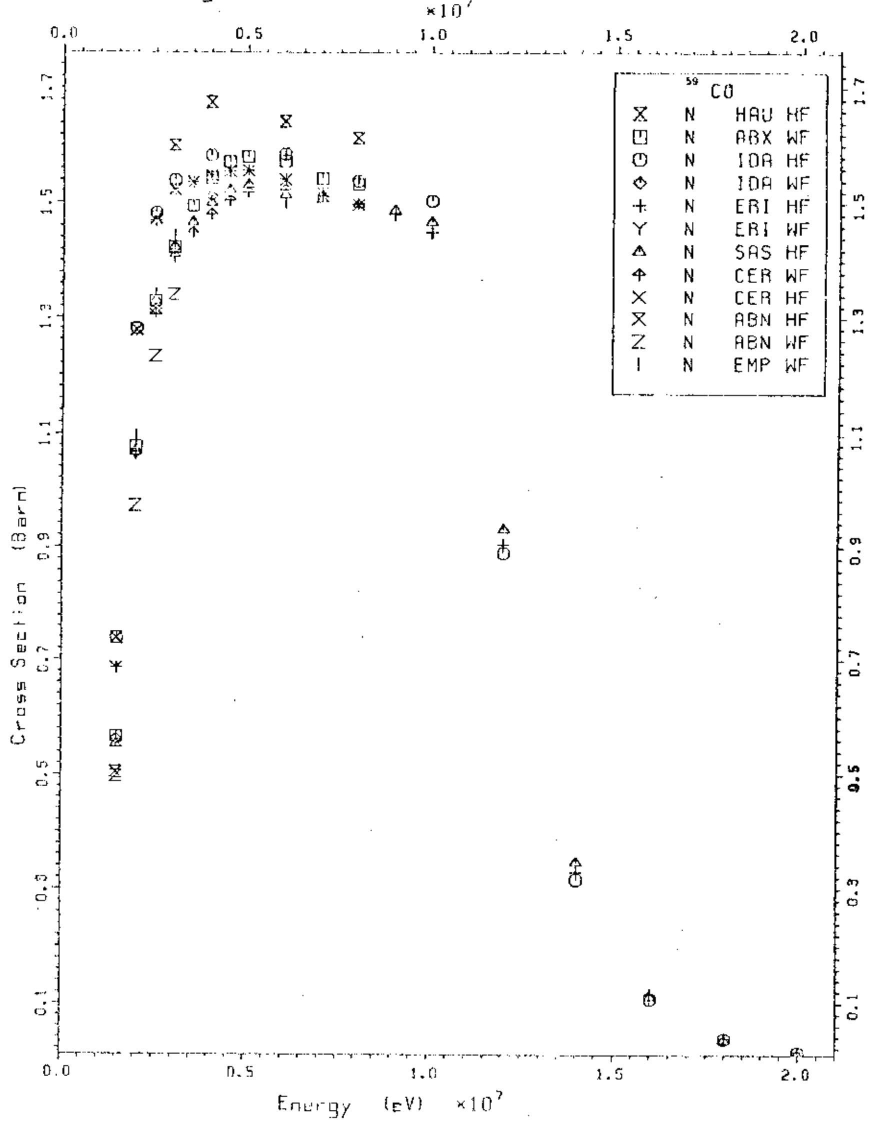


Fig. 14 Inelastic (n,n') Cross-section lin-lin



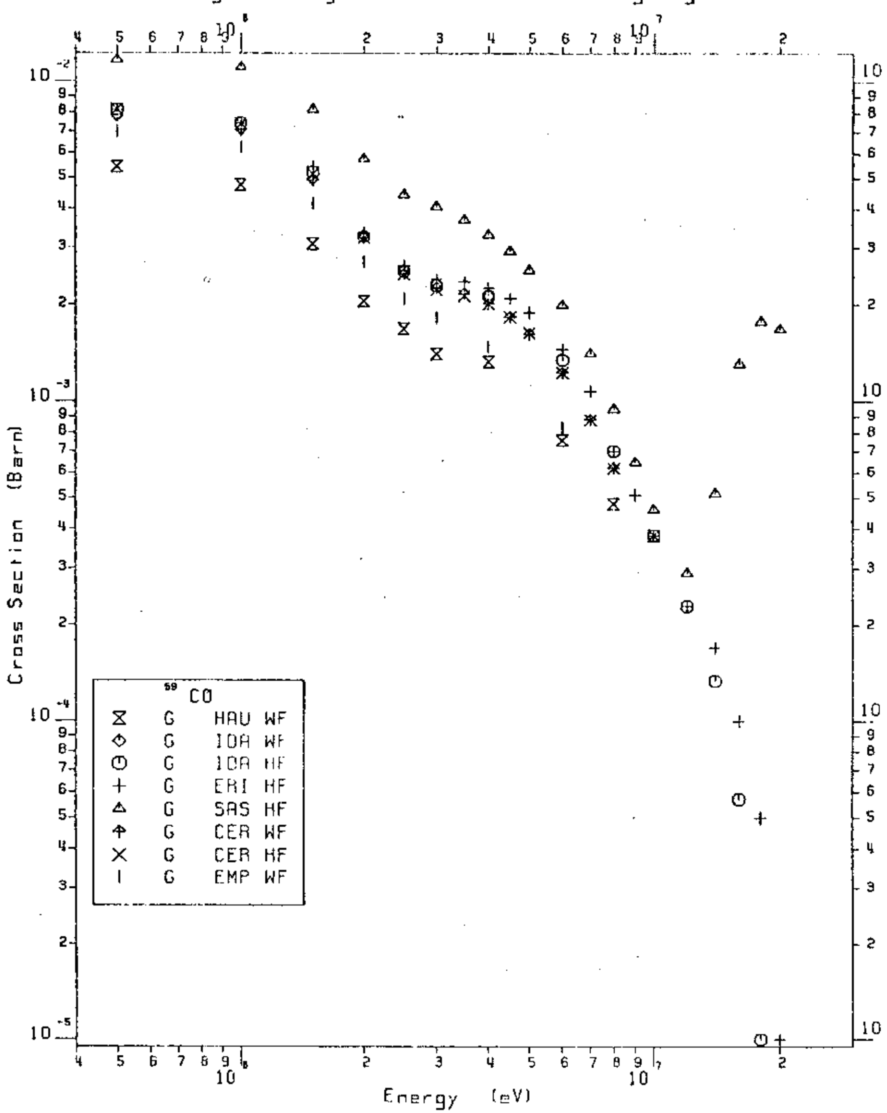


Fig. 15 (n,gamma) Cross-section log-log
Cross Section (Barn)
Energy (eV)
59 CO
G HAU WF
G IDA WF
G IDA HF
G ERI HF
G SAS HF
G CER WF
G CER HF
G EMP WF

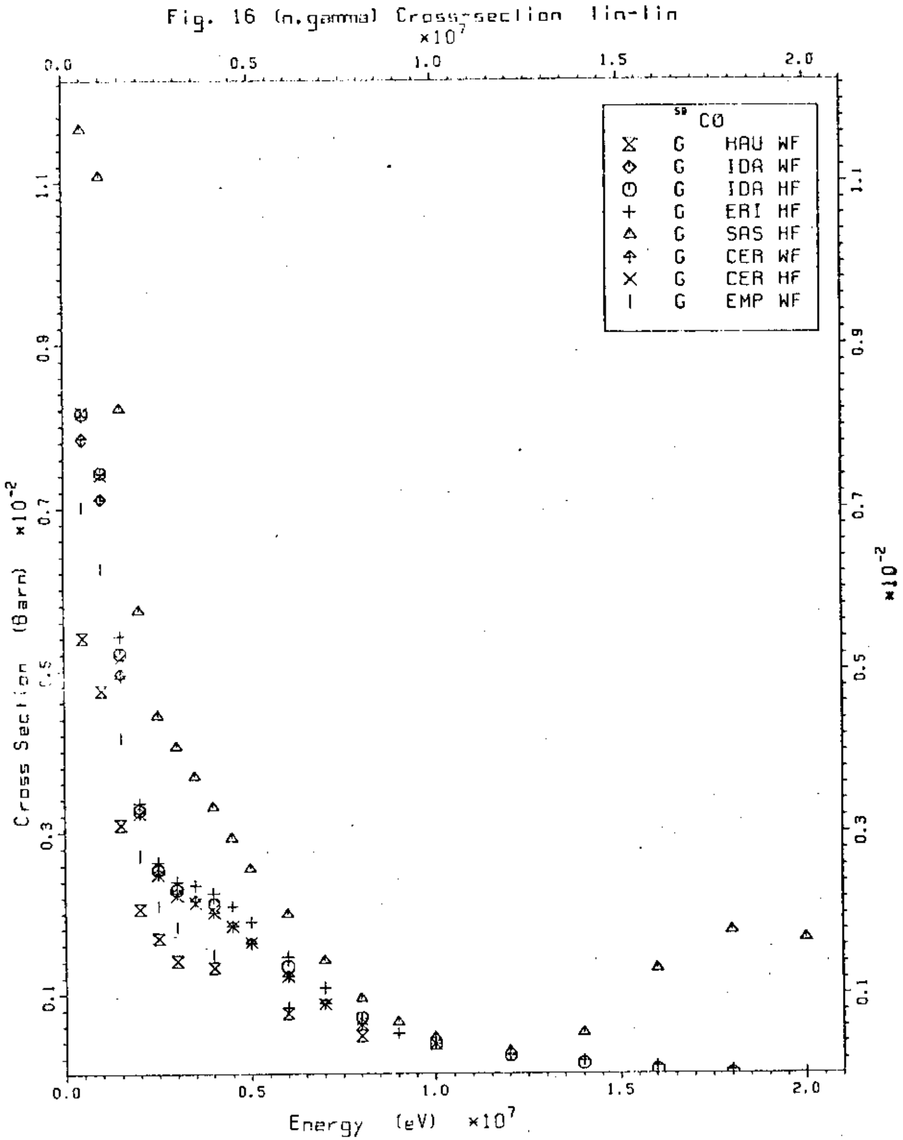


Fig. 16 (n,gamma) Cross-section lin-lin
Cross Section (Barn) ×10⁻²
Energy (eV) ×10⁷
59 CO
G HAU WF
G IDA WF
G IDA HF
G ERI HF
G SAS HF
G CER WF
G CER HF
G EMP WF

Fig. 17 (n,p) Cross-section log-log

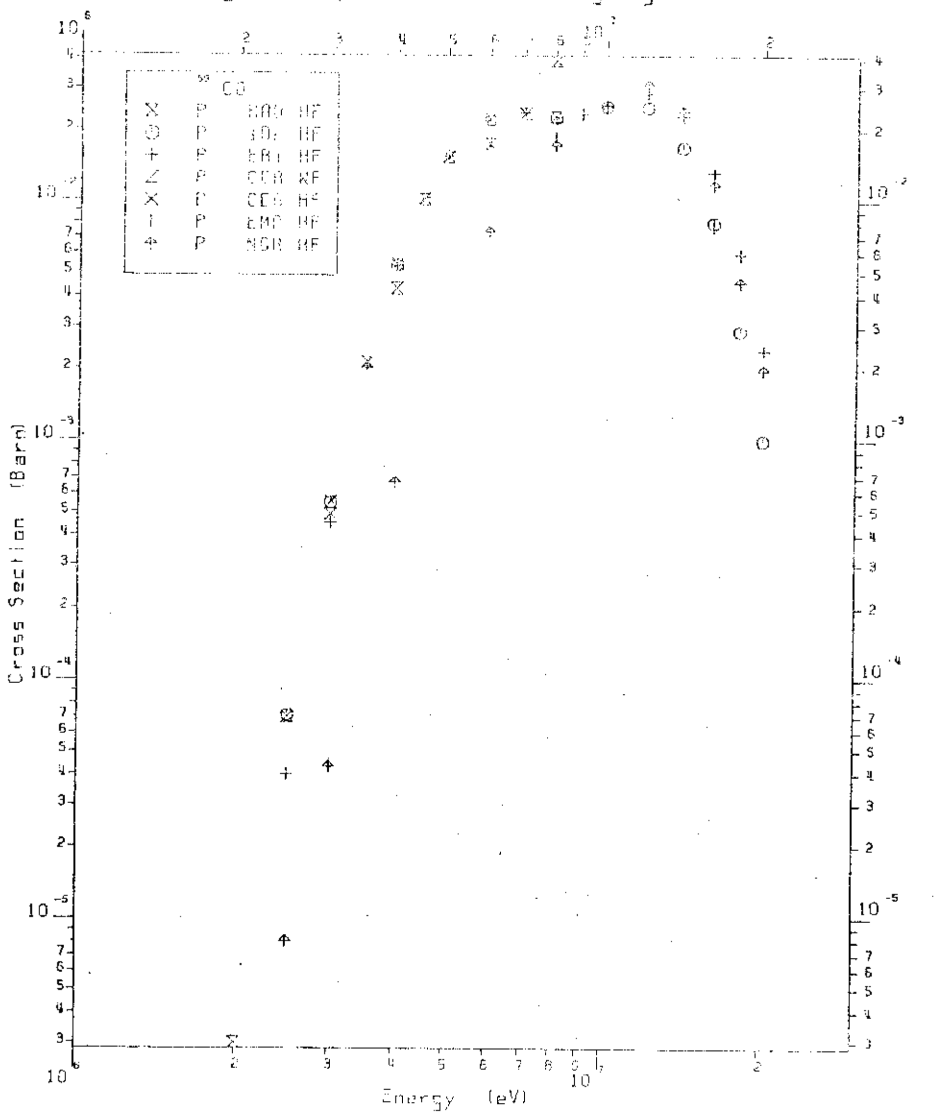
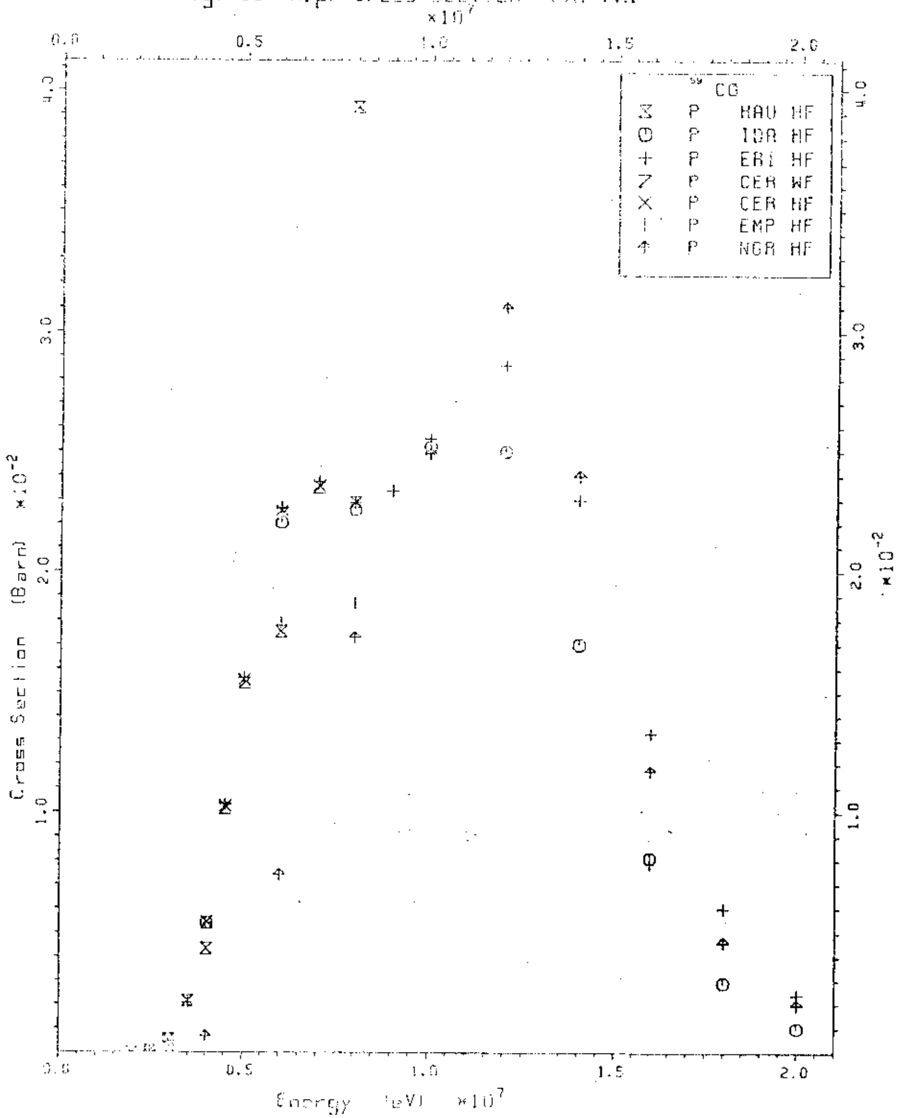


Fig. 18 (n,p) Cross-section lin-lin



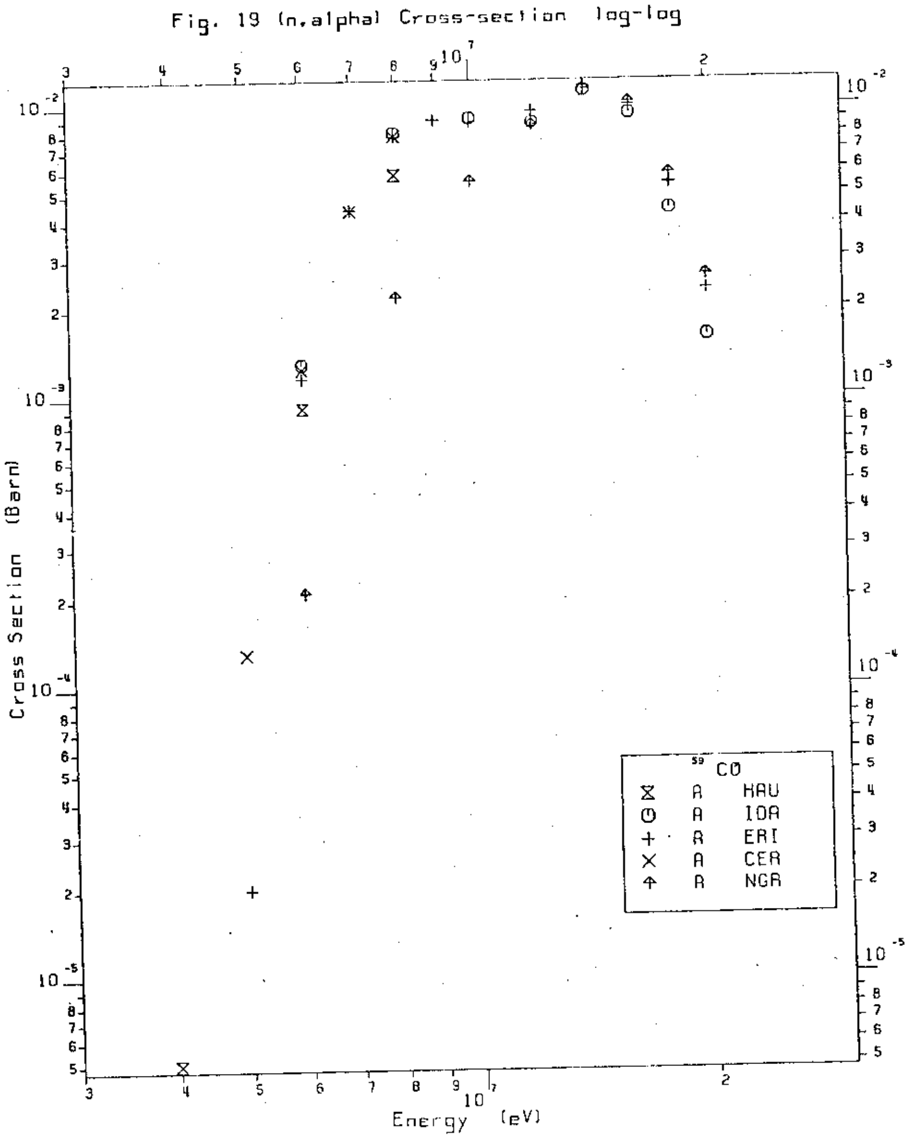


Fig. 19 (n,alpha) Cross-section log-log
Cross Section (Barn)
Energy (eV)
59 CO
A HAU
A IDA
A ERI
A CER
A NGR

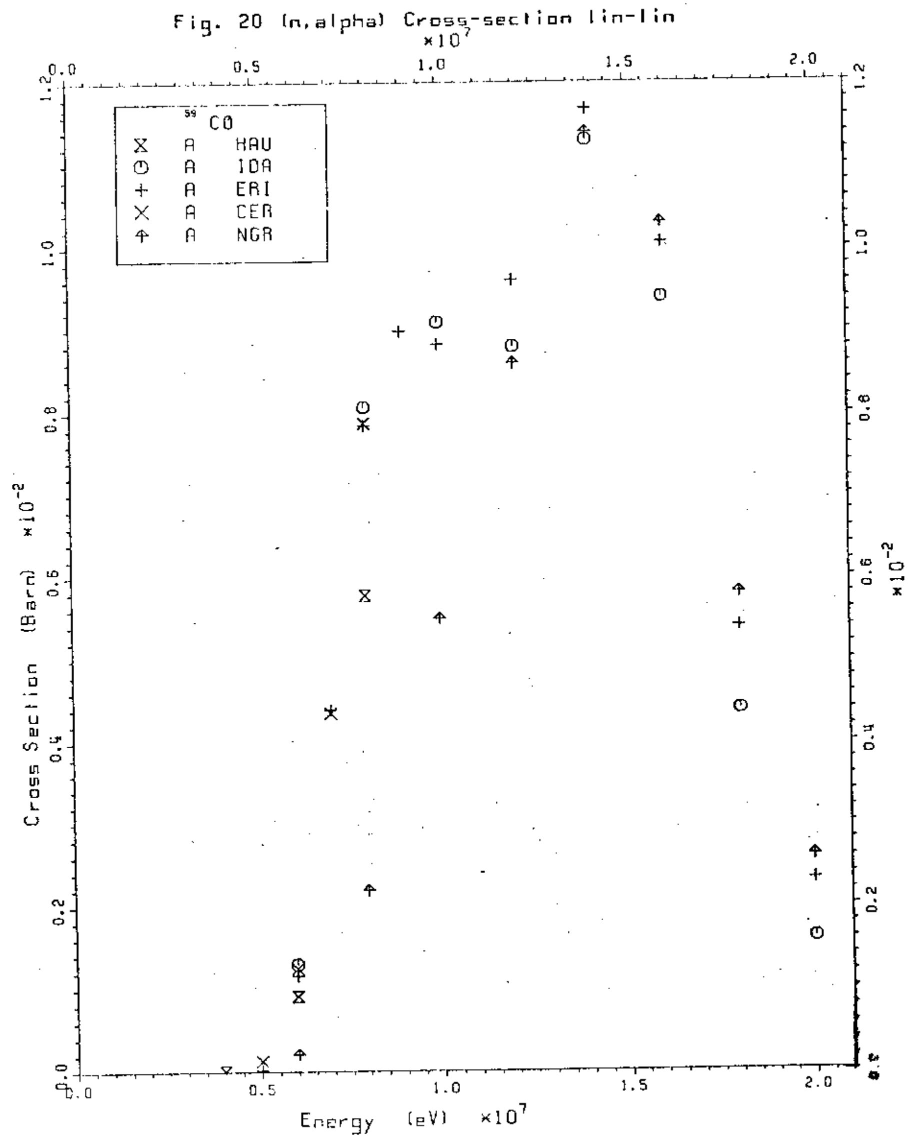


Fig. 20 (n,alpha) Cross-section lin-lin
Cross Section (Barn) ×10⁻²
Energy (eV) ×10⁷
59 CO
A HAU
A IDA
A ERI
A CER
A NGR

Fig. 21 (n,alpha n) Cross-section log-log

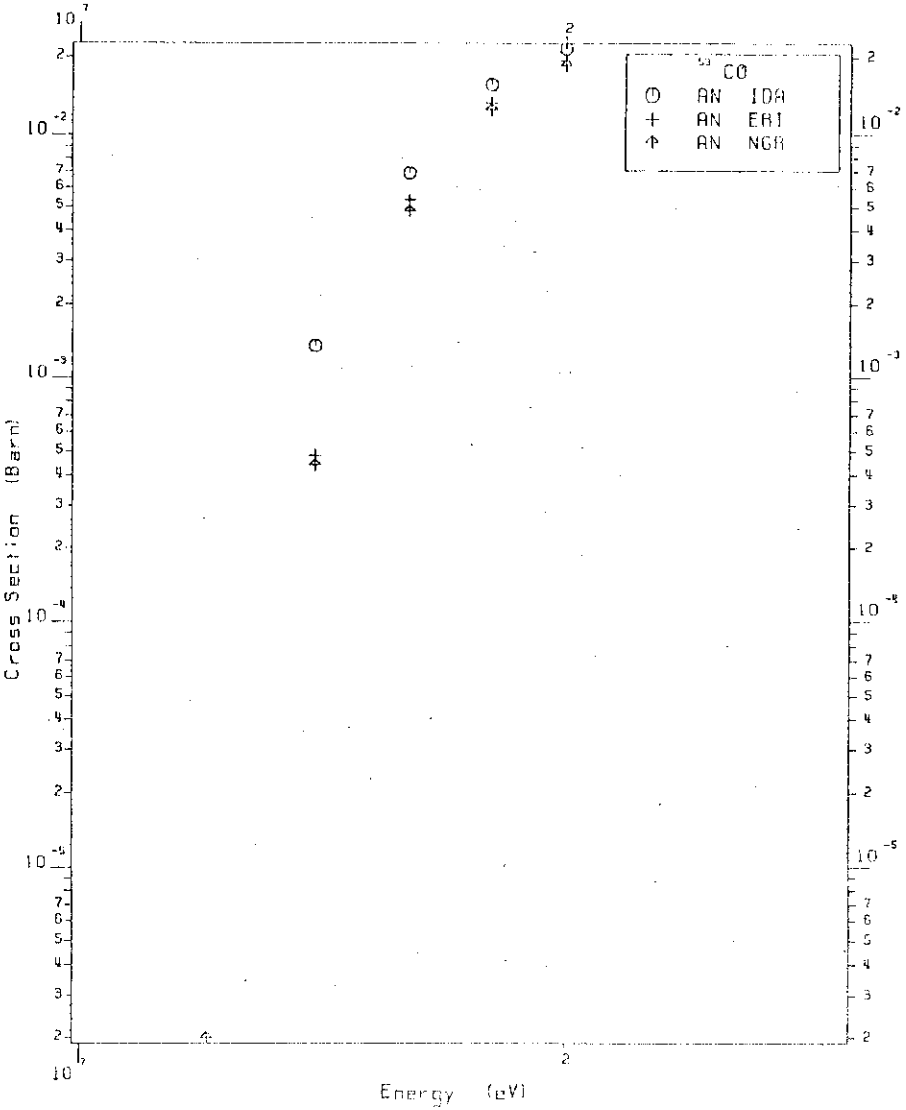


Fig. 22 (n,alpha n) Cross-section lin-lin

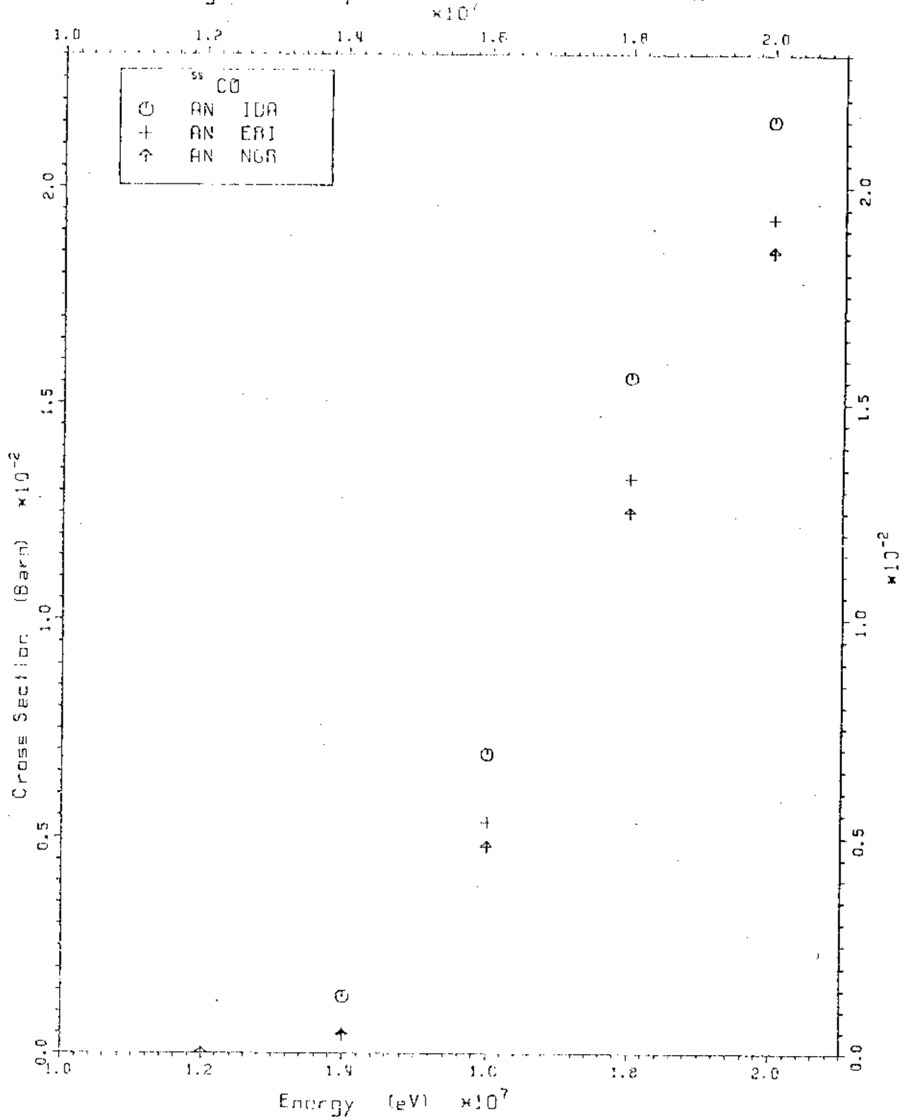


Fig. 23 (n,alpha)+(n,alpha n) Cross-section log-log

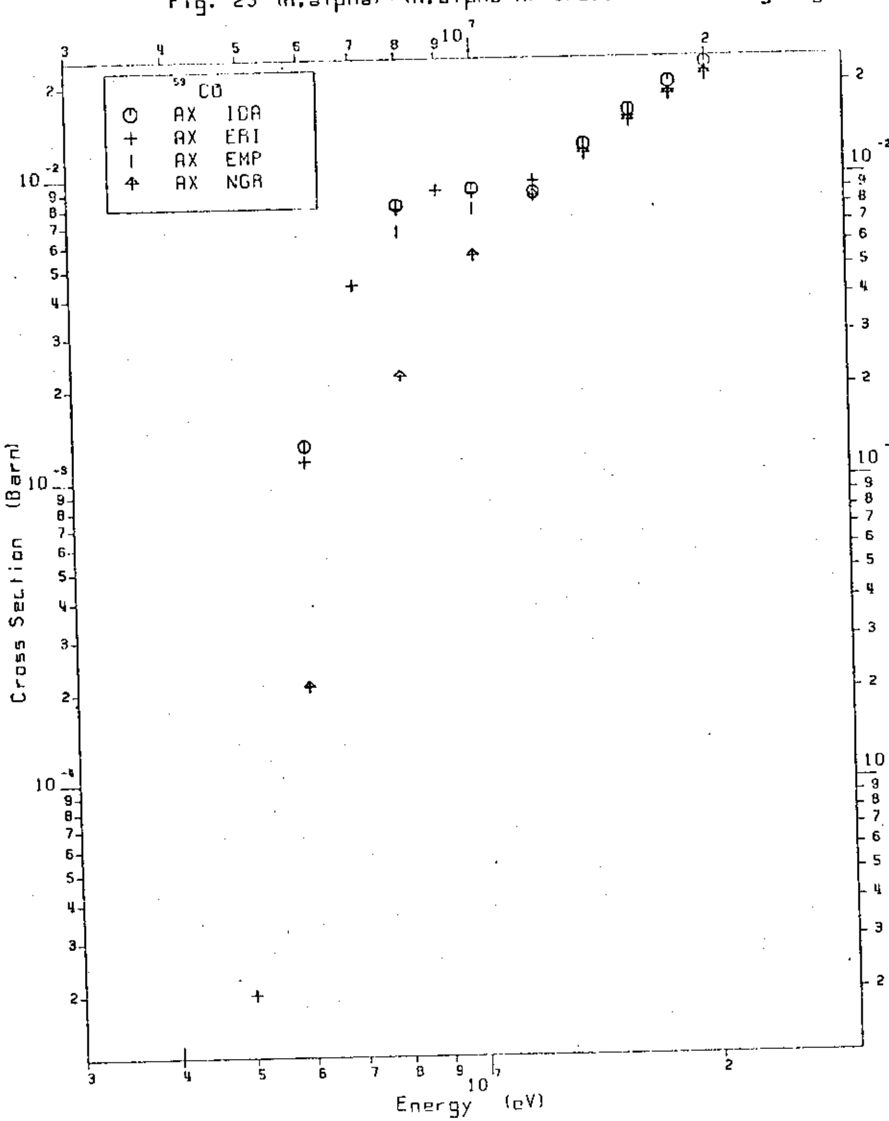


Fig. 24 (n,alpha)+(n,alpha n) Cross-section lin-lin

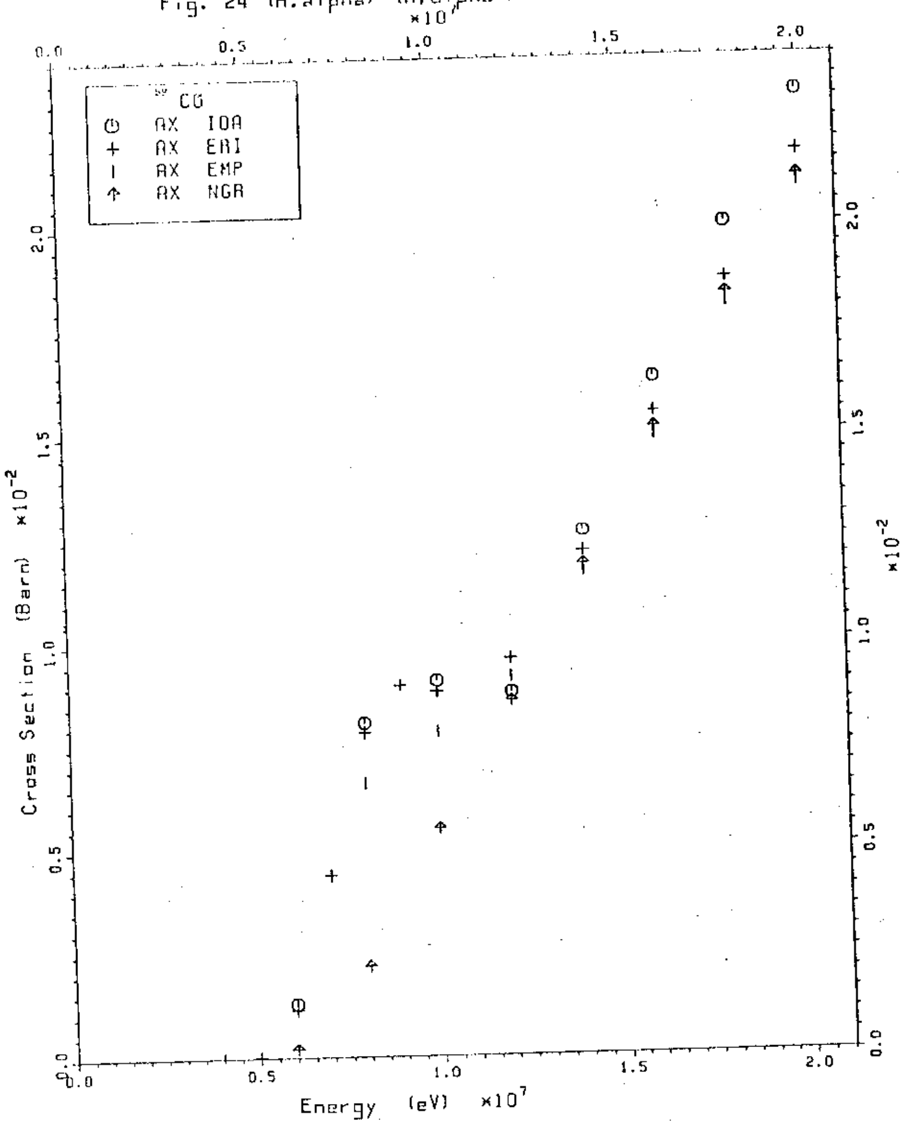


Fig. 25 (n,nn) Crosssection log-log

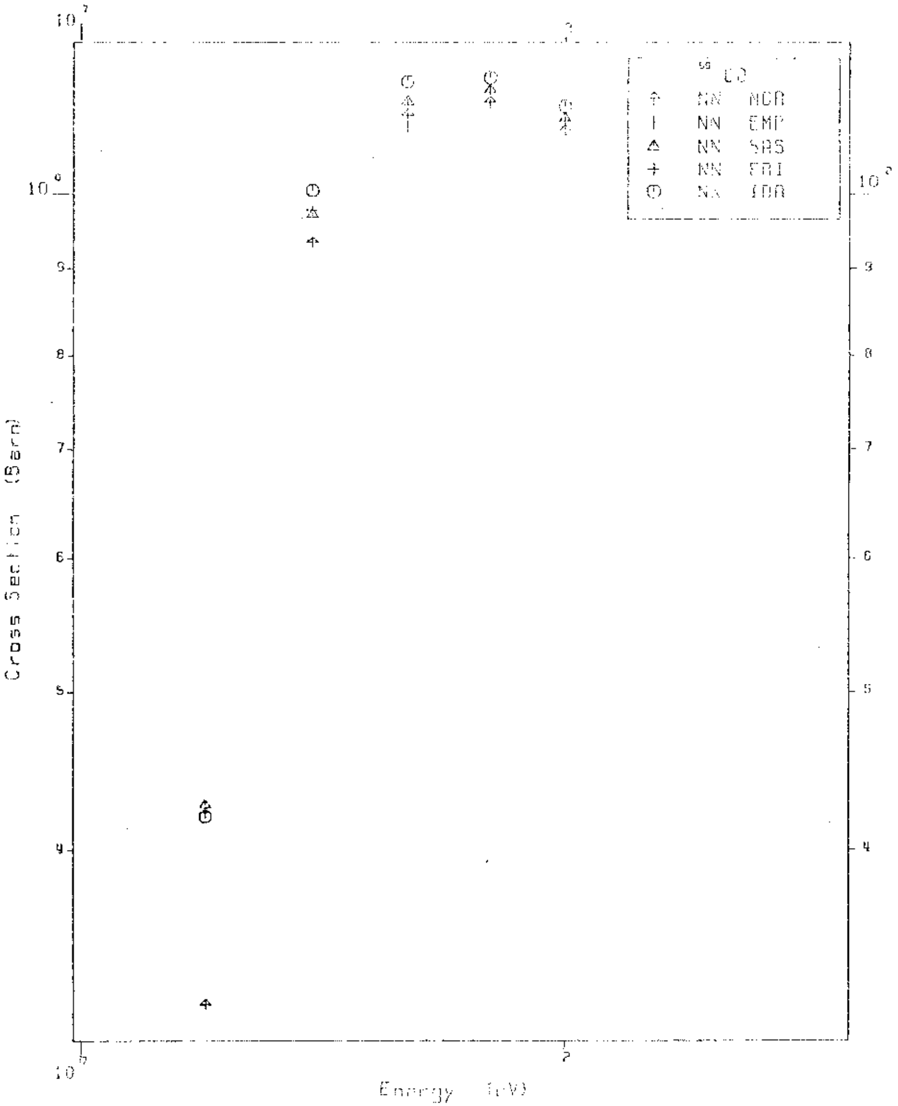


Fig. 25 (n,nn) Cross-section lin-lin

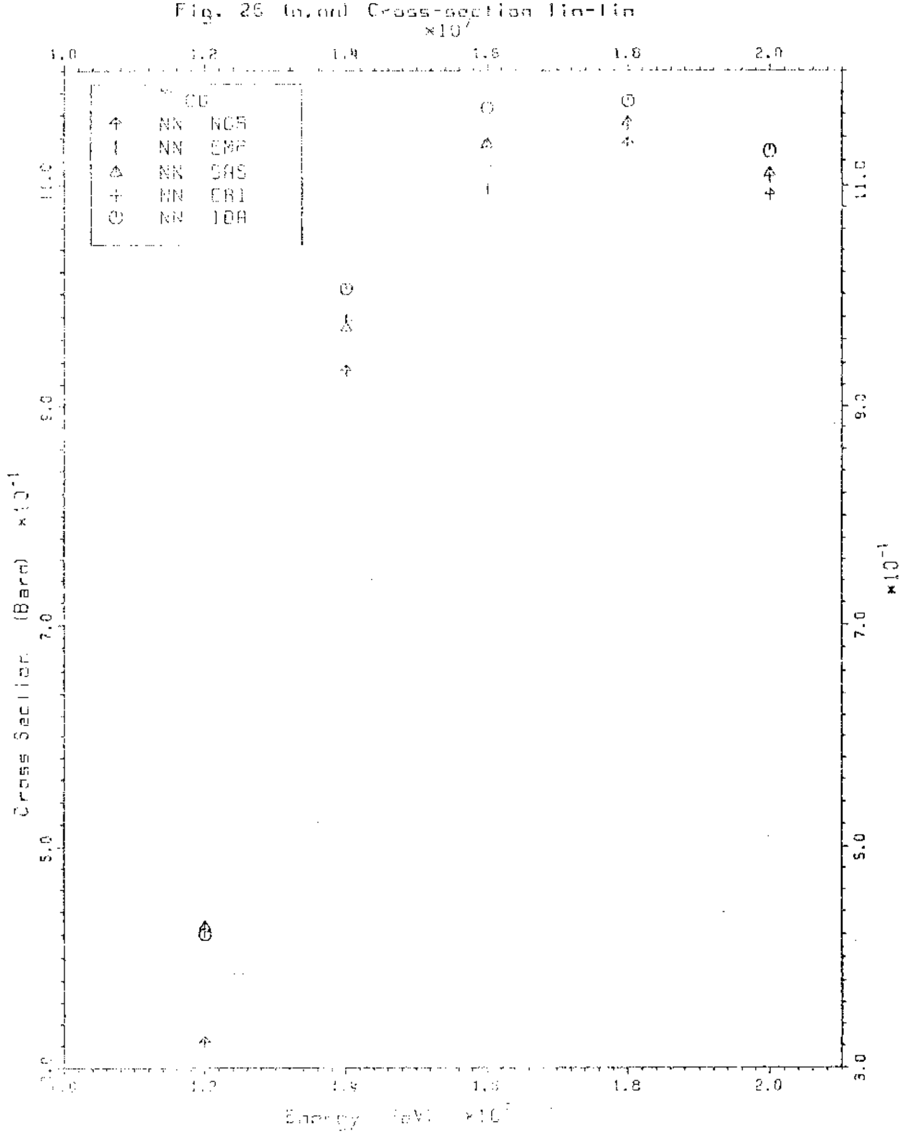


Fig. 27 (n,np) Cross-section log-log

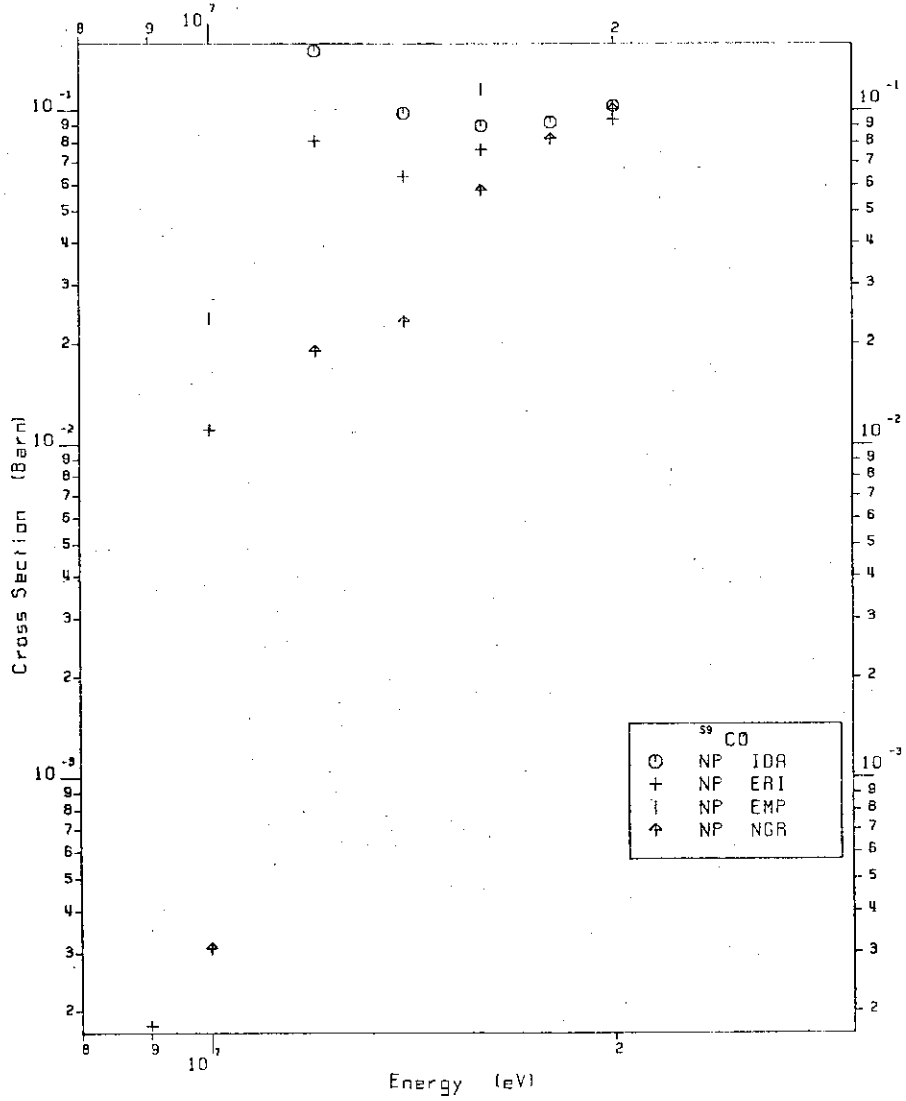


Fig. 28 (n,np) Cross-section lin-lin

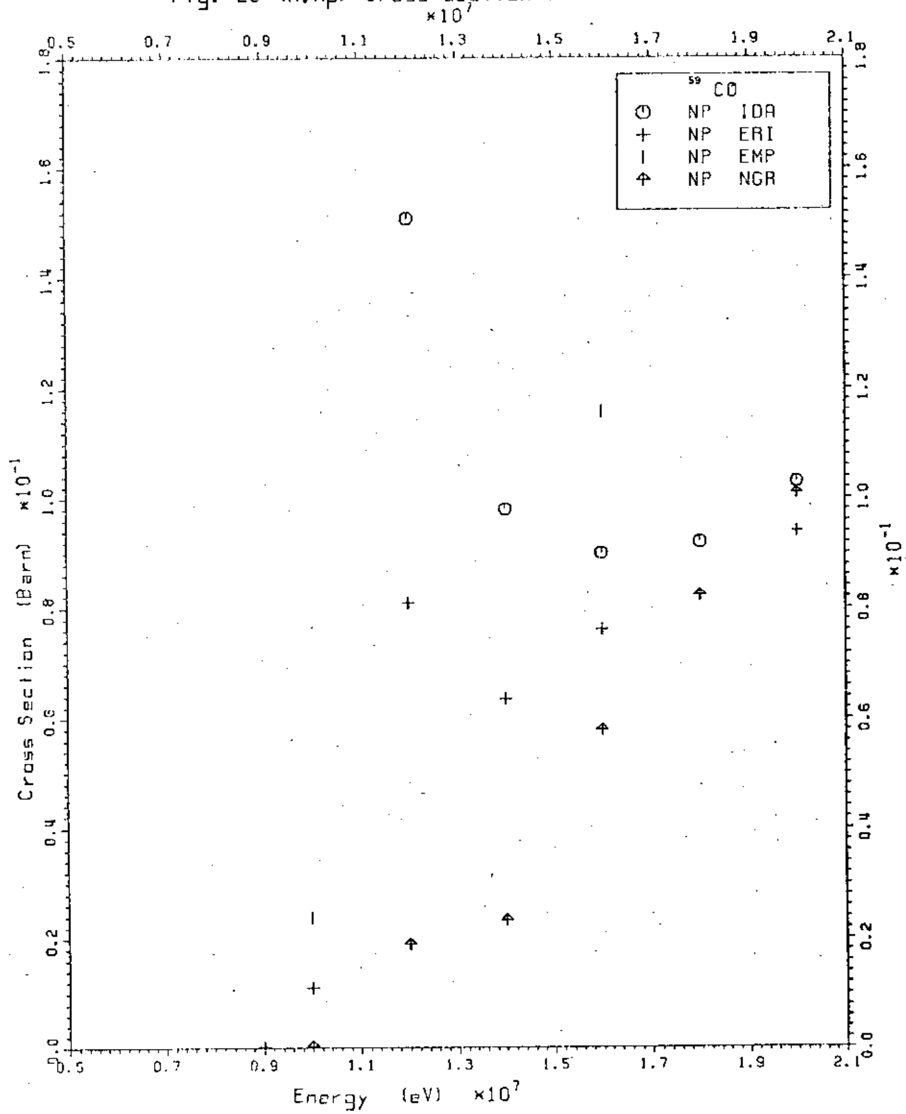


Fig. 29 (n,n alpha) Cross-section log-log

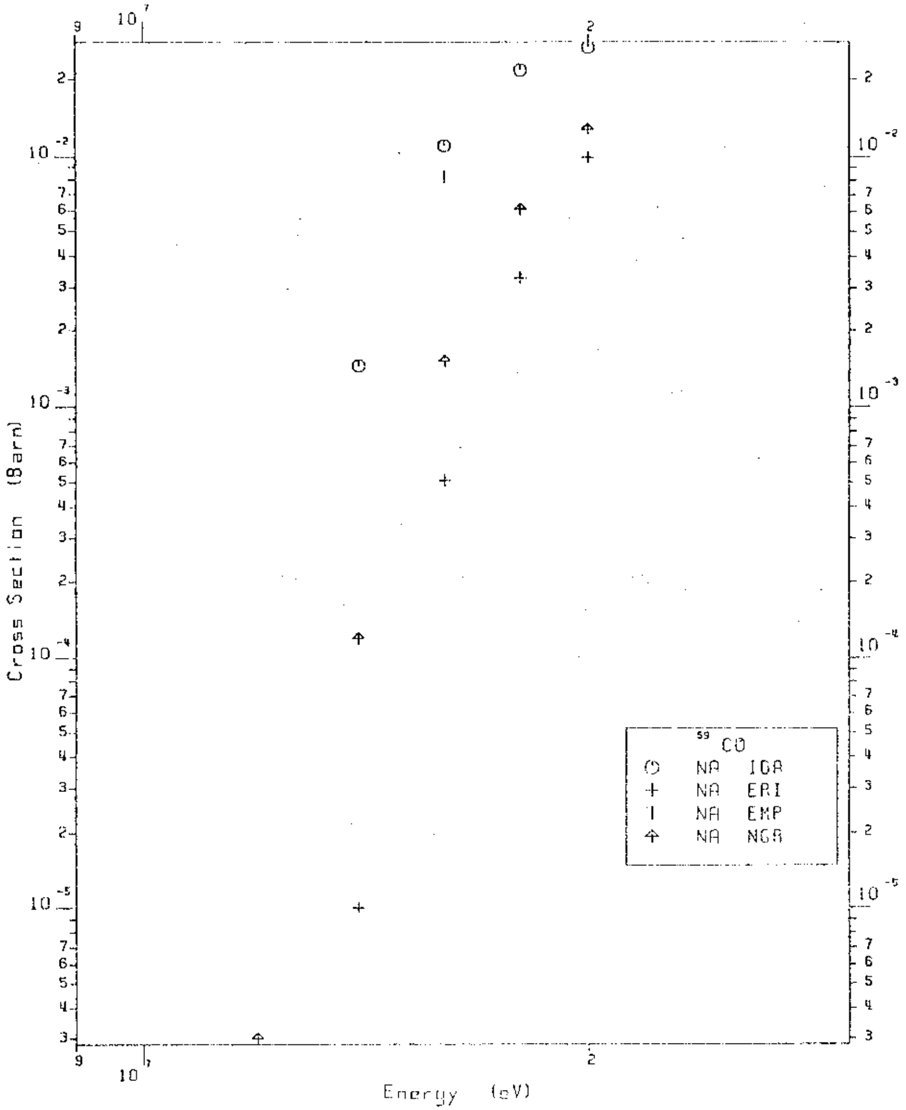


Fig. 30 (n,n alpha) Cross-section lin-lin

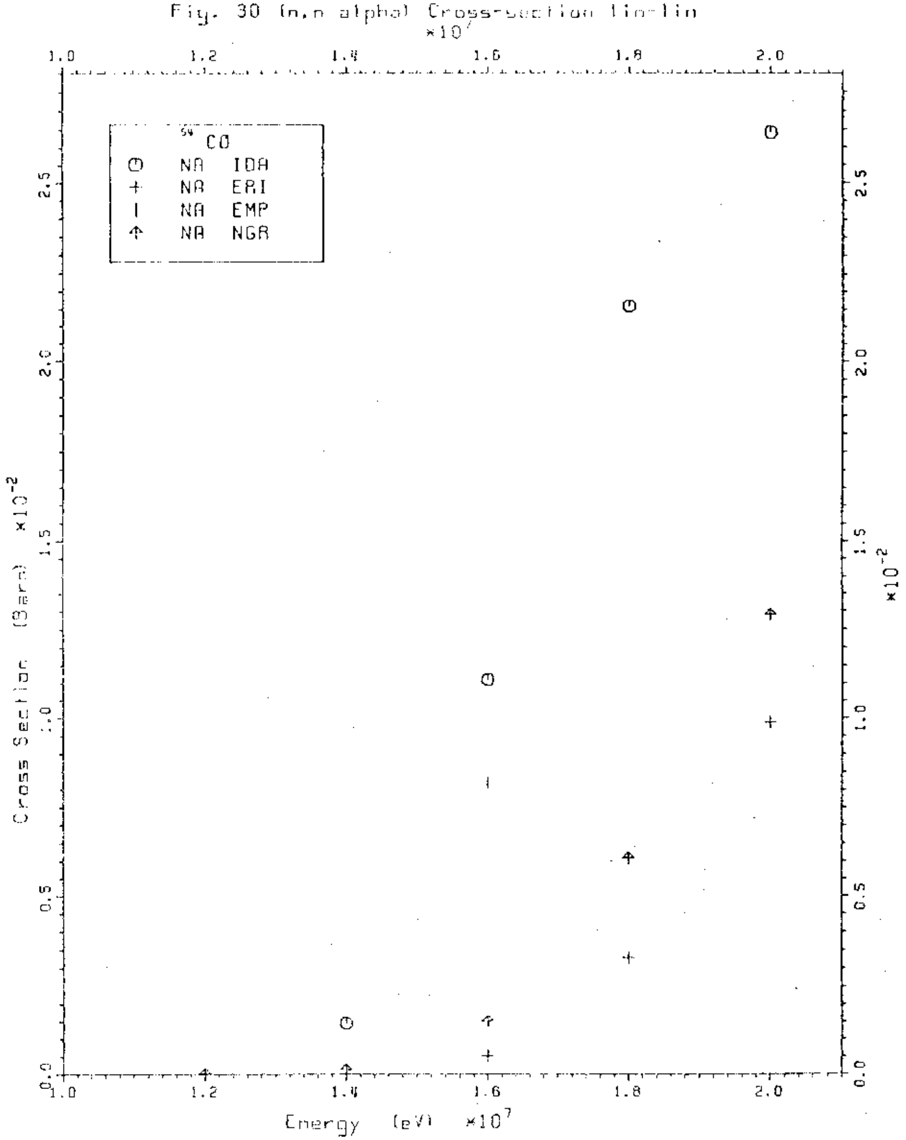


Fig. 31 (n,pn) Cross-section log-log

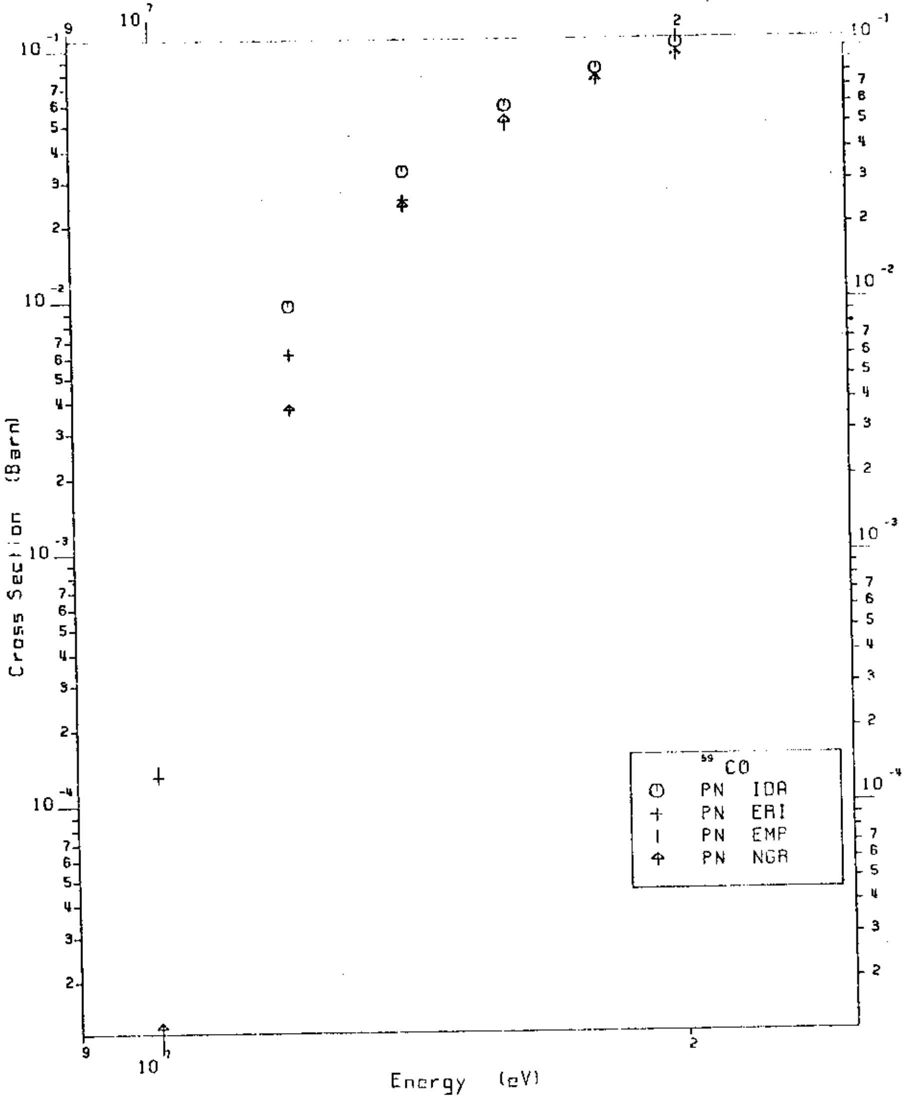
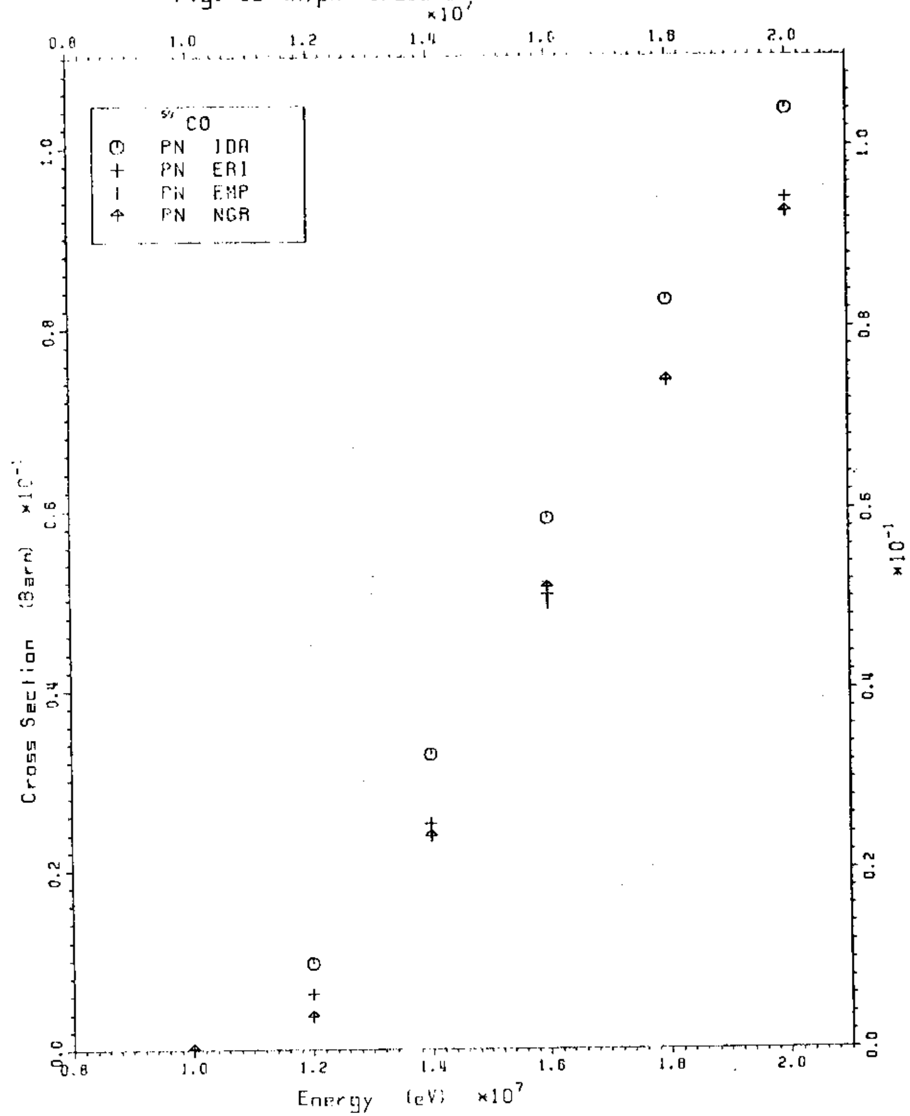


Fig. 32 (n,pn) Cross-section lin-lin



Appendix I

Problem Description

1. The calculation and results

Participants should calculate the cross sections of as many of the possible neutron induced reactions on Co-59 as their codes allow. Parameters are given for calculation of all the following reactions:

Total, Elastic, inelastic, (n,F), (n,p), (n,α), (n,d), (n,He[3]), (n,2n), (n,np) and (n,pn), (n,nα), (n,2p), (n,3n), (n,2n+p), (n,2n+α).

For those who wish to carry out only a subset of these reactions, it is suggested that they omit those involving t and He[3].

a) The calculated quantities to be compared

Calculated cross sections should be given at incident neutron energies between 0.5 and 20MeV. An adequate choice of energy intervals that will permit to analyse competition between different reaction channels is the following:

½ MeV intervals between 0.5 and 5 MeV.
1 MeV intervals between 5 and 10 MeV.
2 MeV intervals between 10 and 20 MeV.

Another acceptable set of energies would be the following:

½ MeV intervals up to 3 MeV.
2 MeV intervals up to 20 MeV.

i.e. 0.5, 1, 1.5, 2, 2.5, 3, 4, 6, 8, 10, 12, 14, 16, 18, 20 MeV.

The choice between these two sets is left to the participant.

The calculation falls into two distinct phases, and in order to identify more easily the origin of any discrepancies that may arise, participants should also give the transmission coefficients generated by the spherical optical model part of the calculation, and used as input in the statistical model calculations.

b) Options

Both energy independent and energy dependent optical model parameters are given. The set appropriate to the code normally used by the participant should be chosen. The energy dependent parameters give a slightly better fit to experimental data for the total cross section.

In the energy range up to 5MeV the calculation [illegible] done either with or without width fluctuation [illegible]

International Nuclear Model Codes Comparison

A. Prince - BNL (USA)

Definition of Optical Potential

(according to Becchetti & Greenlees, Phys. Rev. 182, 1190 (1969))

expression	validity range	explanation
$U_{opt}(r) = -V_R f_R$		central real
$+\left(\frac{\hbar}{m_\pi c}\right)^2 \frac{V_{so}}{r}\left(\frac{d}{dr} f_{so}\right) \vec{l}\cdot\vec{\sigma}$		spin orbit
$+\frac{Zze^2}{2R_c}\left[3-\left(\frac{r}{R_c}\right)^2\right]$	for $r < R_c$	Coulomb
$+\frac{Zze^2}{r}$	for $r \geq R_c$	Coulomb
$-iW_V f_I$		imaginary volume
$+i4a_I W_{SF}\left(\frac{d}{dr} f_I\right)$		imaginary surface

where

$$f_x = f(r, R_x, a_x) = \left[1+\exp(r-R_x)/a_x\right]^{-1}$$

$$R_x = r_x A^{1/3}$$

r_c = Coulomb Radius

Note: Whenever a parameter is omitted, it is assumed that the corresponding potential is not considered.

Optical Model Parameters

Neutron Parameters

V_R = 47.4 - 0.463 E + 0.0022 E^2 (E in MeV-Lab)

r_R = 1.26 fm a_R = 0.7835 fm

r_R = 1.26 + 0.00286 E (E in MeV-Lab) fm Energy dependent option

W_{SF} = 17.5 + 0.358 E - 0.007 E^2

r_I = 1.3136 fm a_I = 0.6319 fm

r_I = 1.3136 - 0.0007 E (E in MeV-Lab) fm Energy dependent option

V_{so} = 6.44

r_{so} = r_R a_{so} = a_R

Matching Radius R_m = 15.585 fm or R_m = R + 10.7 fm.

The real potential is of the Woods-Saxon form; the imaginary potential is surface type with a gaussian form and the spin orbit potential of the Thomas form.

Proton Parameters: Becchetti & Greenlees Phys. Rev. 182, 1190 (1969)

V_R = 54.0 - 0.32 E + 0.4Z/$A^{1/3}$ + 24.0(N-Z)/A MeV

r_R = 1.17 a_R = 0.75

W_V = 0.22E - 2.7 or zero, whichever is greater

W_{SF} = 11.8 - 0.25E + 12.0(N-Z)/A, MeV

or zero, whichever is greater

r_I = 1.32 fm a_I = 0.51 + 0.7(N-Z)/A fm

V_{so} = 6.2 MeV

r_{so} = 1.01 fm a_{so} = 0.75 fm

r_c (coulomb radius) = 1.25 fm

Deuteron Parameters: Perey & Perey, Phys. Rev. 132, 755 (1963)

V_R = 81.0 - 0.22E + 2.0(Z)/$A^{1/3}$

r_R = 1.15 fm, a_R = 0.81 fm

W_{SF} = 14.4 + 0.24E

r_I = 1.34 fm, a_I = 0.68 fm

r_c = 1.25 fm

Helion Parameters

Becchetti-Greenlees - Proc. Third Int'l Symposium, Madison, Wisc. (1970) 682.

V_R = 151.9 - 0.17 E + 50 (N-Z)/A MeV

W_V = 41.7 - 0.33 E + 44 (N-Z)/A MeV

r_R = 1.20 fm., a_R = 0.72 fm

r_I = 1.40 fm., a_I = 0.88 fm

V_{SO} = 2.5 MeV

$r_{so} = r_R$, $a_{so} = a_R$

$r_c = 1.30$ fm.

Tritons

Becchetti - Greenlees - ibid

$V_R = 165.0 - 0.17\ E - 6.4\ (N-Z)/_A$ MeV

$W_v = 46.0 - 0.33\ E - 110\ (N-Z)/_A$ MeV

$r_R = 1.20$ fm, $a_R = 0.72$ fm

$r_I = 1.40$ fm, $a_I = 0.84$ fm

$V_{so} = 2.5$ MeV

$r_{so} = r_R$, $a_{so} = a_R$

$r_c = 1.30$ fm.

Alpha Parameters

McFadden & Satchler, Nucl. Phys. 84, 177 (1966)

$V_R = 164.7$ MeV

$r_R = 1.442$ fm $a_R = 0.520$ fm.

$W_v = 22.4$ MeV

$r_I = r_R$, $a_I = a_R$

$r_c = 1.25$ fm.

Energy Level Schemes for Co^{59}(n,xn) Reactions

$^{60}Co(n,\gamma)$

E(MeV)	J^π
0.0000	5.0^+
0.0590	2.0^+
0.2780	4.0^+
0.2880	3.0^+
0.4360	5.0^+
0.5062	3.0^+
0.5427	3.0^+
0.6144	3.0^+
0.7388	1.0^+
0.7836	4.0^+
1.0056	4.0^+
1.2157	1.0^+
1.5159	4.0^+

$^{59}Co(n,n)$, (n,n')

E(MeV)	J^π
0.0000	3.5^-
1.0993	1.5^-
1.190	4.5^-
1.2915	1.5^-
1.4340	0.5^-
1.4600	5.5^-
1.4810	2.5^-
1.7440	3.5^-
2.0620	3.5^-
2.0870	2.5^-
2.1530	6.5^-

$^{59}Co(n,n)$, (n,n') (cont.)

E(MeV)	J^π
2.1830	3.5^-
2.2060	2.5^-
2.3950	4.5^-
2.4790	2.5^-
2.5420	2.5^-
2.5850	4.5^-
2.7810	1.5^-
2.8240	4.5^-
2.9620	2.5^-

$^{59}Fe(n,p)$

E(MeV)	J^π
0.0000	1.5^-
0.2870	0.5^-
0.4750	2.5^-
0.5700	1.5^-
0.7280	1.5^-
1.0300	3.5^-
1.1620	1.5^-
1.2100	0.5^-
1.5200	4.5^+
1.5700	2.5^-
1.9620	0.5^-

Table I

Energy Level Schemes for Co^{59}(n,xn) Reactions (cont.)

^{56}Mn(n,α) also (n,nHe^3)

E(MeV)	J^π
0.0	3.0^+
0.0266	2.0^+
0.1105	1.0^+
0.2120	4.0^+
0.2151	2.0^+
0.3355	5.0^+
0.3410	3.0^+
0.4543	4.0^+
0.4863	3.0^+
0.7162	3.0^+
0.7540	3.0^+
0.8404	3.0^+
1.1664	1.0^+
1.5094	2.0^+
1.7429	2.0^+
1.8333	1.0^+

^{58}Co(n,2n)

E(MeV)	J^π
0.0000	2.0^+
0.0249	5.0^+
0.0530	4.0^+
0.1114	3.0^+
0.3656	3.0^+

^{58}Co(n,2n) (cont.)

E(MeV)	J^π
0.3740	5.0^+
0.4575	4.0^+
0.8859	4.0^+
1.0400	3.0^+
1.0760	6.0^+
1.1845	5.0^+
1.2366	2.0^+
1.3690	1.0^+
1.4243	1.0^+

^{58}Fe(n,np) (n,pn) also (n,d)

E(MeV)	J^π
0.0000	0.0^+
0.8106	2.0^+
1.6747	2.0^+
2.0763	4.0^+
2.1338	3.0^+
2.2570	0.0^+
2.6000	4.0^+
2.7818	1.0^+
2.8761	2.0^+
2.9700	5.0^-
3.0380	2.0^+
3.2300	2.0^+
3.2442	0.0^+
3.5372	1.0^+
3.6300	2.0^+

Table I

Energy Level Schemes for Co^{59}(n,xn) Reactions (cont.)

^{57}Co(n,3n)

E(MeV)	J^π
0.0000	3.5^-
1.2237	4.5^-
1.3775	1.5^-
1.5047	0.5^-
1.6894	5.5^-
1.7572	1.5^-
1.8969	3.5^-
1.9196	2.5^-
2.1331	2.5^-
2.3113	3.5^-
2.6111	3.5^-

^{57}Fe(n,p,2n) also (n,t) (n,n,d)

E(MeV)	J^π
0.0000	0.5^-
0.0144	1.5^-
0.1366	2.5^-
0.3667	1.5^-
0.7067	2.5^-
1.0080	3.5^-
1.1980	4.5^-
1.2651	0.5^-
1.3568	3.5^-
1.6277	1.5^-
1.7257	1.5^-
1.9750	0.5^-
1.9894	4.5^-
2.1170	2.5^-

^{54}Mn(n,2n,α)

E(MeV)	J^π
0.0000	3.0^+
0.0545	2.0^+
0.1562	4.0^+
0.3678	5.0^+
0.4078	3.0^+
0.8389	4.0^+
1.0097	3.0^+
1.0732	6.0^+
1.1366	5.0^+

^{57}Mn(n,He^3)

E(MeV)	J^π
0.0000	2.5^-
0.0840	3.5^-
0.8510	1.5^-
1.0590	0.5^-
1.0740	4.5^-
1.2270	5.5^-

^{58}Mn(n,2p)

E(MeV)	J^π
0.0000	3.0^+

Table I

Energy Level Schemes for Co^{59}(n,xn) Reactions (cont.)

$^{55}Mn(n,n\alpha)$

E(MeV)	J^{π}
0.0000	2.5^-
0.1260	3.5^-
0.9843	4.5^-
1.2920	5.5^-
1.5280	1.5^-
1.8850	3.5^-
2.1990	3.5^-
2.3660	2.5^-
2.4286	0.5^-
2.5647	1.5^-

Table I

Fe^{56} (n,nt)

Levels Taken from J. Lachlear, et al., NSE 55, 168 (1974)

Excitation Energy (keV)	J^{π}	Excitation Energy (keV)	J^{π}
0.0	0^+	4458.4	3^+
846.8	2^+	4510.0	3^-
2085.1	4^+	4539.5	1^+
2657.6	2^+	4554.0	3^+
2941.7	0^+	4612.3	2^+
2960.0	2^+	4660.0	3^+
3120.0	1^+	4684.7	3^+
3123.0	4^+	4729.9	0^+
3370.2	2^+	4739.6	2^+
3388.1	6^+	4878.0	2^+
3445.4	3^+		
3449.3	1^+		
3601.9	2^+		
3607.0	0^+		
3755.0	6^+		
3832.0	2^+		
3856.5	3^+		
4049.0	3^+		
4100.3	3^+		
4120.0	4^+		
4298.2	4^+		
4302.0	0^+		
4395.0	3^+		
4401	2^+		

Statistical Model Parameters

The level density formalism is based on the analytical methods of Gilbert and Cameron, (Can. J. Phys. 43 (1965) 1446) and some of the parameters are given in Table II.

The normalization constants may be determined from the gamma ray strength functions (s wave) given as $2\pi \frac{\langle \Gamma_\gamma \rangle}{\langle D \rangle}$

For ^{59}Co $\quad \langle \Gamma_\gamma \rangle = 0.5$ eV

$\langle D \rangle = 1400$ eV

The Brink-Axel giant dipole resonance form is to be used for determining the gamma-ray transmission coefficients where

$\Gamma_1 = 2.86$ MeV $\quad E_1 = 16.50$ MeV $\quad \sigma_1 = 0.059$ b

$\Gamma_2 = 5.50$ MeV $\quad E_2 = 19.12$ MeV $\quad \sigma_2 = 0.061$ b

The gamma ray strength functions for the residual nuclei are not specified here. The participant may either use the same as for ^{59}Co or specify his own. In the latter case, the values used should be specified.

Table II

Statistical Model Parameters

Reaction	n,γ	n,n	n,p	n,α	n,2n	n,np	n,nα
Residual Nucleus	$^{60}_{27}Co$	$^{59}_{27}Co$	$^{59}_{26}Fe$	$^{56}_{25}Mn$	$^{58}_{27}Co$	$^{58}_{26}Fe$	$^{55}_{25}Mn$
P(N)	0	1.29	0	0	0	1.29	1.27
P(Z)	0	0	1.54	0	0	1.54	0
S(N) *	15.60	14.92	15.60	14.13	14.13	14.92	13.26
S(Z) *	-17.36	-17.36	-16.37	-15.53	-17.36	-16.37	-15.53
$a^{(1)}$	8.372	7.900	8.370	7.233	6.518	7.465	6.665
U_x(MeV)	5.0	5.04	5.04	5.18	5.086	5.086	5.227
E_x(MeV)	5.0	6.33	6.58	5.18	5.086	7.916	6.497
$E_{cut}^{(2)}$(MeV)	1.6	3.0	2.0	1.9	1.5	3.7	2.6

1) It might be necessary to renormalize the level parameter for ^{60}Co to obtain agreement with the recommended level spacing $\langle D \rangle$

2) E_{cut} = Continuum cut-off energy

* This information is redundant and has been included for completeness only.

Explanation of symbols used in Table [illegible]

P(N), P(Z)	pairing energies
S(N), S(Z)	shell corrections
E_x	exitation energy of the tangency point
U_x	energy at the tangency point (minus pairing energy)
a	level parameter

Level density formulae (Gilbert & Cameron)

Fermi gas Formula

$$\rho_2 = \exp(2\sqrt{aU}) / [12\sqrt{2}\, a^{1/4}\, U^{5/4}\, \sigma]$$

ρ_2 is the density of levels of all angular momenta J

where U = E - P(Z) - P(N)

$$\sigma^2 = 0.146\sqrt{aU} \cdot A^{2/3} \qquad \text{the spin cut-off factor}$$

This formula is valid for all energies greater than E_x, where

$$U_x = 2.5 + 150/A$$

$$E_x = U_x + P(Z) + P(N)$$

Below this energy the constant temperature formula is adopted

$$\rho_1 = (1/T)\exp[(E-E_o)/T]$$

which smoothly joins ρ_2 : i.e. $\rho_1(E_x) = \rho_2(U_x)$

This gives for E_o and T the following relations:

$$1/T = \left(\frac{a}{U_x}\right)^{1/2} - \frac{3}{2U_x} \quad ; \quad E_o = E_x - T\log[T\rho_2(U_x)]$$

Table III

Mass Excesses

Isotope	$-\Delta$ (MeV)
^{57}Co	59.3470
^{58}Co	59.8472
^{59}Co	62.2357
^{60}Co	61.6556
^{54}Mn	55.5570
^{55}Mn	57.7100
^{56}Mn	56.9087
^{57}Mn	57.6200
^{58}Mn	56.6060
^{56}Fe	60.6094
^{57}Fe	60.1838
^{58}Fe	62.1551
^{59}Fe	60.6700

Description of the Computer Codes Used

SCAT-2 (O. Bersillon)

Spherical optical model code employing recent numerical methods in particular for the Coulomb function calculations.

ABACUS-2 (A.E. Auerbach)

This code is a combination of the Optical Model and the Hauser-Feshbach formalism. It has a 4 class capability:

- Class 1 - scattering by an optical potential: gives σ_T, σ_{SE}, and σ_R only.
- Class 2 - computes the bound state radial wave function for a specific ℓ and j.
- Class 3 - uses method of Class 1 to generate transmission coefficients for use in Hauser-Feshbach Theory. Computes σ_T, σ_{SE}, σ_{CE}, and $\sigma_{nn'}$.
- Class 4 - calculates radial integrals from partial waves generated by Class 1 and 2. A multidimensional search procedure is included for obtaining best optical model parameters.

OPTICAL (M.E. Smith, S. Camarda, with modifications by T.W. Phillips)

Spherical optical model code for calculation of σ_T, σ_{el}, σ_R, $d\sigma_{el}/d\theta$. An option for INMC potential has been included by Phillips.

ABACUS-NEARREX (P.A. Moldauer, S. Zawadski)

It is a combination of ABACUS (optical model code) and NEARREX (Hauser-Feshbach + Moldauer theories code) which computes neutron-induced, average fluctuation (or compound nucleus) cross sections. Provision is made for the computation of compound elastic and inelastic neutron cross section, radiative capture and fission cross sections, as well as other processes, such as proton emission. It can also be used to compute proton-induced average cross sections.

ABAREX (P.A. Moldauer)

A revised and improved version of ABACUS-NEARREX. The neutron channel fluctuation degrees of freedom are calculated according to the formula given in Ref. 13.

- The width fluctuation correction can be computed for all compound cross sections, including capture.
- In addition to the n-gamma cross section ABAREX can compute the capture cross section which is obtained from n-gamma by subtracting the effect of neutron re-emission. This can be significant above 1 MeV.
- ABAREX is capable of fitting neutron s and p wave strength functions and R' and total cross sections and differential cross sections for elastic and inelastic neutron scattering to individual or lumped levels, simultaneously for several incident neutron energies.

ABAREX permits only one giant resonance to be specified.

NGROGI (Y. Harima, M. Kawai)

Improved version of GROGI III by Takahashi. Uses the ELIESE-2 module for spherical optical model calculations. Wapstra-Bos's mass table is incorporated. The Gilbert-Cameron type composite formula for level density calculation is built into the code. As another option, Lang's formula can be used. Several kinds of gamma-ray strength functions are available: Brink-Axel type profile function, Berman type strength function, Weisskopf's single particle model (optionally), E1 sum-rule for dipole transition, E2 sum-rule for quadrupole transition (optionally); Yrast energies which are not given by the user are calculated in the code by $E_J = J(J+1)/aR$, $aR = 2\sigma_o^2/T$, where a is the level density parameter, σ_o is the spin cut-off factor and T is the nuclear temperature.

NGROGI is capable of calculating the pre-equilibrium process based on the Kalbach-Cline procedure (Ref. 15).

EMPIRE (M. Herman, A. Marcinkowski)

Pre-equilibrium and equilibrium decay, both angular momentum dependent, are included. Populations of discrete levels are calculated due to the angular momentum conservation and full gamma cascade are accounted for. The code is designed for calculations of capture and multistep reactions. The precompound mechanism is included in the first step of the decay, according to the geometry dependent HYBRID model of M. Blann. The method of Hofmann, Richert, Tepel and Weidenmüller with an improved formula for the elastic enhancement factor (Ref. 14) is used to account for width fluctuations. The code is capable of treating reactions with neutrons, protons, alphas and gammas. Deuterons are treated in the incoming channel only.

ELIESE-3 (S. Igarasi)

Calculates elastic and inelastic scattering cross sections and any kind of reaction cross sections involving absorption and emission of neutrons, protons, deuterons and alpha particles. Polarization is also calculated. Local and non-local spherical optical models and Hauser-Feshbach theory with and without the width fluctuation corrections are allowed.

HAUSER-5 (F.M. Mann)

Calculates angle-integrated reaction cross sections, which can include capture and fission channels. If required, angle-differential cross sections may be computed. Cross sections for discrete [illegible] can be calculated, as well as the total for each residual [illegible]. Arbitrary reactions can be calculated in two channel [illegible]. There is no restriction on the types of the particles. It is based on three models of nuclear reactions: the statistical [illegible] model, the pre-equilibrium model (exciton [illegible]) and a statistical model for direct reactions. Transmission coefficients are interpolated from a table of previously-calculated transmission coefficients which can be supplied as input data or calculated by solving the Schrödinger equation with a spherical potential using Numerov's method unless the value is less than 0.001. The real spherical potential is taken to be the Woods-Saxon shape and the derivative can be Woods-Saxon or Gaussian shape. The fission transmission coefficients are based on the Hill-Wheeler equation. HAUSER-5 is designed to predict nuclear cross sections over [illegible] energy range less than about 60 MeV. Presently, the only statistical direct [illegible] included is the (n, alpha) pickup reaction. The Coulomb Aspect [illegible] to be replaced if heavy ions far below the Coulomb barrier are used. A maximum of six reaction [illegible] can be [illegible]. Residual nuclei can be described by 100 discrete levels and by the constant temperature level density and/or the Fermi-gas level description. The maximum number of [illegible] angular momentum and energies for [illegible] [illegible] is 30. The angular distribution expressed at [illegible] angles from 0 to 180 degrees can be calculated for up to 20 discrete levels. The program does not follow gamma-ray cascades down [illegible].

CERBERO-3 (G. Reffo, F. Fabbri)

Local and non-local spherical optical model calculations are allowed. Hauser-Feshbach and Moldauer theories are included. Width fluctuations can be accounted for according to an effective number of degrees of freedom as described in the latest works by Moldauer. It calculates σ_T, σ_R, σ_{el} (angle-integrated or angle-differential as well as any type of binary reaction (x,a) where a can be indifferently n, p, α, γ. Particle and primary gamma-ray spectra are given as well as the cross section for discrete level excitations of all residual nuclei involved. The cross section is also given for those processes (e.g. (n, γ,n)) initiated by gamma-ray emission and followed by subsequent particle emission. As a calculation test on integration techniques involved at the end of each run the percentual difference is given between optical model compound nucleus formation cross section and the sum of all compound elastic and inelastic contributions. Only E1 transitions are considered in gamma decay which is treated according to the Brink-Axel model. The code is designed for the use below threshold for the second emission.

ERINNI (F. Fabbri, G. Reffo)

Computes multiple particle emissions like (x;abc) x,a,b being n,p,α, indifferently, and c only n and γ. The code is designed for calculations between 5-20 MeV; [illegible]

GROGI-EPA (V. Benzi, F. Fabbri, L. Zuffi, improved by H. Gruppelaar)

Initially the code calculated σ_T, σ_R, total and differential σ_{el} and also carried out Hauser-Feshbach calculations for neutrons only. Gruppelaar included the calculations of (n, 2n) as well as neutron radiative capture with width fluctuation corrections. There is an option to use the method of Tepel et al. for the calculation of the width fluctuation factor above a given energy. Reduced cross sections are used to reduce the compound-formation cross sections. In this way competition of charged particle emission cross sections is accounted for.

IDA Modular System (G. Reffo, F. Fabbri)

It consists of a code-system; the most important modules are: POLIFEMO, NAUSIKAA, TELEMACO.

POLIFEMO is designed for binary reactions.

Direct and compound nucleus contributions to the excitation of discrete levels are calculated as well as angle differential cross sections for elastic and inelastic contributions. Particle and gamma-ray spectra are calculated. Valence capture is computed according to Lynn or Lane-Mughabghab models. The fission competition is included. As a consistency test the percentual difference between the optical model reaction cross section and the sum of all direct and compound nucleus cross section contributions, are printed. The modules involved can optionally select a part or all the data on a shared data library containing mass excesses, evaluated level schemes, giant resonance parameters, optical model data sets, local systematics for level density parameters, etc.

NAUSIKAA is designed for multiple particle and gamma-ray cascading emissions. (Eleven subsequent emissions are possible of which each of the first four can be indifferently n, p, α, γ while the last seven can only be γ). In addition to complete channel competition the pre-equilibrium component in the first emission is computed within the framework of a unified model accounted for any projectile and ejectile n, p, α, γ (Ref. 12.); angular momentum and parity conservation are considered. When partial cross sections are summed over all the exciton numbers, the unified model option is used for pre-equilibrium and equilibrium emissions. The fission competition is included.

TELEMACO combines the output of NAUSIKAA to produce the requested spectra for any particle in the cascade. Separate spectra for all particles and gamma-rays emitted in any cascading emission may be requested as well as the total spectrum for a particular emission type at any given energy. Isomeric ratios can also be calculated. TELEMACO can display partial and/or total spectra together with evaluated experimental data sets taken from a data base.

RELATIONS BETWEEN THE CODES

- The codes SCAT-2, ABACUS-2, OPTICAL only compute the optical model cross sections like σ_T, σ_R, $\sigma_{sh.el}$. They have been independently developed and therefore no particular relation exists among them.

- ABACUS-NEARREX consists of the fusion of the two codes: ABACUS-2 for calculating the optical model quantities and NEARREX for the Hauser-Feshbach theory calculations with width fluctuation corrections. ABAREX is an improved version of ABACUS-NEARREX and contains the latest developments in width fluctuation correction factors.

- EMPIRE is a general code which accounts for equilibrium and pre-equilibrium emissions with inclusion of spin and parity conservation, giving integrated and energy differential cross sections. Where necessary the width fluctuation correction is also used. It has been developed recently and independently from other codes used in this exercise.

- ELIESE-3. The set of ELIESE codes are very well known and widely used for optical model and Hauser-Feshbach calculations with width fluctuation cross sections for binary reactions.

- NGROGI is an extended version of ELIESE-2 and includes multiple cascading emissions and pre-equilibrium effects.

- CERBERO, POLIFEMO, SASSI, ERINNI, NAUSIKAA belong to a complex and integrated chain of codes. They all share the same modules: SMOG (spherical) and CIRCE (deformed) for the optical model and CERBERO for the statistical model. The first two are designed for binary reactions and the second is a more general and versatile version of the first. The last three are designed for multiple particle emissions and can be used each up to incident energies of ~ 15 MeV, ~ 20 MeV, ~ 50 MeV, respectively.