COMITETUL DE STAT PENTRU ENERGIA NUCLEARA
INSTITUTUL DE FIZICA ATOMICA

CRD-50-1972 [redacted]

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Abstract : Differential and total cross-sections for neutron elastic scattering and inelastic scattering to the first excited state of ^{60}Ni have been calculated from 2 to 8.5 MeV in about 1 MeV steps. The cross-sections were computed by using the optical model for the elastic scattering, the statistical theory for the compound processes and the DWBA theory for the direct inelastic scattering. The optical model parameters of Wilmore and Hodgson were used. The combined predicts of Hauser-Feshbach-Molhauer, optical model and DWBA calculations are in good agreement with available experimental data.

INTRODUCTION

The reactor physicists and designers are the principal users of the neutron data. Their requirement is for the cross-sections of all neutron induced absorption and scattering reactions ranging from 0 to 15 MeV, for a large portion of nuclei over the whole periodic table [1].

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* Work supported by the State Committee for Nuclear Energy

Taking into account the difficulty of some neutron measurements concerning their precision and, in some cases the experimental methods still not sufficiently developed, a solution seems to be the use of the nuclear model calculations. These calculations can be as accurate as an experimental measurement.

Since the scattering data on ^{60}Ni are included in lists of neutron nuclear data requests, reported in this paper are the calculations of neutron scattering cross-sections on ^{60}Ni in the energy range from 2 to 8.5 MeV. The differential and total cross-sections were obtained using the optical model for the elastic scattering the statistical theory for the compound processes and the DWBA theory for the direct inelastic scattering.

The calculations are compared with available experimental data [2]. Since a good agreement was obtained, the same computational procedure has been used for obtaining cross-sections on ^{60}Ni at other energies.

RESULTS OF THE CALCULATIONS

The calculations for neutron scattering cross-sections on ^{60}Ni were performed at E_n = 2, 3, 4, 5.05, 6.44, 7.54 and 8.56 MeV. The inelastic scattering was calculated for the first excited state of ^{60}Ni. The direct interaction component of the calculated cross-sections was added to the compound nucleus contribution, assuming that there is no interference between compound and direct processes. The details of the procedure are given elsewhere [3].

To obtain the shape elastic cross-sections the computer code SANDA [4] was used. The optical potential form used was of standard type with a Saxon-derivative imaginary part and without spin-orbit coupling term. The direct-interaction contribution to the inelastic scattering was calculated with the computer code ELISA* in the disorded-waves Born approximation (DWBA) with zero-range interaction and neglecting the spin-orbit coupling. The value of β_2 for the first 2^+ excited state in ^{60}Ni was taken as 0.20 in accordance with previous data [5]. The nonlocal optical model parameters of Perev and Buck [6] were used throughout this work. In the computer codes SANDA and ELISA they entered in their local equivalent form by Wilmore and Hodgson [7].

The compound-elastic cross-sections together with compound - inelastic cross-sections were estimated by the Hauser-Feshbach theory with the computer code COSTIN [8]. The Moldauer corrections for the level width fluctuations was taken into account. The statistical model calculations are referred below as HFM calculations. The trans - misions coefficients calculated with the nonlocal optical model parameters of Perev and Buck are used in the estimation of the compound processes. The competition of (n,p) and (n,α) open channels is considered. The known energy levels populated in the residual nuclei via the compound nucleus are treated explicitly, while the unknown level schemes at higher excitations are simulated by the level density function of Gilbert and Cameron [9].

The combined predictions of the optical model, DWBA and the HFM calculations are in good agreement with measured data, as it can be seen in figs.1,2 and 3. Therefore, it can be concluded that in the corresponding energy region the measured elastic and inelastic cross-sections for ^{60}Ni are well described by the predictions of the statistical model and the direct interaction mechanism. The quality of

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the fit gives confidence to extrapolate the calculation at lower energies, where, in the authors' knowledge, measurements are lacking. The results of the calculations are given in tables I-III. It can be seen that the excitation of the first state in ^{60}Ni by inelastic scattering is mainly caused by direct processes at energies higher than 6 MeV.

The level of precision corresponding to the use of average optical model parameters justifies the fact no effort was made to introduce more refinements into the calculations, e.g. a coupled-channels approach to the direct interaction. Also the resonance-interference effect [10] was neglected in the compound elastic scattering. On the other hand, previous measurements in the same mass region [11] provide best-fit sets of optical model parameters, which at energies lower than 4 MeV show appreciable fluctuations. Consequently, at higher energies the conventional nuclear reactions theories with average optical model parameters provide an efficient and reliable aid in evaluating neutron scattering data on even-even nickel isotopes, while the results of the calculations below 4 MeV incident energy should be regarded with some care.

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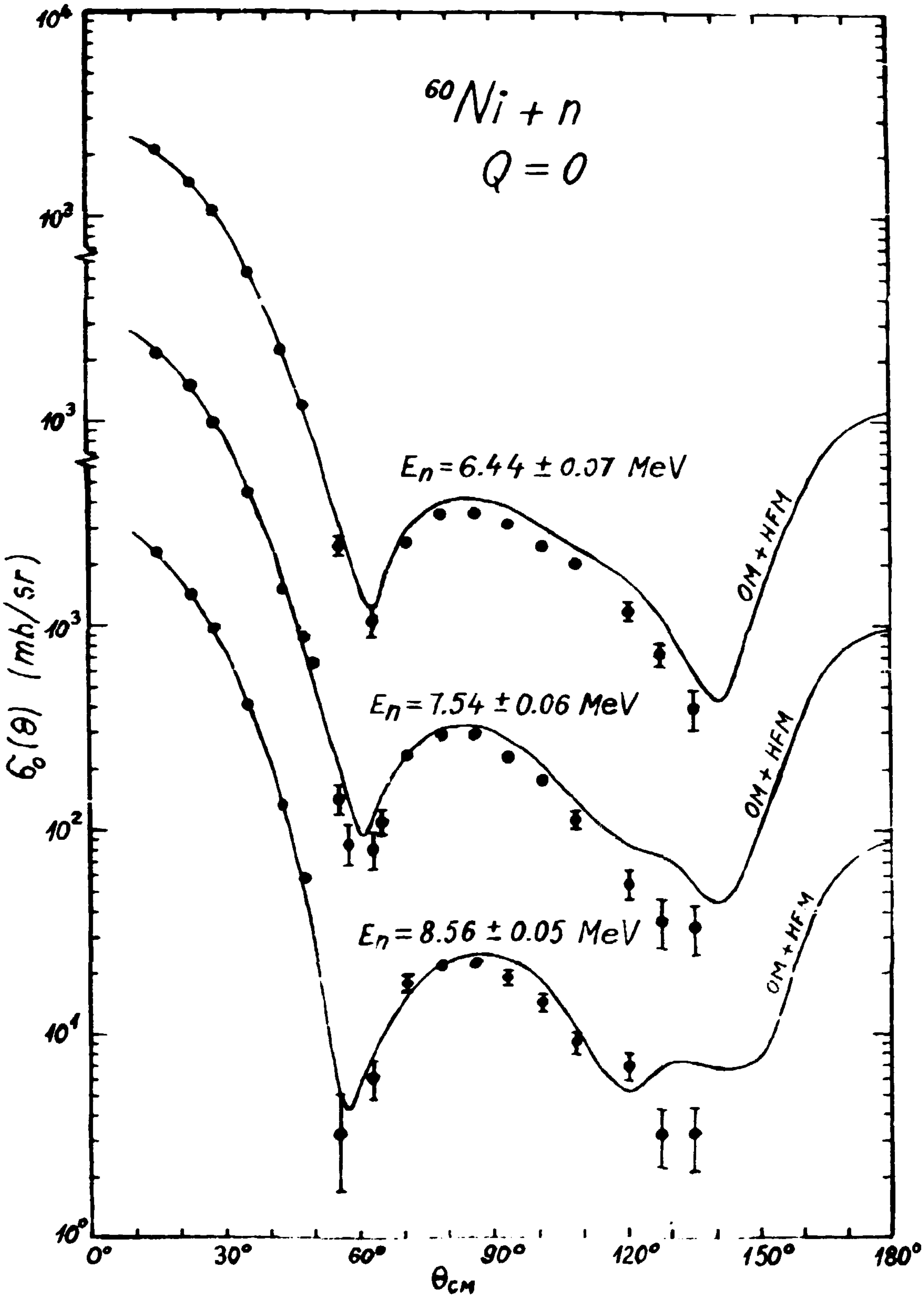

Fig.1.

Comparison between calculated elastic differential cross-sections and measured data. The experimental data were taken from ref.2.

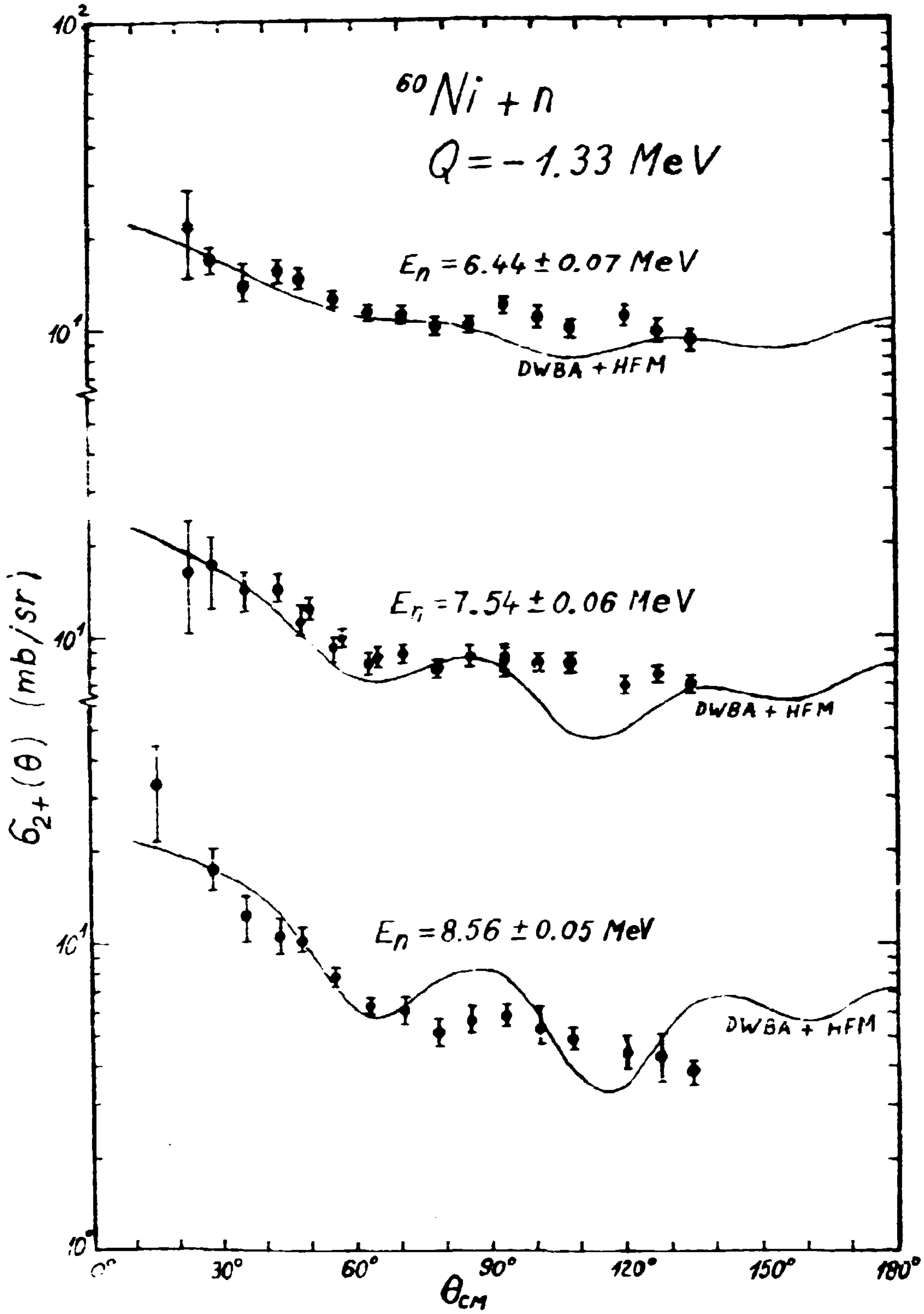

Fig.2.

Comparison between calculated inelastic differential cross-sections and experimental data. The measured angular distributions were taken from ref. 2.

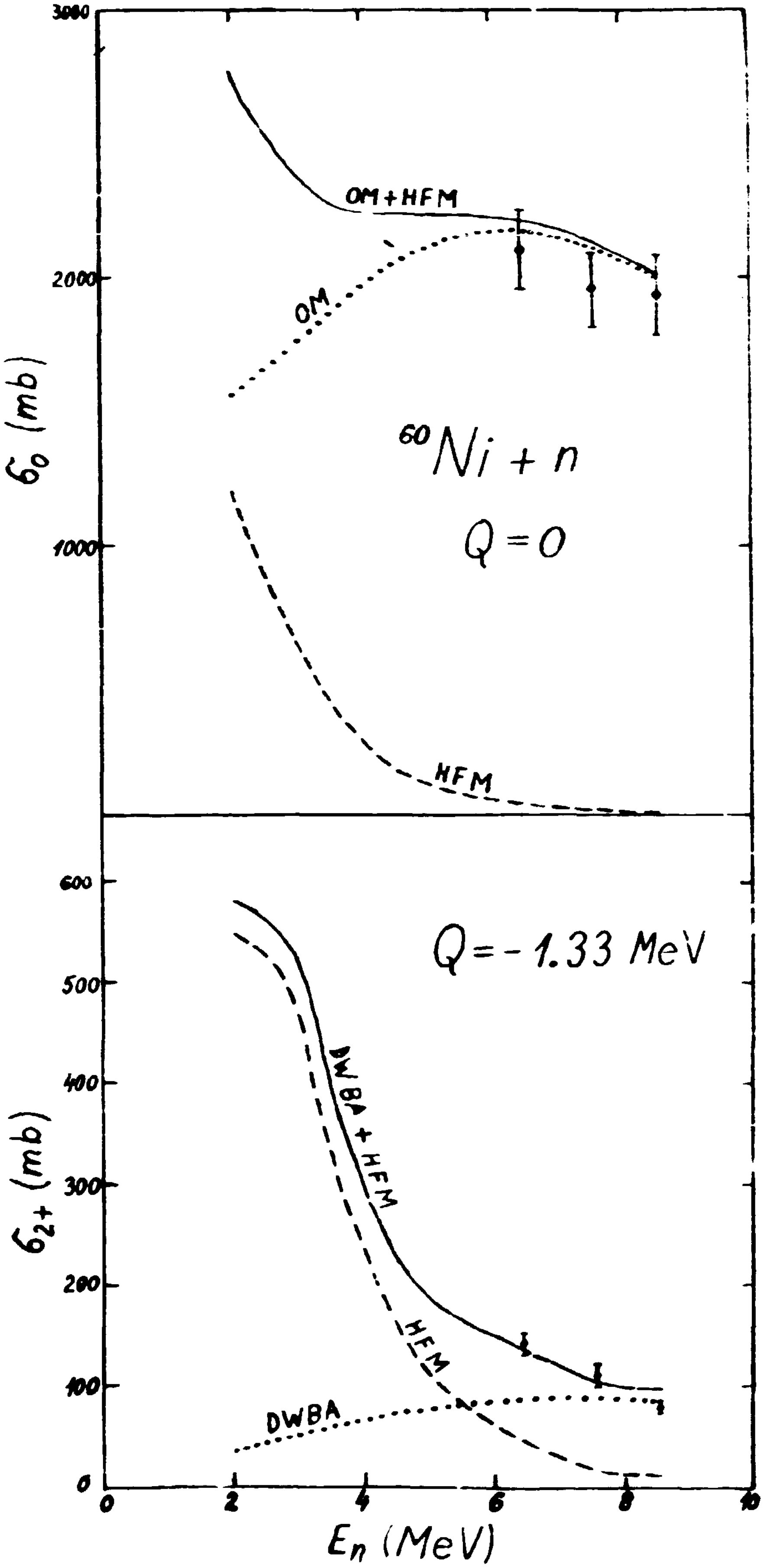

Fig.3. The theoretical integrated cross-sections (full line) represent the sum of the direct interaction (dotted curves) computed by using the optical model (elastic) and DWBA (inelastic) and the compound nucleus contribution, computed with the Hauser-Feshbach theory (dashed curves). The experimental data were taken from ref.2.

TABLE I.

The calculated differential cross-sections for neutron elastic scattering on ^{60}Ni in mb/sr. The optical model calculations were denoted by OM and the statistical model calculations by HFM.

θ^0	E_n = 2 MeV			E_n = 3 MeV		
	$\sigma(\theta)_{OM}$	$\sigma(\theta)_{HFM}$	$\sigma(\theta)$	$\sigma(\theta)_{OM}$	$\sigma(\theta)_{HFM}$	$\sigma(\theta)$
10	877.8	178.6	1056	1202	102.8	1305
20	732.1	160.3	892.4	964.3	89.85	1054
30	533.4	136.4	669.8	655.8	73.58	729.4
40	330.3	113.0	443.3	363.3	58.71	422.0
50	164.7	94.47	259.2	148.3	47.90	196.2
60	59.57	82.05	141.6	31.76	41.34	73.10
70	16.17	74.94	91.11	0.112	37.87	37.99
80	18.30	71.53	89.83	20.87	36.24	57.11
90	41.69	70.55	112.2	58.62	35.76	94.38
100	63.70	71.53	135.2	85.77	36.24	122.0
110	71.95	74.94	146.9	88.19	37.87	126.1
120	64.22	82.05	146.3	66.89	41.34	108.2
130	48.45	94.47	142.9	35.04	47.90	82.94
140	35.25	113.0	148.3	10.33	58.71	69.04
150	31.63	136.4	168.0	4.776	73.58	78.35
160	37.34	160.3	197.6	17.58	89.85	107.4
170	45.98	178.6	224.6	35.95	102.8	138.8
180	49.96	185.5	235.5	44.37	107.8	152.2

TABLE I.

(continued)

θ°	$E_n = 4$ MeV			$E_n = 5{,}05$ MeV		
	$\sigma(\theta)_{OM}$	$\sigma(\theta)_{HFM}$	$\sigma(\theta)$	$\sigma(\theta)_{OM}$	$\sigma(\theta)_{HFM}$	$\sigma(\theta)$
10	1590	49.24	1639	2022	22.46	2044
20	1222	41.59	1264	1486	18.21	1504
30	773.3	32.59	805.9	868.8	13.53	882.3
40	385.9	25,16	411.1	384.5	10.04	394.5
50	136.4	20.44	156.8	115.2	8.103	123.3
60	24.66	17.94	42.60	21.42	7.217	28.64
70	6.142	16.63	22.77	18.17	6.758	24.93
80	30.26	15.90	46.16	38.61	6.445	45.05
90	60.85	15.64	76.49	52.81	6.318	59.13
100	78.32	15.90	94.22	55.37	6.445	61.81
110	75.06	16.63	91.69	48.07	6,758	54.83
120	52.96	17.94	70,90	32.49	7.217	39.71
130	23.07	20.44	43,51	12,88	8.103	20.98
140	2,399	25.16	27.56	0.373	10.04	10.41
150	4.556	32.59	37.15	8.398	13.53	21.93
160	29.02	41,59	70.61	39.35	18.21	57.56
170	58,94	49.24	108.2	76.20	22.46	98.66
180	72.27	52.27	124.5	92.73	24.19	116.9

TABLE I.

(continued)

θ°	E_n = 6,44 MeV			E_n = 7,54 MeV		
	$6(\theta)_{OM}$	$6(\theta)_{HFM}$	$6(\theta)$	$6(\theta)_{OM}$	$6(\theta)_{HFM}$	$6(\theta)$
10	2486	9.165	2495	2738	5.076	2743
20	1727	7.269	1734	1810	3.924	1814
30	914.2	5.268	919.5	878.8	2.784	881.6
40	345.5	3.855	349.4	290.4	2.034	292.4
50	80.45	3.123	83.57	53.93	1.656	55.59
60	15,06	2.802	17,86	9.238	1.485	10.72
70	24.58	2.631	27.21	20.46	1.392	21.85
80	38.56	2,511	41,07	30.74	1.329	32.07
90	38.55	2,460	41,01	29,67	1.302	30.97
100	29.90	2,511	32,41	20.81	1.329	22.14
110	20.89	2.631	23,52	11.44	1.392	12.85
120	13.83	2,802	16.63	7.079	1.485	8.564
130	6.295	3.123	9.418	5.426	1.656	7.082
140	0,482	3.855	4.337	2.427	2,034	4.461
150	8.328	5.268	13.60	6.686	2.784	10.47
160	38.78	7,269	46.05	32.84	3.924	36.76
170	78.67	9.165	87.84	73.00	5.076	78.08
180	97.48	9,960	107.4	93.20	5.574	98.77

TABLE I.

(continued)

θ°	E_n = 8,56 MeV		
	$\sigma(\theta)_{OM}$	$\sigma(\theta)_{HFM}$	$\sigma(\theta)$
10	2899	2,412	2901
20	1818	1.812	1820
30	803,0	1,260	804.3
40	228.6	0,927	229.5
50	32.77	0.759	33.53
60	4.744	0,678	5.424
70	13,70	0.635	14.34
80	22,13	0,609	22.74
90	24.44	0.597	25.04
100	18.66	0.609	19.27
110	8.885	0.636	9.525
120	4.538	0.678	5,216
130	6.604	0.759	7.363
140	6,108	0,927	7,035
150	6.223	1.260	7.483
160	26.10	1.812	27.91
170	64,64	2,412	67.05
180	85.59	2.679	88,27

TABLE II.

The combined predictions of DWBA and HFM for differential cross-sections of neutron inelastic scattering to the first excited state of ^{60}Ni (in mb/sr)

θ°	$E_n = 2$ MeV			$E_n = 3$ MeV		
	$\sigma(\theta)_{DWBA}$	$\sigma(\theta)_{HFM}$	$\sigma(\theta)$	$\sigma(\theta)_{DWBA}$	$\sigma(\theta)_{HFM}$	$\sigma(\theta)$
10	3.663	41.65	45.31	7.668	35.20	42.87
20	3.555	42.14	45.70	7.242	35.81	43.05
30	3.414	42.78	46.19	6.613	36.54	43.15
40	3.283	43.36	46.64	5.878	37.09	42.97
50	3.198	43.74	46.94	5.145	37.29	42.43
60	3.170	43.87	47.04	4.534	37.14	41.67
70	3.178	43.81	46.99	4.150	36.78	40.93
80	3.172	43.70	46.87	4.037	36.45	40.49
90	3.092	43.64	46.73	4.125	36.31	40.43
100	2.890	43.70	46.59	4.231	36.45	40.68
110	2.559	43.81	46.37	4.139	36.78	40.92
120	2.134	43.87	46.00	3.736	37.14	40.87
130	1.688	43.74	45.43	3.103	37.29	40.39
140	1.297	43.36	44.66	2.481	37.09	39.57
150	1.015	42.78	43.79	2.115	36.54	38.65
160	0.850	42.14	42.99	2.073	35.81	37.88
170	0.776	41.65	42.43	2.207	35.20	37.41
180	0.757	41.46	42.22	2.289	34.96	37.25

TABLE II.
(continued)

θ°	E_n = 4 MeV			E_n = 5,05 MeV		
	$\sigma(\theta)_{DWBA}$	$\sigma(\theta)_{HFM}$	$\sigma(\theta)$	$\sigma(\theta)_{DWBA}$	$\sigma(\theta)_{HFM}$	$\sigma(\theta)$
10	7.877	18,82	26.70	10,50	9.513	20.01
20	7,574	19.06	26.63	9.455	9.587	19.04
30	7,265	19.26	26.52	8,586	9.566	18.15
40	6.978	19,25	26.23	8.200	9.355	17.55
50	6,578	18,98	25.56	8.005	8,961	16.97
60	5,956	18.51	24,47	7.586	8.479	16.06
70	5,217	18.01	23.23	6,815	8.035	14.85
80	4,653	17.63	22.28	5.904	7.731	13.63
90	4.523	17,49	22.01	5,250	7.624	12.87
100	4.805	17.63	22.43	5,165	7,731	12,90
110	5.130	18,01	23.14	5.547	8,035	13.58
120	5.022	18.51	23.53	5.795	8.479	14,27
130	4,299	18.98	23,28	5.308	8,961	14.27
140	3,281	19.25	22.53	4,186	9.355	13.54
150	2.566	19,26	21,83	3,281	9.566	12.85
160	2.494	19.06	21,55	3.320	9.587	12.91
170	2,836	18.82	21,65	4.048	9.513	13,56
180	3,044	18.72	21.76	4.474	9.468	13.94

TABLE II.

(Continued)

θ^o	E_n = 6,44 MeV			E_n = 7,54 MeV		
	$\sigma(\theta)_{DWBA}$	$\sigma(\theta)_{HFM}$	$\sigma(\theta)$	$\sigma(\theta)_{DWBA}$	$\sigma(\theta)_{HFM}$	$\sigma(\theta)$
10	18.03	4.340	22.06	20.99	1.599	22.59
20	15.26	4.389	19.65	18.09	1.613	19.70
30	[illegible]	4.366	16.83	15.04	1.595	16.64
40	10.21	4.215	14.43	11.79	1.526	13.32
50	9.449	3.956	13.41	8.317	1.421	9.738
60	7.[illegible]	3.635	11.06	6.069	1.310	7.379
70	7.171	3.412	10.58	6.144	1.220	7.364
80	7.4[illegible]	3.250	10.7[illegible]	7.274	1.163	8.437
90	[illegible]	3.4[illegible]	9.[illegible]40	7.142	1.144	8.286
100	5.600	3.950	9.550	5.271	1.163	6.434
110	4.[illegible]90	3.[illegible]12	[illegible]	3.516	1.220	4.736
120	4.274	3.363	7.637	3.574	1.310	4.884
130	[illegible]	[illegible]	[illegible]	4.797	1.421	6.218
140	[illegible]	4.215	[illegible]	5.285	1.526	6.811
150	4.[illegible]49	4.33[illegible]	8.[illegible]45	4.727	1.595	6.322
160	4.476	4.359	8.835	4.676	1.613	6.289
170	[illegible].340	4.[illegible]40	9.980	5.776	1.599	7.375
180	[illegible]	4.309	10.[illegible]4	6.527	1.589	8.116

TABLE II.

(continued)

θ^c	E_n = 8,56 MeV		
	$\sigma(\theta)_{DWBA}$	$\sigma(\theta)_{HFM}$	$\sigma(\theta)$
10	20.37	1.298	21.67
20	18.18	1.300	19.48
30	15.97	1.264	17.24
40	12.73	1.180	13.91
50	8.301	1.071	9.372
60	5.164	0.969	6.133
70	5.230	0.893	6.123
80	6.986	0.848	7.834
90	7.345	0.833	8.178
100	5.266	0.848	6.144
110	2.786	0.893	3.679
120	2.503	0.969	3.472
130	4.290	1.071	5.361
140	5.510	1.180	6.690
150	4.907	1.264	6.171
160	4.298	1.300	5.596
170	5.118	1.298	6.416
180	5.8[illegible]	1.291	7.159

T A B L E III.

Summary of theoretical integrated cross-sections for neutro

elastic and inelastic (Q = - 1,33 MeV) scattering on ^{60}Ni

E_n MeV	^{60}Ni(n,n$_0$)			^{60}Ni(n,n$_1$)		
	σ_{OM}	σ_{HFM}	σ	σ_{DWBA}	σ_{HFM}	σ
2	1558	1204	2762	33.23	546.2	579.4
3	1753	628.0	2381	52.96	461.3	514.3
4	1964	277.0	2241	64.00	231.7	295.7
5.05	2117	114.0	2231	77.34	107.6	184.9
6.44	2170	44.39	2214	88.01	46.96	135.0
7.54	2111	23.63	2135	88.25	16.92	105.2
8.56	2007	10,84	2018	85,22	12.78	98.00