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NEUTRON NUCLEAR REACTION THEORY AND APPLICATION

Four papers by Chinese authors

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Contents

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Systematics of Average Total Radiative Widths for s- and p-Wave Resonances

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Abstract

The experimental values of total radiative widths, $\langle\Gamma_\gamma\rangle$, for 208 nuclides (Z=11-98, A=23-249) are compiled and analysed. Two empirical formulas for the radiative widths which are dependent on atomic number Z, mass number A and neutron binding energy Sn of compound nucleus are obtained: $\langle\Gamma_\gamma^0\rangle = 31\ Z^{-2.5}A^{0.56}Sn^{0.83}$ and $\langle\Gamma_\gamma^1\rangle = 24\ Z^{1.3}A^{-2.6}Sn^{0.95}$ (in eV). Using the strong-coupling dipole model, the coupling coefficients Cr which are varied smooth with the mass numbers A are also obtained. The values Cr from the smoothed curves can be used to calculate the radiative widths $\langle\Gamma_\gamma^0\rangle$ for those nuclides which are deficient in the experimental data.

Introduction

Average total radiative widths of neutron resonance are one of the resonance parameters which are necessary for application in astrophysics, reactor physics and fission physics. But there are quite a number of nuclides which lack experimental values $\langle\Gamma_\gamma\rangle$. Thus it is necessary to systematically study average radiative widths to derive $\langle\Gamma_\gamma\rangle$ for those nuclides. Moreover, the determination of the dependence of radiative widths on nutron spacing, spin and parity of the initial state, excitation energy, nuclear size and nuclear structure effects is of particular interest from a theoretical and evaluation point of view.

In 1956 J.S.Levin and D.J.Hughes[1] carried out the first attempt to study systematically average radiative widths and to interpret them in terms of Blatt-Weisskopf's estimates of partial radiative widths. In 1957 by a similar study A.Stolovy and J.A.Harrey[2] arrived at the following empirical expression for $\langle\Gamma_\gamma\rangle$:

$$\langle\Gamma_\gamma\rangle = 5.3\cdot10^{-4}\ A^{2/3}[D(U)]^{0.25}\ U^{4.3}\quad \text{(in meV)}, \qquad (1)$$

Where U and D(U) are the effective excitation energy in MeV and the spacing of levels with the same spin and parity as the radiating levels around the excitation energy U, respectively.

In 1971 H.Malecky et al.[3] noted that the previously derived relations of total radiative widths can be expressed in terms of a combination of the parameters A, a, U and T. A least squares fit of the experimental data for 108 nuclides (Z=27-96, A=59-246) was carried out. It has the following form

$$\langle\Gamma_\gamma\rangle = 9\ U^{0.9}\ A^{-0.9}\ a^{-0.57}\ (1-0.011\ I^2)\quad \text{(in eV)}, \qquad (2)$$

where I stands for the spin of the target nuclides, a is the level density parameter, and U and a^{-1} are expressed in MeV. As pointed out by H.Malecky et al.,[3] there is a general agreement between the experimental values and those calculated on the basis of Eq.(2) with a few exceptions. Because those $\langle\Gamma_\gamma\rangle$ compiled by H.Malecky et al. are published in 1966-1969, and in addition, there are no average radiative widths for p-wave resonance, we have carried out a further systematical study.

The purpose of this work is to extend the range of nuclides, to compile more recent experimental values $\langle\Gamma_\gamma\rangle$ as much as possible, to fit them using an empirical expression for $\langle\Gamma_\gamma\rangle$, to carry out theoretical analysis and calculation of average radiative widths and from which some regularity may be found out for setting up a more complete systematics of average radiative widths.

Experimental Systematics of Average Total Radiative Widths

The experimental values of average radiative widths for neutron resonance are collected according to CINDA 1982, and average radiative widths of s- and p-wave neutron resonances for 208 nuclides (Z=11-98, A=23-249) are selected, in which 207 nuclides for s-wave and 56 nuc-

lides for p-wave. These experimental or evaluated data are published in 1973-1981, most of them are taken from BNL-325 (the fourth edition, 1981)[4] and our evaluation (1981)[5].

The variation of the average s-wave radiative widths with mass number A is illustrated in Fig.1. Two interesting features emerge from this plot: (a) the general monotonic decrease of $\langle \Gamma_\gamma^0 \rangle$ with A in the mass region 60-190, this is favourable to the study of systematics, and (b) the maxima at about the mass numbers A=50 and 208, which are related to the magic numbers Z=28 and 82, these should be the results of shell effect.

The variation of p-wave radiative widths with mass number is shown in Fig.2, which demonstrates the same qualitative features as for s-wave radiative widths.

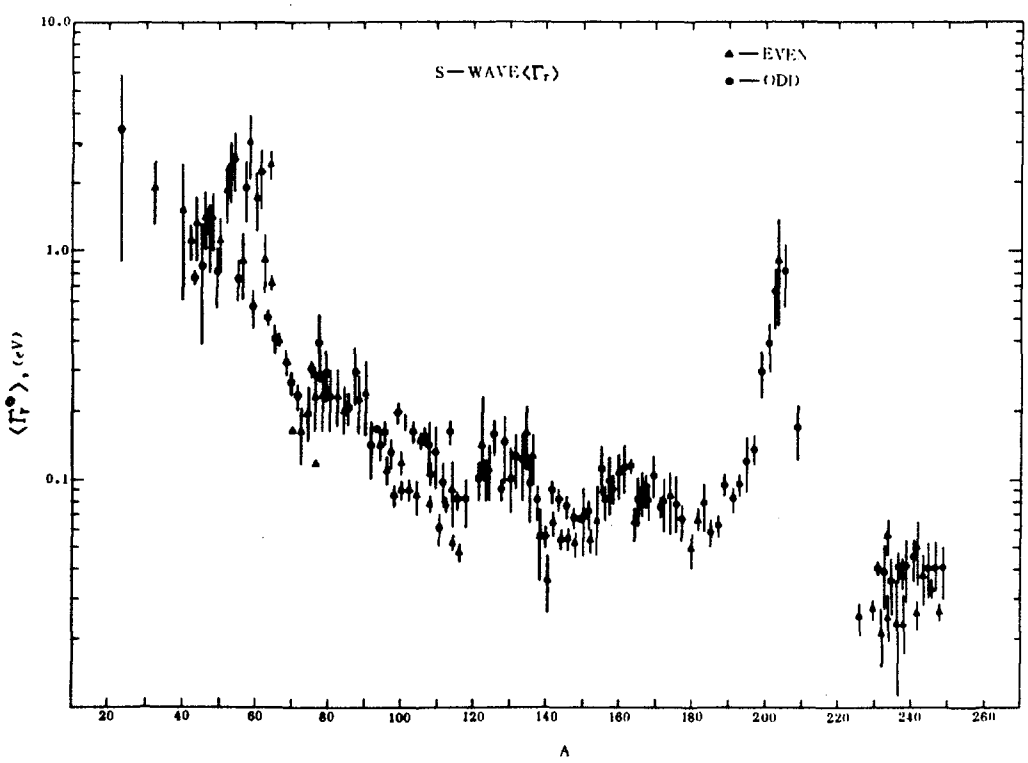

Figure 1. The average s-wave radiative widths plotted versus mass number A of target nucleus

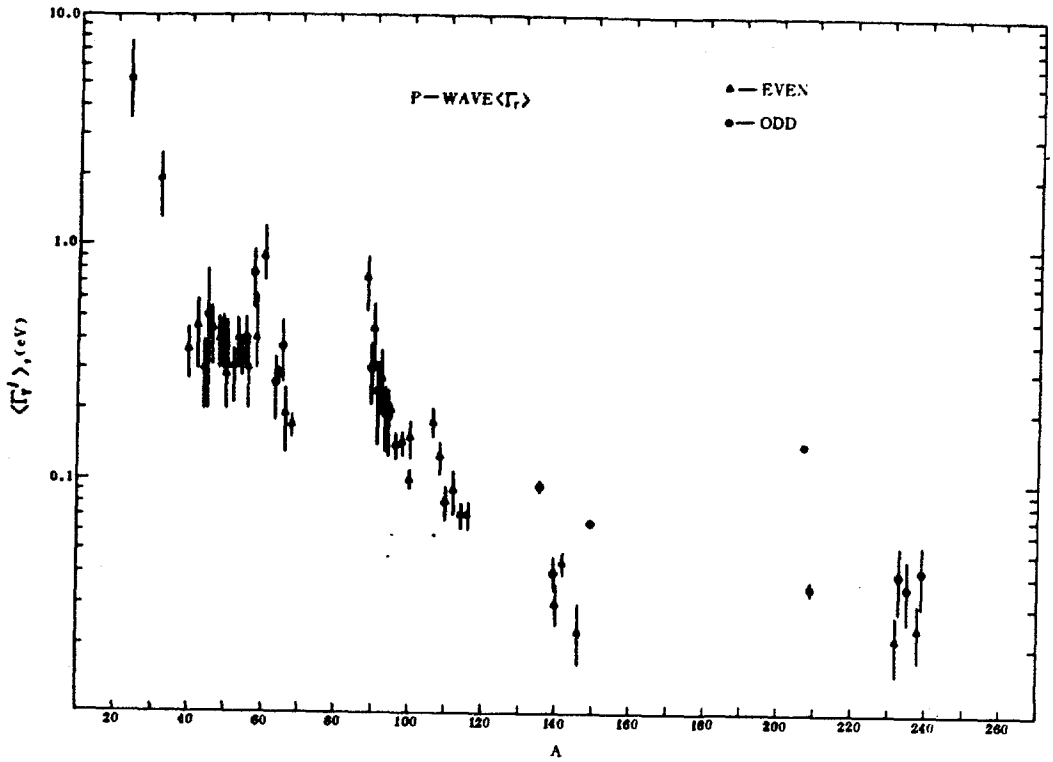

Figure 2. Variation of the average p-wave radiative widths with mass number A of target nucleus

By means of an empirical experession $\langle \Gamma_\gamma \rangle = K\ Z^{\alpha} A^{\beta} Sn^{\gamma}$, which is similar to reference (3), and the least squares analysis, average radiative widths are fitted with the following forms:

$$\langle \Gamma_\gamma^0 \rangle = 31\ Z^{-2.5}\ A^{0.56}\ Sn^{0.83} \qquad \text{(in eV)}, \qquad (3)$$

$$\langle \Gamma_\gamma^1 \rangle = 24\ Z^{1.3}\ A^{-2.6}\ Sn^{0.95} \qquad \text{(in eV)}. \qquad (4)$$

where the neutron binding energy Sn is experessed in MeV. Generally, the experimental values are in resonable agreement with those calculated on the basis of Eq.(3) and (4) except 16 nuclides which are around A=50 and 208 as well as ^{114}, ^{116}Cd for s-wave radiative widths and ^{23}Na, ^{32}S, ^{60}Ni, ^{88}Sr, ^{140}Ce, ^{146}Nd and ^{207}Pb for p-wave.

Analysis of the Strong-Coupling Dipole Model for Average Total Radiative Widths $\langle \Gamma_\gamma^0 \rangle$

In the fast neutron capture calculations there are three reac-

tion mechanisms which are usually used, i.e. compound-nucleus, direct and semidirect interation theories. From a qualitative point of view, the relative importance of these contributions to (n,γ) cross sections is given in Fig.3. For orientation, the rapid falloff of the compound-nucleus contribution typically occurs near En=1 MeV, and the peak in the semidirect contribution is in the neighborhood of 14 MeV, where the (n,γ) cross section is $\sim$1 mb. For most applications the contribution of compound-nucleus is the most important among the three ones.

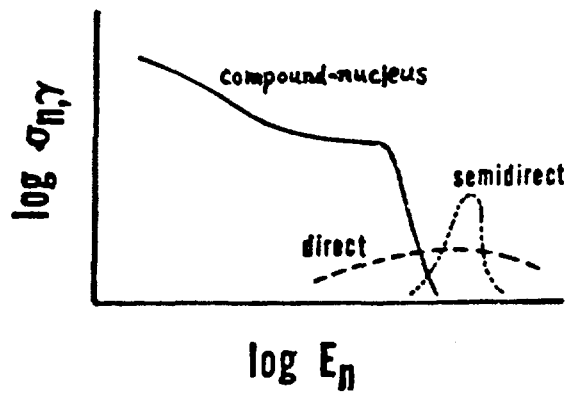

Figure 3. Schematic view of the relative importance of different reaction mechnisms to neutron capture in a medium-weight nucleus.

There are two models which are commonly used to determine radiative widths in compound-nucleus theory calculations, they are the Weisskopf strong coupling model[8] and the giant dipole resonance model[9]. The former was adopted by us because it has a more complete set of parameters. For example, using Cameron type[10] level density formula and parameters, 202 nuclides among 207 ones can be analysed and calculated.

In terms of compund-nucleus theory[11] an estimate of average total radiative width can be expressed as:

$$\langle \Gamma_\gamma (E,A) \rangle = \frac{1}{\rho(E,A)} \int_0^E f(E,\varepsilon_\gamma)\, \rho(E-\varepsilon_\gamma, A)\, d\varepsilon_\gamma , \qquad (5)$$

where ρ(E,A) and ρ(E-ε_γ,A) are the level densities of the compound nucleus and the residnal nucleus respectively, the gamma-ray strength function f(E,ε_γ) contains the energy dependent transition matrix elements and phase space factor $\varepsilon_\gamma^{2\ell+1}$ which is dependent on the transition multipolarity. For electric dipole emission, which usually gives the largest contribution to the radiative decay process, the radiative width for s-wave neutron at the binding energy Sn is

$$\langle \Gamma_\gamma^0(S_n,A)\rangle = \frac{C_\gamma}{\rho(S_n,A)} \int_0^{S_n} f_{E1}(\varepsilon_\gamma)\, \varepsilon_\gamma^3\, \rho(S_n-\varepsilon_\gamma, A)\, d\varepsilon_\gamma \quad , \qquad (6)$$

where $f_{E1}(\varepsilon_\gamma)$ stands for the strength function of electric dipole radiation and C_γ is the coupling coefficient introduced.

Puting, $f_{E1}(\varepsilon_\gamma)=1$, the formula (6) becomes the Weisskopf formula, as described by J.E.Lynn,

$$\langle \Gamma_\gamma^0(S_n,A)\rangle = \frac{C_\gamma}{\rho(S_n,A)} \int_0^{S_n} \varepsilon_\gamma^3\, \rho(S_n-\varepsilon_\gamma, A)\, d\varepsilon_\gamma \quad , \qquad (7)$$

The strength function for electric dipole radiation is usually taken as Lorentzian in shape. More recently D.G.Gardner et al.[12,13] have investigated the use of Breit-Wigner shapes and have developed expressions for f_{E1} based on systematics covering the mass range A>40, that is an energy dependent Breit-Wigner (EDBW) model. The Cameron type level density formula and parameters[10] are used by us.

Firstly, the known experimental values $\langle \Gamma_\gamma^0 \rangle$ are utilized to determine a set of coupling coefficients C_γ. For 202 nuclides the values C_γ from formulas (6) and (7) are between $10^0 \sim 10^1$ MeV^{-3} and $10^{-8} \sim 10^{-7}$ MeV^{-3} respectively (See Fig.4 and 5). The values C_γ from the smoothed curves are used to calculate the radiative widths $\langle \Gamma_\gamma^0 \rangle$ in order to test the status of agreement with the experimental data. The radiative widths of the nuclides which are deficient in the experimental data could be calculated from the smoothed values of C_γ.

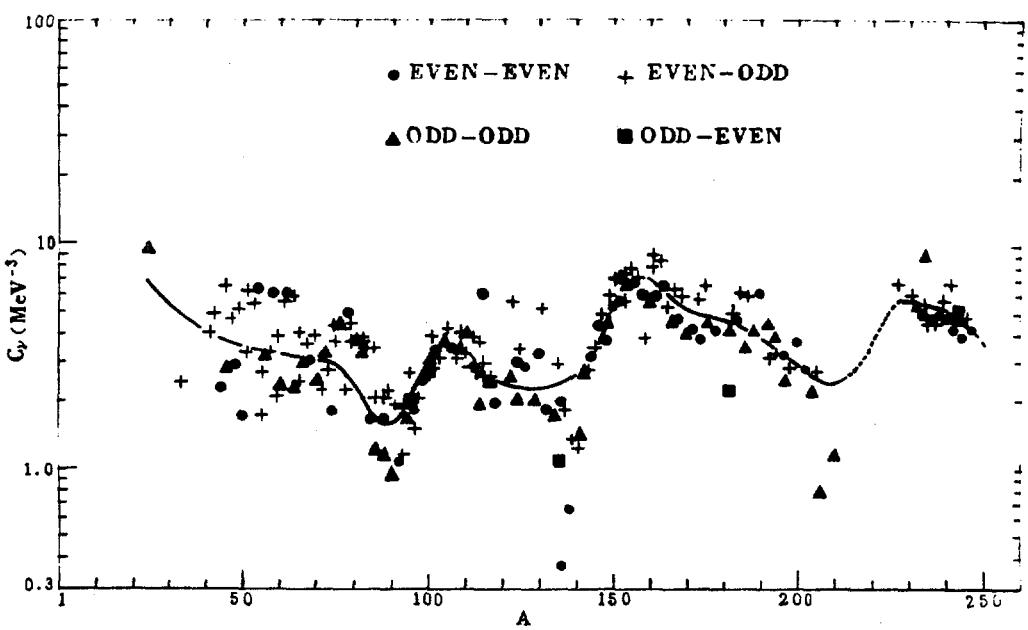

Figure 4. The coupling coefficients C_r from formula (6) plotted versus mass number A of compound nucleus.

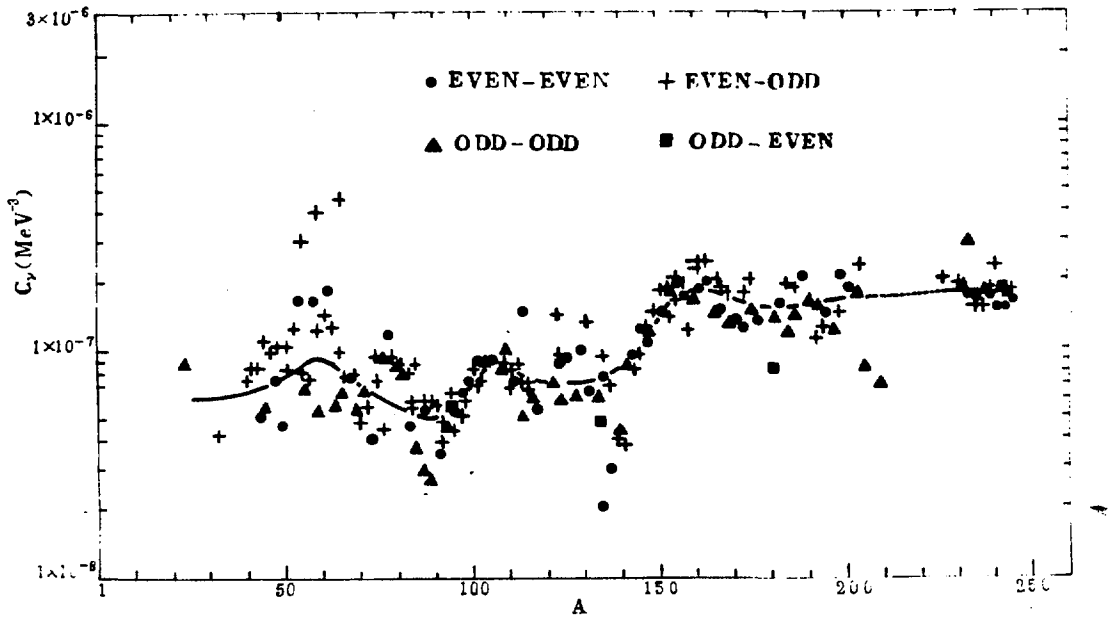

Figure 5. Variation of the coupling coefficients C_r from formula (7) with mass number A of compound nucleus.

Result and Discuss

In the above passages the expirical expression and the strong-coupling dipole model are utilized to fit and analyse the experimental values $\langle\Gamma_\gamma^0\rangle$ and/or $\langle\Gamma_\gamma^1\rangle$. The goodness of fit can be expressed by the value χ_r^2:

$$\chi_r^2 = \frac{\sum_{i=1}^{N} (\Gamma_{\gamma i} - \Gamma_{\gamma f i})^2 / (\Delta\Gamma_{\gamma i})^2}{\nu}, \qquad (8)$$

where $\Gamma_{\gamma i}$ and $\Delta\Gamma_{\gamma i}$ are experimental values and their corresponding errors, $\Gamma_{\gamma f i}$ is the fitting or calculated value, and ν is the number of degrees of freedom. The χ_r^2 values are listed in Table 1.

Table 1. the values χ_r^2 of the results

fitting method	experimerimental expression		strong-coupling dipole model	
	formula (3)	formula (4)	formula (6)	formula(7)
nuclear numbers fitted	191	50	202	202
χ_r^2	7.9	4.2	7.3	4.0

All of the formulas (3),(4),(6) and (7) can be used to calculate average total radiative widths of nuclides which lack experimental values. Formula (3) and (4) are suitable to calculate the values $\langle\Gamma_\gamma^0\rangle$ and $\langle\Gamma_\gamma^1\rangle$ for all nuclides except those around A=50 and 208 respectively; formulas (6) and (7) are appropriate to all nuclides from Na to Cm. And it can be noticed that for $\langle\Gamma_\gamma^0\rangle$ the value χ_r^2 of formula (7) is the smallest.

We have respectively utilized formulas (6) and (7) as well as their correspounding values C_r interpolated to calculate the values $\langle\Gamma_\gamma^0\rangle$ of 83 nuclides which have the neutron binding energy but have not experimental data. They are shown in Table 2.

The level density is an important physical magnitude in the calculations of neutron reaction cross sections, spectrums and angular distributions. Unforturately, there is very deficient in direct experimental information about it. For this reason it is interesting to compare the calculated $\langle\Gamma_\gamma(Sn)\rangle$ values using statistical model with the experimental ones. In this comparison one may notice follwing things:

In terms of the smoothed values $\langle\Gamma_\gamma\rangle$ from formulas (6) and (7) respectively, it may be seen that the most result of even-even and odd-odd or odd A nuclides don't show obvious deviation. This indicates that the parameters of level density for these nuclides are rather suitable. However, there are a few even-even or odd nuclides whose C_r deviate obviously from those of odd-odd nuclides. For these nuclides one may conclude that either experimental values $\langle\Gamma_\gamma^0\rangle$ and/ or their binding energies are unreliable, or the pairing energies are unsuitable. Illustrate with examples, the pairing energies for even-even nuclides A=78, 114 etc. seem to be larger; perhaps those of even-even and odd A nuclides A=136, 138, 181 are smaller.

If level density formula is reasonable, the parameters in this formula are suitable for pairing energies and shell corrections and

Table 2. the values $\langle \Gamma_\gamma^\circ \rangle$ from the systematics for those nuclides which lack experimental data.

target nuclide	$\langle \Gamma_\gamma^\circ \rangle$ (meV) (7)*	(6)*	target nuclide	$\langle \Gamma_\gamma^\circ \rangle$ (meV) (7)*	(6)*	target nuclide	$\langle \Gamma_\gamma^\circ \rangle$ (meV) (7)*	(6)*
12-Mg-24	2700	3000	46-Pd-107	110	110	68-Er-164	84	80
12-Mg-25	4000	6800	50-Sn-115	110	110	68-Er-170	70	67
12-Mg-26	1900	1700	50-Sn-116	80	70	70-Yb-168	75	70
13-Al-27	2700	3100	50-Sn-118	76	67	70-Yb-170	72	69
14-Si-28	3600	4800	50-Sn-120	78	68	70-Yb-176	57	59
14-Si-29	3800	6200	50-Sn-122	98	92	71-Lu-176	85	97
14-Si-30	1800	1700	50-Sn-124	110	110	72-Hf-174	60	61
15-P -31	2500	3000	52-Te-124	88	84	72-Hf-176	64	64
16-S -33	2800	4800	52-Te-128	110	120	72-Hf-178	56	58
16-S -34	1500	1500	52-Te-130	190	230	72-Hf-179	69	75
17-Cl-35	2000	2400	53-I -129	120	130	72-Hf-180	57	59
17-Cl-37	920	730	54-Xe-124	62	50	73-Ta-182	77	80
18-Ar-36	2000	2500	54-Xe-126	67	56	74-W -180	62	65
18-Ar-40	690	510	54-Xe-128	70	62	76-Os-187	69	63
19-K -39	1300	1300	54-Xe-130	83	81	78-Pt-196	110	95
19-K- 41	600	350	54-Xe-132	120	150	78-Pt-198	140	130
20-Ca-46	880	790	54-Xe-134	220	310	80-Hg-196	130	120
20-Ca-48	850	730	54-Xe-136	210	260	80-Hg-200	210	220
23-V -50	1900	2300	56-Ba-132	61	56	80-Hg-202	370	430
23-V -51	1100	920	57-La-138	240	330	81-Tl-204	1100	1800
27-Co-60	890	820	58-Ce-136	76	70	82-Pb-206	2100	3800
30-Zn-70	230	200	58-Ce-138	110	120	82-Pb-207	3800	9000
34-Se-82	190	160	58-Ce-142	61	59	82-Pb-208	540	430
40-Zr-93	140	140	61-Pm-148	72	75	90-Th-228	26	26
40-Zr-96	86	73	62-Sm-150	45	42	90-Th-229	35	38
46-Pd-102	160	180	66-Dy-156	72	75	92-U -232	34	37
46-Pd-104	120	120	66-Dy-158	80	83	92-U -237	31	32
46-Pd-106	91	82	68-Er-162	85	83			

* The values calculated by use of formula (7) or (6).

strength fuction of electric dipole emission are reliable, the variation of the values C_r from theoretical formula (6) with mass number A would be a constant nears one. From Fig.4 and 5 the values C_r of formula (6) are between 1.0~10; however those of formula (7) are between $3.0\times10^{-8} \sim 3.0\times10^{-7}$. Therefore the strength function $fE1(\varepsilon_\gamma)$ of elactric dipole radiation within $40 < A < 208$ given by M.A.Gardner et al. is appropriate and can be extend to more wide range which we have dealed with.

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A New Set of Level Density Parameters for Fermi Gas Model

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Abstract In order to recommend more accurate and reliable parameters of nuclear level density, three kinds of experimental data have been collected and evaluated. Based on the newest and more kinds of experimental data a new set of level density parameters has been obtained. It may be seen from the results that our parameters are in good agreement with these more accurate and newer measurements, especially to level spacings.

Nuclear level densities are a crucial ingredient in the statistical models, for instance, in the calculations of the widths, cross sections, emitted particle spectra etc. for various reaction channels. Up to now, the Gilbert-Cameron type level density formula [1] as well as parameters is still applied to the calculations on the statistical models widely. Based on their work, Cook et al.[2] have also got a set of parameters. Because these parameters only depend on Z and N, the numbers of proton and neutron in the nucleus respectively, Gilber-Cameron's formula is universally applicable. However, their parameters are based on the available experimental data at that time. The present work attempt to obtain a new set of parameters based on the newest and more kinds of experimental data.

In order to recommend more accurate and reliable parameters of level density, three kinds of experimental data have been collected and evaluated: average level spacing D_0 and radiative capture width Γ_γ^0 at the neutron binding energy and cumulative number N_0 of level (all spin) at the low excitation energy in the amount of 667 which reported during the period of 1973 to 1983 [3]. While that in Gilbert-Cameron's are 129 level spacings which are report-

ed during the peropd of 1959 to 1964. So the experimental data adopted in this work are of high precision, wide distribution of nuclei and more kinds of data.

Based on these experimental data especilly D_o and N_o, the parameters S(Z), S(N), P(Z) and P(N) have been adjusted. And a new set of level density parameters has been obtained (denoted as work 1). Next the empirical parameters have also been reobtained to fit the experimental data which we have collected. In the Gilbert-Cameron formula, the corresponding quantities including the empirical parameters are as follows:

$$a = \left[0.00917(S(Z)+S(N))+QB\right]A,$$
$$U_x = 2.5+150/A. \qquad (1)$$

The new ones of 0.00880, 1.4 and 263 are adopted respectively instead of 0.00917, 2.5 and 150 used in the formula. Thus, the formula are rewriten as follows (denoted as work 2):

$$a = \left[0.00880(S(Z)+S(N))+QB\right]A,$$
$$U_x = 1.4+263/A. \qquad (2)$$

Where the values of QB are taken as:

$$QB = \begin{cases} 0.142, & 29 \leq Z \leq 62 \text{ (and } N \leq 89); \; 79 \leq Z \leq 85; \\ 0.120, & Z < 28; \; 62 \text{ (and } N > 89) \leq Z \leq 78; \; Z \geq 86. \end{cases}$$

A detailed comparison with Gilbert-Cameron's and Cook's is shown in Table 1, where the percentages of the nuclei whose relative deviations of calculated values to the experimental data are within a certain scope are given.

Table 1 A comparison between three results

Relative Diviation		Gilbert-Cameron	Cook et al	Work 1	Work 2
δD_0	$\leqslant \pm 20\%$	21.5	22.4	47.8	48.7
	$\leqslant \pm 50\%$	29.4	28.1	36.4	37.3
	$\leqslant \pm 100\%$	24.1	27.6	15.4	13.2
	$> \pm 100\%$	25.0	21.9	0.4	0.8
$\chi^2_{D_0}$		175.9	120.9	11.3	11.4
δN_0	$\leqslant \pm 20\%$	13.0	13.9	18.5	18.9
	$\leqslant \pm 50\%$	30.7	23.9	36.1	31.5
	$\leqslant \pm 100\%$	49.2	50.0	41.2	44.5
	$> \pm 100\%$	7.1	12.2	4.2	5.1
$\chi^2_{N_0}$		13.9	47.9	11.5	10.1
$\delta \Gamma_\gamma^0$	$\leqslant \pm 20\%$	26.9	26.4	27.9	30.8
	$\leqslant \pm 50\%$	39.8	40.8	37.3	35.8
	$\leqslant \pm 100\%$	30.3	29.8	31.8	30.8
	$> \pm 100\%$	3.0	3.0	3.0	2.6
$\chi^2_{\Gamma_\gamma^0}$		9.6	9.7	11.0	9.3
$\chi^2_{D_0} + \chi^2_{N_0} + \chi^2_{\Gamma_\gamma^0}$		199.4	178.5	33.8	30.8

From Table 1, the good agreement with these more accurate and newer measurements, especially to level spacings D_0 should be obtained. The number of nuclei whose relative deviations are less than ±20% is nearly a half of the total one and the deviations which are more than ±100% is reduced to 1% of the total one. Intuitively this new set of level density parameters seems to be more accurate. Of course, it should be tested by the calculations on statistical models. The parameters adopted by our work are listed in Table 2.

The giant dipole resonance parameters are necessary for calculating radiative capture widths, which are taken from measured values [6]. But lack of experimental data for some nuclei, usually their values are substituted by those of adjacent nuclides. In this work, the adopted giant dipole resonance parameters [7] are matched with recommended level density parameters and also they are worth recommending to be used in theoretical calculations.

It is worth noting that there is not a distinct improvement in the calculations of N_0 and Γ_γ^0. And the negative relative deviations of N_0 are much more than the positive ones (even improved in this work). It turns out there are some problems remained at the low excitation energies in Gilbert-Cameron's formula to be improved.

The outhors are grateful to Profs. Zhou Delin and Ding Dazhao for their help with this work.

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Table 2 the level density parameters of this work

N OR Z	PN	SN	PZ	SZ
11	0.00	6.80	0.00	-5.40
12	2.67	7.53	2.00	-3.80
13	0.00	7.55	0.00	-5.72
14	1.80	7.21	2.09	-7.80
15	0.00	7.44	0.00	-8.97
16	1.67	8.07	1.45	-9.50
17	0.00	9.10	0.00	-10.10
18	1.86	9.81	1.62	-10.70
19	0.00	10.60	0.00	-11.38
20	2.01	11.39	1.75	-12.00
21	0.00	13.85	0.00	-12.10
22	1.64	13.68	1.53	-12.80
23	-0.10	14.50	-0.26	-12.20
24	1.40	14.10	1.20	-14.30
25	-0.10	14.93	0.00	-14.00
26	1.36	13.70	1.30	-14.40
27	-0.20	14.55	-0.10	-14.75
28	1.20	12.50	1.20	-16.57
29	0.00	13.70	0.00	-17.10
30	1.15	13.45	1.06	-17.95
31	-0.20	15.45	0.00	-17.68
32	1.32	14.98	1.06	-16.78
33	-0.15	15.80	0.00	-16.65
34	1.30	16.38	1.35	-16.35
35	-0.18	17.25	0.00	-16.70
36	1.50	17.55	1.10	-15.20
37	-0.10	18.05	0.20	-16.20
38	1.90	17.65	1.24	-16.41
39	0.00	18.59	0.29	-17.05
40	1.43	18.71	1.35	-16.75
41	-0.28	18.95	0.00	-15.40
42	1.50	18.99	1.17	-15.85
43	-0.10	18.60	-0.15	-15.50
44	1.70	18.25	1.15	-17.29
45	-0.10	18.20	-0.10	-18.44
46	1.57	17.38	1.20	-17.82

N OR Z	PN	SN	PZ	SZ
47	0.00	16.72	0.34	-18.62
48	1.60	14.25	1.36	-18.58
49	-0.28	14.88	0.28	-19.65
50	1.20	12.88	1.47	-19.95
51	0.10	12.95	0.00	-19.44
52	0.75	13.65	1.00	-17.75
53	-0.30	14.80	0.00	-17.70
54	1.12	15.20	1.12	-16.72
55	0.00	15.89	0.26	-16.95
56	1.15	17.15	1.20	-14.37
57	0.00	17.00	0.10	-14.44
58	0.80	17.73	1.40	-14.00
59	-0.25	19.75	0.93	-12.30
60	1.35	18.80	1.36	-11.91
61	-0.32	19.45	0.36	-11.59
62	1.25	19.51	1.22	-10.78
63	-0.44	20.17	-0.20	-11.40
64	1.14	19.85	0.97	-10.21
65	0.08	19.98	-0.20	-10.00
66	1.32	20.05	0.78	-9.35
67	-0.11	20.28	0.00	-9.30
68	1.15	19.83	0.52	-8.85
69	-0.16	20.20	0.00	-8.91
70	1.06	19.44	0.68	-8.13
71	0.22	18.64	0.00	-7.90
72	1.65	17.31	0.68	-7.45
73	-0.20	17.08	0.00	-7.24
74	1.37	16.16	0.69	-7.30
75	-0.16	16.65	0.00	-7.05
76	1.20	15.33	0.58	-6.68
77	-0.54	15.35	0.28	-8.28
78	0.92	13.54	0.78	-7.57
79	-0.57	13.17	0.20	-7.80
80	1.17	10.75	0.73	-7.89
81	-0.30	10.40	0.20	-8.70
82	0.85	9.15	0.80	-8.50
83	-0.37	10.00	0.00	-7.71
84	1.40	10.07	0.89	-6.38

N OR Z	PN	SN	PZ	SZ
85	-0.11	12.50	0.00	-5.47
86	1.12	11.80	0.79	-4.78
87	-0.16	12.40	0.00	-4.37
88	1.09	12.35	0.80	-4.05
89	-0.35	13.60	0.00	-4.12
90	0.72	13.47	0.58	-4.00
91	-0.20	13.00	0.00	-5.00
92	0.92	12.11	0.61	-5.24
93	-0.30	12.15	0.00	-5.60
94	0.73	11.21	0.51	-6.15
95	0.30	11.25	0.00	-6.45
96	0.79	9.80	0.72	-6.93
97	0.00	10.43	0.00	-7.20
98	0.80	9.70	0.77	-7.74
99	0.00	9.75		
100	0.80	8.65		
101	0.00	8.72		
102	0.80	8.23		
103	0.00	7.80		
104	0.85	7.50		
105	0.00	7.40		
106	0.50	7.35		
107	0.00	7.15		
108	0.75	6.96		
109	0.00	6.94		
110	0.75	6.55		
111	0.00	6.72		
112	0.86	6.49		
113	-0.10	6.69		
114	1.10	6.00		
115	-0.26	5.60		
116	0.84	4.53		
117	-0.33	4.25		
118	0.72	2.60		
119	0.03	2.39		
120	0.96	1.58		
121	0.10	2.15		
122	0.52	0.46		

N OR Z	PN	SN	PZ	SZ
123	-0.05	-0.85		
124	0.41	-1.69		
125	-0.20	-2.63		
126	0.38	-3.16		
127	0.00	-1.37		
128	0.45	-0.41		
129	0.00	0.71		
130	0.61	1.66		
131	0.00	2.62		
132	0.78	3.22		
133	0.00	3.76		
134	0.67	4.10		
135	0.00	4.46		
136	0.67	4.83		
137	0.00	5.09		
138	0.79	5.18		
139	0.00	5.25		
140	0.80	4.75		
141	0.00	5.09		
142	0.60	4.95		
143	0.00	5.08		
144	0.49	4.87		
145	0.00	5.10		
146	0.52	4.88		
147	0.00	5.58		
148	0.58	5.18		
149	0.00	5.80		
150	0.39	5.50		

CALCULATIONS OF THE DOUBLE DIFFERENTIAL CROSS SECTION FOR PARTICAL EMISSIONS IN THE CONTINUUM REGION

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Abstract

Based on the framework of the width fluctuation-corrected Hauser-Feshbach theory, this work will give the formulae for calculating the double differential cross section in the continuum region. Taking the neutron-induced inelastic scattering as an example, we calculated the spectra for given outgoing angles, the angular distributions and the spectra. All the calculated cross sections are found reasonable and self-consistent.

To study the double differential cross sections of the secondary particles in the continuum region based on the framework of the width-fluctuation-corrected Hauser-Feshbach theory, we should pay attention to the extensions from the original theory. The discretization method has been employed to deal with the width fluctuation correction factor and the statistical description has been used to treat the continuum levels of the residual nucleus as the two essential points.

For the neutron induced reactions the inelastic scattering cross section and angular distribution of kth level (u_k, I_k, h_k) can be written in the form.

$$\sigma(U_k,I_k,\pi_k)=\frac{\pi\lambda_n^2}{2(2I_0+1)}\sum_{J\pi l l' l_k j_k}(2J+1)\frac{T_{ll}^{J\pi}(E_c)T_{l_k j_k}^{J\pi}(E_c-U_k)}{T^{J\pi}}$$

$$\times W_{ll,l_k j_k}^{J\pi}(U_k). \qquad k=0,1,\cdots,K_m \tag{1}$$

$$\sigma(U_k,I_k,\pi_k,\theta_c)=\sum_{L=0,2,4\cdots}B_c(L,U_k)P_L(\cos\theta_c). \tag{2}$$

$$B_c(L,U_k)=\frac{\lambda_n^2}{8(2I_0+1)}\sum_{J\pi l_k j_k}(2J+1)Q_L^J(I_0 I_k j j_k)$$
$$\times\frac{T_{lj}^{J\pi}(E_c)T_{l_k j_k}^{J\pi}(E_c-U_k)}{T^{J\pi}}W_{lj,l_k j_k}^{J\pi}(U_k). \qquad (3)$$
$$k=0,1,\cdots,K_m$$

In particular if the residual nucleus keeps its excitation energy in the continuum region, the inetastic cross section can be written in the form

$$\sigma_I(E_c)=\frac{\pi\lambda_n^2 I}{2(2I_0+1)}\sum_{J\pi lj}(2J+1)\frac{T_{lj}^{J\pi}(E_c)T_n^{J\pi}}{T^{J\pi}}\times W_{lj}^{J\pi} \qquad (4)$$

Where $T_n^{J\pi}$ is the transmition coefficient of neutron emission in the continuum region. which reads

$$T_n^{J\pi}=\int_{U_{K_m}}^{E_c}\sum_{J'\pi'}\sum_{lj}T_{lj}^{J\pi}(E_c-U)\rho_A^{J'\pi'}(U)\mathrm{d}U. \qquad (5)$$

Where $\rho_A^{J\pi}$ is the level density of residual nucleus A with the excitation energy u.

Thus the total transmition coefficient can be obtained by

$$T^{J\pi}=\sum_{k=0}^{K_m}\sum_{l_k j_k}T_{l_k j_k}^{J\pi}(E_c-U_k)+T_n^{J\pi}+T_f^{J\pi}+T_\gamma^{J\pi}+\cdots. \qquad (6)$$

Where $W_{l_k j_k}(l_k)$ and W_{lj} in (1), (3) and (4) are the width fluctuation correction factor[1].

$$W_{lj,l_k j_k}^{J\pi}(U_k)=\frac{1+2\delta_{U_0 U_k}\delta_{ll_k}\delta_{jj_k}}{2}\int_0^1\mathrm{d}y$$
$$\times\exp\left[-\frac{T_n^{J\pi}+T_f^{J\pi}+T_\gamma^{J\pi}}{2T^{J\pi}}\left(\frac{1}{y}-1\right)\right]y^{-2}\left[1+\frac{T_{lj}^{J\pi}(E_c)}{T^{J\pi}}\left(\frac{1}{y}-1\right)\right]^{-1}$$
$$\times\left[1+\frac{T_{l_k j_k}^{J\pi}(E_c-U_k)}{T^{J\pi}}\left(\frac{1}{y}-1\right)\right]^{-1}$$
$$\times\prod_{k'=0}^{K_m}\prod_{l_{k'}}\prod_{j_{k'}}\left[1+\frac{T_{l_{k'} j_{k'}}^{J\pi}(E_c-U_{k'})}{T^{J\pi}}\left(\frac{1}{y}-1\right)\right]^{-\frac{1}{2}}. \qquad (7)$$

$$W_{lj}^{J\pi}=\frac{1}{2}\int_0^1\mathrm{d}y\exp\left[-\frac{T_n^{J\pi}+T_f^{J\pi}+T_\gamma^{J\pi}}{2T^{J\pi}}\left(\frac{1}{y}-1\right)\right]y^{-2}$$
$$\times\left[1+\frac{T_{lj}^{J\pi}(E_c)}{T^{J\pi}}\left(\frac{1}{y}-1\right)\right]^{-1}\prod_{k'=0}^{k_m}\prod_{l_{k'}}\prod_{j_{k'}}\left[1+\frac{T_{l_{k'} j_{k'}}^{J\pi}(E_c-U_{k'})}{T^{J\pi}}\times\left(\frac{1}{y}-1\right)\right]^{-\frac{1}{2}}. \qquad (8)$$

In order to calculate the spectra of secondary particle emission in the continuum region at a given outgoing angle, the whole continuum region should be divided into N intervals Δu_n (n=1,2,··· N). Which implies that all of the levels in Δu_n are concentrated at the point u_n. This is the discretization method.

Hence one can get the double differential cross section as

$$\sigma(E_c-U_n,\theta_c)=\sum_{I_n\pi_n}\rho_\lambda^{I_n\pi_n}(U_n)\sigma(U_n,I_n,\pi_n;\theta_c)\,. \tag{9}$$

Where E_c-u_n is the energy of outgoing neutrons.

The Gilbert-Cameron type level density formula is employed to make the discretization level density as mentioned above.

The width fluctuation correction factor must be modified in our model. The whole particle emissions in the continuum region were treated as one channel only as did before. Then the width fluctuation correction factor in (7), (8) are available. But in our model the discretization method is used to treat the whole continuum region. Thus the width fluctuation correction factor becomes into

$$\begin{aligned}W_{I_iI_qj_q}^{I\pi}(U_q)=&\frac{1+2\delta_{U_0U_q}\delta_{I_iI_q}\delta_{j_ij_q}}{2}\int_0^1 dy\exp\left[-\frac{T_I^{I\pi}+T_\nu^{I\pi}}{2T^{I\pi}}\left(\frac{1}{y}-1\right)\right]\\&\times y^{-2}\left[1+\frac{T_{I_i}^{I\pi}(E_c)}{T^{I\pi}}\left(\frac{1}{y}-1\right)\right]^{-1}\left[1+\frac{T_{I_qj_q}^{I\pi}(E_c-U_q)}{T^{I\pi}}\left(\frac{1}{y}-1\right)\right]^{-1}\\&\times\prod_{k'=0}^{K_m}\prod_{I_{k'}}\prod_{j_{k'}}\left[1+\frac{T_{I_{k'}j_{k'}}^{I\pi}(E_c-U_{k'})}{T^{I\pi}}\left(\frac{1}{y}-1\right)\right]^{-\frac{1}{2}}\\&\times\prod_{n'=1}^{N}\prod_{I_{n'}}\prod_{\pi_{n'}}\exp\left[-\frac{1}{2}\rho_\lambda^{I_{n'}\pi_{n'}}(U_{n'})\Delta U_{n'}\ln\prod_{I_{n'}j_{n'}}\right.\\&\left.\left(1+\frac{T_{I_{n'}j_{n'}}^{I\pi}(E_c-U_{n'})}{T^{I\pi}}\left(\frac{1}{y}-1\right)\right)\right].\end{aligned} \tag{10}$$

$$q=\begin{cases}k & \text{the discrete energy level}\\ n & \text{the continuum region}\end{cases}$$

The width fluctuation factor for radiation capture channel and fission channel is

$$W_l^{\prime} := \frac{1}{2}\int_0^1 \mathrm{d}y \exp\left[-\frac{T_l^{\prime\pi}+T_l^{\prime\nu}}{2T^{\prime\pi}}\left(\frac{1}{y}-1\right)\right] y^{-2}$$

$$\times\left[1+\frac{T_l^{\prime\pi}(E_c)}{T^{\prime\pi}}\left(\frac{1}{y}-1\right)\right]\prod_{k'=0}^{K_m}\prod_{l_{k'}^{\prime}l_{k'}}\left[1+\frac{T_{l_{k'}^{\prime}l_{k'}}^{\prime\pi}(E_c-U_{k'})}{T^{\prime\pi}}\left(\frac{1}{y}-1\right)\right]^{-\frac{1}{2}}$$

$$\times\prod_{n'=1}^{N}\prod_{l_{n'}^{\prime}}\prod_{\pi_{n'}^{\prime}}\exp\left[-\frac{1}{2}\rho_{\lambda}^{\prime n^{\prime}\pi_{n^{\prime}}}(U_{n^{\prime}})\Delta U_{n^{\prime}}\ln\prod_{l_{n^{\prime}}^{\prime}l_{n^{\prime}}}\right.$$

$$\left.\left(1+\frac{T_{l_{n^{\prime}}^{\prime}l_{n^{\prime}}}^{\prime\pi}(E_c-U_{n^{\prime}})}{T^{\prime\pi}}\left(\frac{1}{y}-1\right)\right)\right]. \tag{11}$$

It is easy to extend the formulae mentioned above into the situation in which the other types of particale imissions are taken into account. As before if we need to calculated the spectra of these channels for the fixed outgoing angles only, the particale emissions in whole continuum region was considered as one reaction channel, the formulae (7) and (8) are available. Otherwise, if the double differential cross section is needed to be calculated then formulae (10) and (11) should be used in stead.

The angular distribution for particale emission in continuum will be given by the integration over the energy E'.

$$\sigma_I(\theta_c)=\int_0^{E_c-U_{k_m}} \mathrm{d}E'\sigma(E',\theta_c)\,. \tag{12}$$

Also the inelastic scattering cross section can be obtained by the integration over the whole solid angle.

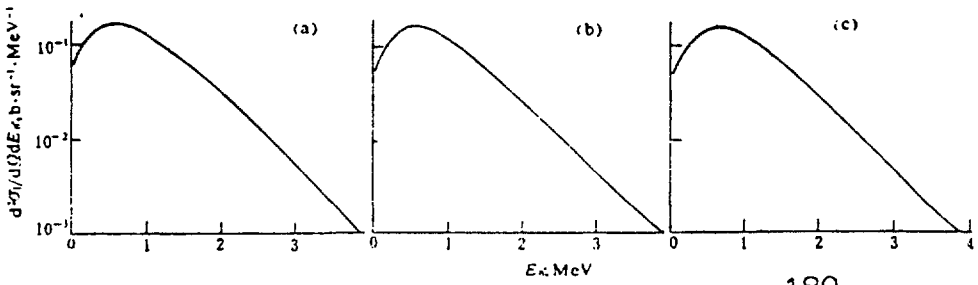
$$\begin{aligned}\sigma_I(E_c)&=\int\sigma_I(\theta_c)\mathrm{d}\Omega_c\\&=2\pi\int_0^{\pi}\sin\theta_c\mathrm{d}\theta_c\int_0^{E_c-U_{k_m}}\mathrm{d}E'\sigma(E',\theta_c)\,.\end{aligned} \tag{13}$$

Then the normalized spectra of neutron emission is given by

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E'}=2\pi\int_0^{\pi}\sin\theta_c\mathrm{d}\theta_c\sigma(E_c-U_n,\theta_c)/\sigma_I(E_c). \tag{14}$$

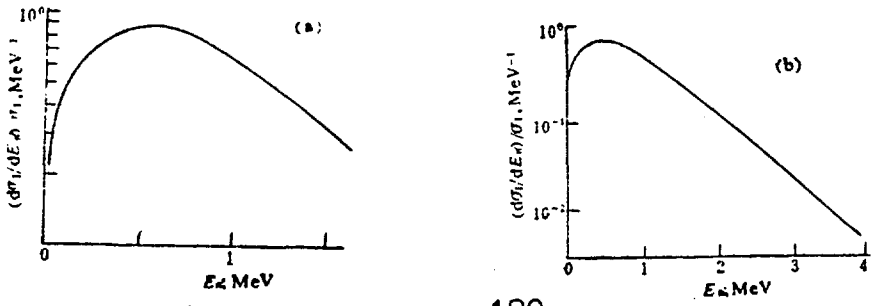
Finally, we took ^{179}Hf(n,n') and ^{180}Hf(n,n') as the examples. The inelastic scattering spectra for given outgoing angles, the angular distributions and the spectra are shown in Fig. 1.

Fig.1.



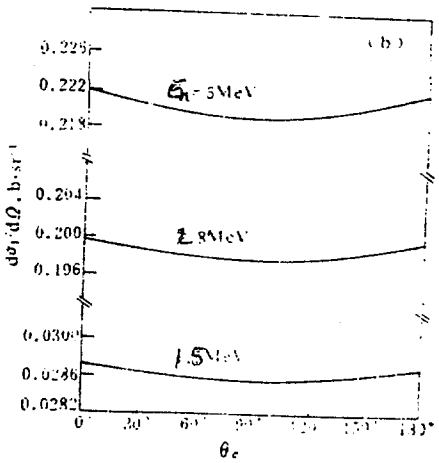
the double differential cross section for ^{180}Hf(n,n')

E_n=5MeV; (a) θ_c=20°; (b) θ_c=90°; (c)=120°.



the spectra for ^{180}Hf(n,n')

(a) E_n=2.8MeV; (b) E_n=5MeV.



the angular distributions for ^{180}(n,n')

In the calculations the excitation energies u_{km} of the highest discrete energy level are 0.4761 MeV for ^{179}Hf, 1.1416 MeV for ^{180}Hf respectively.

As shown in Fig. 1. the spectras of emitted particlae have the characteristices of Marxwell distribution, and the angular distribution are nearly istropic. Obersely, this is caused by the theoretical model limited in the statistical theory for compound nucleus and the mechanism of preequilibrium stage is exclusive.

[1]. Su Zongdi et al., China Phys., 1, 952(1981).

THE STATISTICAL THEORY OF COMPOUND NUCLEUS REACTION AND NUCLEAR DATA CALCULATIONS

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Abstract Our work about the statistical theory of compound nucleus reaction and its application in nuclear data calculations is summarized. The work involves deriving some formulas, adjusting the level density parameters and calculating neutron reaction data.

1. INTRODUCTION

The optical model, the statistical theory of the nuclear reaction etc. are the most important and widely used theories in the calculation of the neutron reaction data. This paper will only concern the work about the statistical theory of the compound nucleus reaction and its applications. The different effects in compound nucleus reaction have been compared. The unified treatment of the width fluctuation correction (WFC) have been made for including all kinds of reaction channels in a compound nucleus reaction. We adjusted a new set of level density parameters, which are worth recommending for use, Finally, we shall present briefly our calculated results.

2. THE COMPARISON OF THE DIFFERENT EFFECTS

The statistical theory of nuclear reaction has gone through a series of steps, which are the Hauser-Feshbach (HF) theory [1], the width fluctuation corrected Hauser-Feshbach (WHF) theory [2], the Moldauer theory [3], the Weidenmüller theory [4] etc. respectively. Today it has become even perfect, accurate and self-consistent. In this work we have studied and compared the effects

of the different corrections. For example, the WFC can increase compound elastic scattering cross section and decrease the other cross sections. In contrast the level-level correlation which is taken into account in the Moldauer theory will decrease the compound elastic cross section and increase others. But these effects can not be just canceled with each other. The compound elastic cross section based on the WHF theory is twice or three times larger than one on the HF theory. The calculated results of various cross sections of n+^{235}U reaction are given in Table 1 as a special example

Table 1 The comparison of the results of the WHF theory and the HF theory

En (MeV)	Calculation Method	σ_{abs} (b)	σ_{ce} (b)	σ_{non} (b)	σ_{in} (b)	$\sigma_{n,F}$ (b)	$\sigma_{n,r}$ (b)
0.01	HF	4.18	0.45	3.73	0	2.36	1.37
	WHF	4.18	0.90	3.28	0	2.13	1.15
0.1	HF	3.27	0.55	2.72	0.57	1.58	0.56
	WHF	3.27	0.98	2.29	0.44	1.38	0.47
0.3	HF	3.31	0.48	2.83	1.59	1.00	0.24
	WHF	3.31	0.84	2.47	1.33	0.92	0.22
0.5	HF	3.14	0.36	2.78	1.69	0.91	0.19
	WHF	3.14	0.60	2.54	1.54	0.82	0.17

However, the level-level correlation will affect the compound elastic cross section only by twenty percent as compared with that of the WHF theory. In order to compare the level-level correlation with the WFC, the calculated results and the experimental values of ^{238}U(n,n')^{238}U*(2^+,0.0449 MeV) inelastic scattering are given in Fig 1.

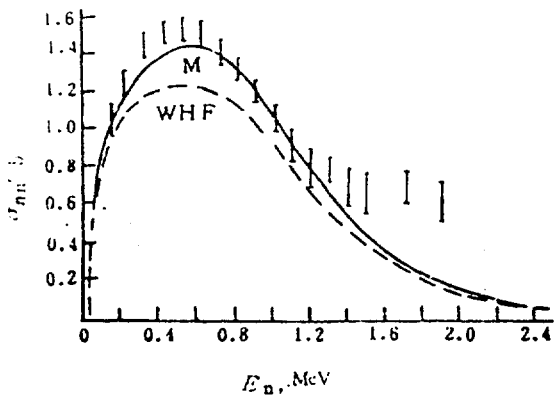

Fig1. The inelastic scattering excitation curves calculated by two kinds of theories (the WHF theory and the Moldauer theory) and the experimental values for $^{238}U(n,n')^{238}U^*$ (2^+, 0.0449 MeV) reaction.

It is seen from the above results that these effects only have a significance in the energy region where the compound elastic cross section is big enough. And the WFC is dominant in the statistical theory of the nuclear reaction. In fact, these secondary are concealed by the parameterization in the nuclear reaction calculation. Therefore, the WHF theory is commonly used to calculate the nuclear data today.

3. THE WIDTH FLACTUATION CORRECTION

We have developed the WHF theory and applied to a nuclear reaction process including radiative capture, fission and particle emission with the residual nucleus in the continuum. The formula of the double differential cross section for particle emission in the continuum region has been derived within the framework of the WHF theory. The cumbersome problems in the derivation of the double differential cross section are how to deal with the continuum states. First, we use a discretization method. The whole continuum region is divided to n intervals. The levels in each interval ΔU_n are accumulated on one point U_n. Therefore, a discretized and degenerate spectrum is formed. Secondly, the continuum levels of residual nucleus are described by a statistical method. Thus, the spectra for given outgoing angles can be written as

$$\sigma(E_c-U_n,\theta_c)=\sum_{I_n\pi_n}\rho_A^{I_n\pi_n}(U_n)\sigma(U_n,I_n,\pi_n,\theta_c)\,.$$

Where E_c-U_n is the energy of the outgoing particles, $\rho_A^{I_n\pi_n}(U_n)$ is the level density of the residual nucleus. The $\sigma(U_n,I_n,\pi_n,\theta_c)$ can be obtained from the angular distribution calculation of the discrete energy level, which have been simplified [5]. In the angular distribution and the cross section formulas for particle emissions in discrete states and in continuum the WFC factor should be extended as

$$\begin{aligned}W_{cc_q'}=\frac{1+2\delta_{cc_q'}}{2}\int_0^1 dy\,\exp\Big[-\frac{T_f^{\mu}+T_\gamma^{\mu}}{2T^{\mu}}\Big(\frac{1}{y}-1\Big)\Big]\\ \times y^{-2}\Big[1+\frac{T_c(E_c)}{T^{\mu}}\Big(\frac{1}{y}-1\Big)\Big]^{-1}\Big[1+\frac{T_{c_q'}(E_c-U_q)}{T^{\mu}}\Big(\frac{1}{y}-1\Big)\Big]^{-1}\\ \times\prod_{k'}^{K_M}\prod_{c_{k'}}\Big[1+\frac{T_{c_{k'}}(E_c-U_{k'})}{T^{\mu}}\Big(\frac{1}{y}-1\Big)\Big]^{-\frac{1}{2}}\\ \times\prod_{n'}^{n}\prod_{I_{n'}\pi_{n'}}\Big[-\frac{1}{2}\rho_A^{I_{n'}\pi_{n'}}(U_{n'})\Delta U_{n'}\,\ln\prod_{c_{n'}}\Big[1+\frac{T_{c_{n'}}(E_c-U_{n'})}{T^{\mu}}\Big(\frac{1}{y}-1\Big)\Big]\,,\end{aligned}\qquad(2)$$

$$q=\begin{cases}k & \text{the discrete energy level,}\\ n & \text{the continuum region.}\end{cases}$$

For the radiative capture and fission channels, the WFC factor can be similarly obtained

$$\begin{aligned}W_c=\frac{1}{2}\int_0^1 dy\,\exp\Big[-\frac{T_f^{\mu}+T_\gamma^{\mu}}{2T^{\mu}}\Big(\frac{1}{y}-1\Big)\Big]y^{-2}\\ \times\Big[1+\frac{T_c(E_c)}{T^{\mu}}\Big(\frac{1}{y}-1\Big)\Big]^{-1}\prod_{k'}^{K_M}\prod_{c_{k'}}\Big[1-\frac{T_{c_{k'}}(E_c-U_{k'})}{T^{\mu}}\Big(\frac{1}{y}-1\Big)\Big]^{-\frac{1}{2}}\\ \times\prod_{n'}^{n}\prod_{I_{n'}\pi_{n'}}\Big[-\frac{1}{2}\rho_A^{I_{n'}\pi_{n'}}(U_{n'})\Delta U_n\,\ln\prod_{c_{n'}}\Big[1+\frac{T_{c_{n'}}(E_c-U_{n'})}{T^{\mu}}\Big(\frac{1}{y}-1\Big)\Big]\,.\end{aligned}\qquad(3)$$

Making use of the above formulas, the spectra for given outgoing angles and various reaction cross sections can be calculated.

Therefore, the angular distributions, the spectra and inelastic cross sections for particle emissions in continuum region are readily calculated by the following formulas, respectively

$$\sigma_I(\theta_c)=\int_0^{E_c-U_{K_M}} dE'\,\sigma(E',\theta_c)\,, \tag{4}$$

$$\frac{d\sigma_I}{dE'}=2\pi\int_0^{\pi}\sin\theta_c\,d\theta_c\,\sigma(E_c-U_n,\theta_c)\Big/\sigma_I(E_c) \tag{5}$$

$$\begin{aligned}\sigma_I(E_c)&=\int_\Omega \sigma_I(\theta_c)\,d\Omega\\ &\equiv 2\pi\int_0^{\pi}\sin\theta_c\,d\theta_c\int_0^{E_c-U_{K_M}} dE'\,\sigma(E',\theta_c)\end{aligned} \tag{6}$$

We take the neutron-induced inelastic scattering as an example, and calculate the spectra for given outgoing angles, the angular distributions, and the spectra. All the calculated cross sections are found reasonable and consistent with each other. The calculated results have the typical feature of the compound nucleus reaction. The spectra are Maxwell type spectra. And the angular distributions are nearly isotropic.

The particle emissions in the continuum region can be described by one transmition coefficient T_p^{μ} when the double differential cross section need not be calculated. In this way a unified formula of the WFC was obtained, which is available for fission, radiative capture and particle emission in continuum simultaneously [6]. The WFC factor of the particle emissions with the residual nucleus in a discrete energy level region can be written as

$$\begin{aligned}W_{cc'_k}=&\frac{1+2\delta_{cc'_k}}{2}\int_0^1 dy\,\exp\left[-\frac{T_p^{\mu}+T_f^{\mu}+T_\gamma^{\mu}}{2T^{\mu}}\left(\frac{1}{y}-1\right)\right]\\ &\times y^{-2}\left[1+\frac{T_c(E_c)}{T^{\mu}}\left(\frac{1}{y}-1\right)\right]^{-1}\left[1+\frac{T_{c'_k}(E_c-U_k)}{T^{\mu}}\left(\frac{1}{y}-1\right)\right]^{-1}\\ &\times\prod_{k'}^{K_M}\prod_{c_{k'}}\left[1-\frac{T_{c_{k'}}(E_c-U_{k'})}{T^{\mu}}\left(\frac{1}{y}-1\right)\right]^{-1/2}.\end{aligned} \tag{7}$$

And for radiative capture, fission and the particle emission in continuum, the WFC factor can be similarly written as

$$W_c^{\mu} = \frac{1}{2}\int_0^1 dy \, exp\left[-\frac{T_p^{\mu}+T_f^{\mu}+T_\gamma^{\mu}}{2T^{\mu}}\left(\frac{1}{y}-1\right)\right] \times y^{-2}\left[1+\frac{T_c(E_c)}{T^{\mu}}\left(\frac{1}{y}-1\right)\right]^{-1}\prod_{K'}^{K_M}\prod_{C_{K'}}\left[1+\frac{T_{C_{K'}}(E_c-U_{K'})}{T^{\mu}}\left(\frac{1}{y}-1\right)\right]^{-1/2}. \quad (8)$$

These formulas are successful in practical application and can also be extended to other theory (for example, the Moldauer theory).

4. A NEW SET OF LEVEL DENSITY PARAMETERS

The nuclear level density plays an important role in the statistical theory of nuclear reaction. It affects directly the calculation results of the widths, cross sections, emitted particle spectra etc. for various reaction channels. The Gilbert-Cameron [7] type level density formula as well as parameters has been widely employed in the statistical theory. Based on their work, Cook et al [8] . have also got a set of parameters. Because these parameters only depend on Z and N, i.e. the numbers of proton and neutron in the nucleus respectively, Gilbert-Cameron's formula is universally applicable. However, their parameters are based on the experimental data at that time. The present work attempts to obtain a new set of parameters based on the newest and more kinds of experimental data.

In order to recommend more accurate and reliable parameters of level density, we have collected and evaluated three kinds of experimental data: average level spacing D_0 and radiative capture width Γ_γ^0 at the neutron binding energy and the cumulative number N_0 of the levels at the low exitation energy, which amount to 667 and were reported from 1973 to 1983.

Based on these experimental data, especially D_0 and N_0, the parameters S(Z), S(N), P(Z) and P(N) have been readjusted (denoted as work 1). Next the empirical parameters have also been reobtained to fit the experimental data which we have collected. In the Gilbert-Cameron's formula, the corresponding quantities

including the empirical parameters are as follows:

$$a=[0.00917(S(Z)+S(N))+QB]A$$
$$U_x= 2.5+150/A \qquad (9)$$

The new ones of 0.00880, 1.4 and 263(denoted as work 2) are adopted respectively instead of 0.00917, 2.5 and 150 used in the formulas. Thus, the formulas are rewritten as

$$a=[0.00880(S(Z)+S(N))+QB]A$$
$$U_x= 1.4+263/A \qquad (10)$$

where the values of QB are taken as:

$$QB=\begin{cases} 0.142, & 29\leq Z\leq 62 \text{ (and } N\leq 89); \; 79\leq Z\leq 85; \\ 0.120 & Z\leq 29; \; 62(\text{ and } N>89)\leq Z\leq 78; \; Z\geq 86. \end{cases} \qquad (11)$$

The relative deviations of the calculated values in our work to the experimental data for each nucleus whose data have been collected are obtained. The percentages of those nuclei with the relative deviation in a certain scope are compared with that of Gilbert-Cameron's and Cook's which are shown in Table 2.

Table 2 A comparison between three results

relative deviations		Gilbert-cameron	Cook et al	work 1	work 2
δD_0	$\leq\pm 20\%$	21.5	22.4	47.8	48.7
	$\leq\pm 50\%$	29.4	28.1	36.4	37.3
	$\leq\pm 100\%$	24.1	27.6	15.4	13.2
	$>\pm 100\%$	25.0	21.9	0.4	0.8
$\chi^2_{D_0}$		175.9	120.9	11.3	11.4
δN_0	$\leq\pm 20\%$	13.0	13.9	18.5	18.9
	$\leq\pm 50\%$	30.7	23.9	36.1	31.5
	$\leq\pm 100\%$	49.2	50.0	41.2	44.5
	$>\pm 100\%$	7.1	12.2	4.2	5.1
$\chi^2_{N_0}$		13.9	47.9	11.5	10.1
$\delta\Gamma^0_\gamma$	$\leq\pm 20\%$	26.9	26.4	27.9	30.8
	$\leq\pm 50\%$	39.8	40.8	37.3	35.8
	$\leq\pm 100\%$	30.3	29.8	31.8	30.8
	$>\pm 100\%$	3.0	3.0	3.0	2.6
$\chi^2_{\Gamma^0_\gamma}$		9.6	9.7	11.0	9.3
$\chi^2_{D_0}+\chi^2_{N_0}+\chi^2_{\Gamma^0_\gamma}$		199.4	178.5	33.8	30.8

It is shown in Table 2 that our parameters are in a good agreement with these more accurate and newer experimental data, especially the level spacings D_0. Intuitively this new set of level density parameters seems to be more accurate. Of course, it should be tested by the calculations on statistical models. The new set of parameters S(Z), S(N), P(Z) and P(N) are listed in Table 3. But it is worth noting that there are some problems remained at the low excitation energies in the Gilbort-Cameron formula to be improved.

5. SOME CALCULATED RESULTS

The neutron reaction data (including all kinds of cross sections, the outgoing neutron spectra and the neutron angular distributions) for a series of uranium, plutonium isotopes and some natural elements (e.g. Hf, Zr, Cr etc.) have been calculated with the WHF theory and the Moldauer theory. The calculated neutron energy region is from 1 keV to several MeV. The comparison of some calculated results with the experimental data is given in Fig 2-3. It can be seen from these figures, that the results are in a good agreement with the evaluated experimental data. We also extended the calculation procedure to the regions where lack of the experimental data after we had made a systematic review of the relavant parameters. Some results for the fissionable nuclei are given Fig.4.

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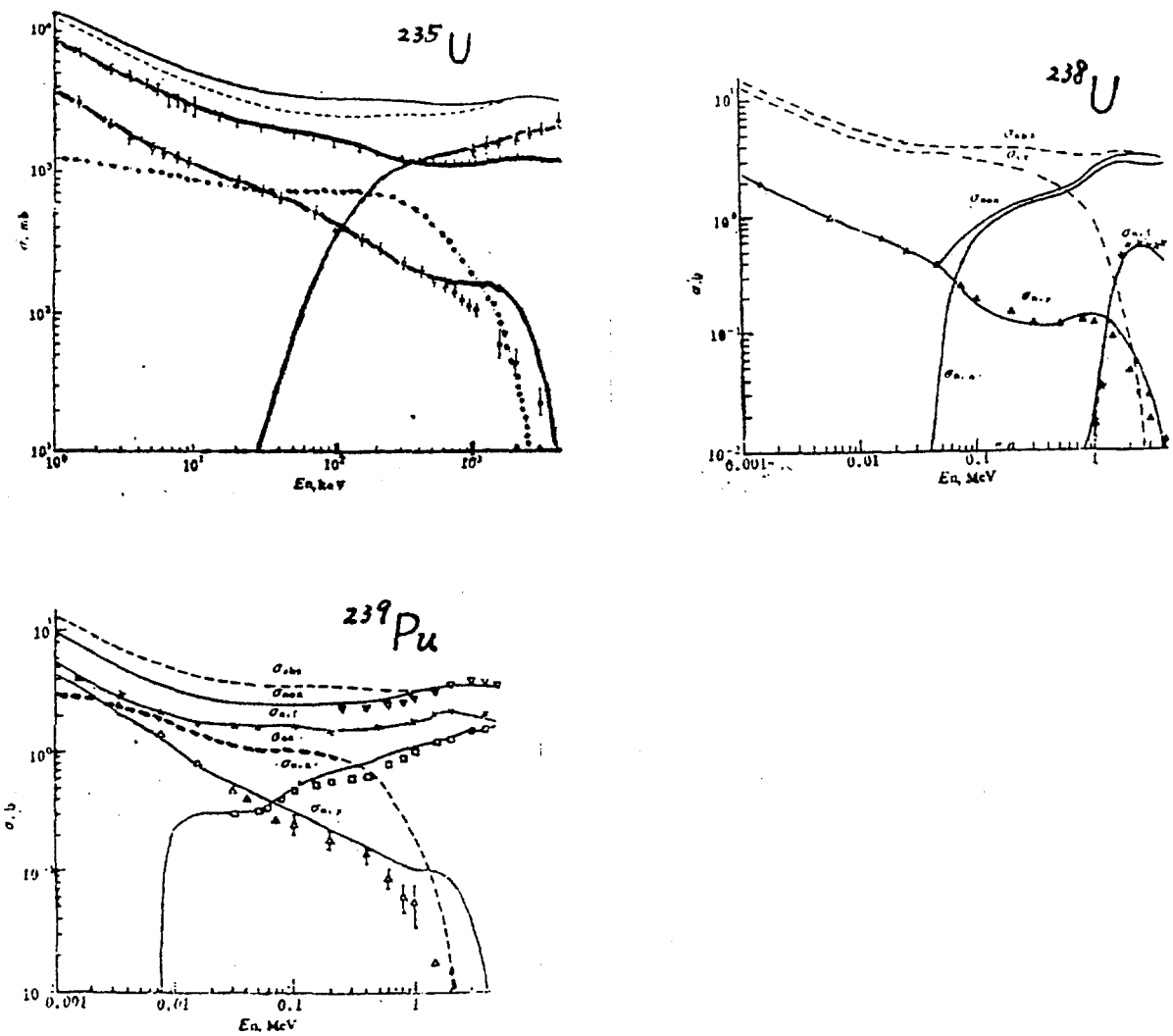
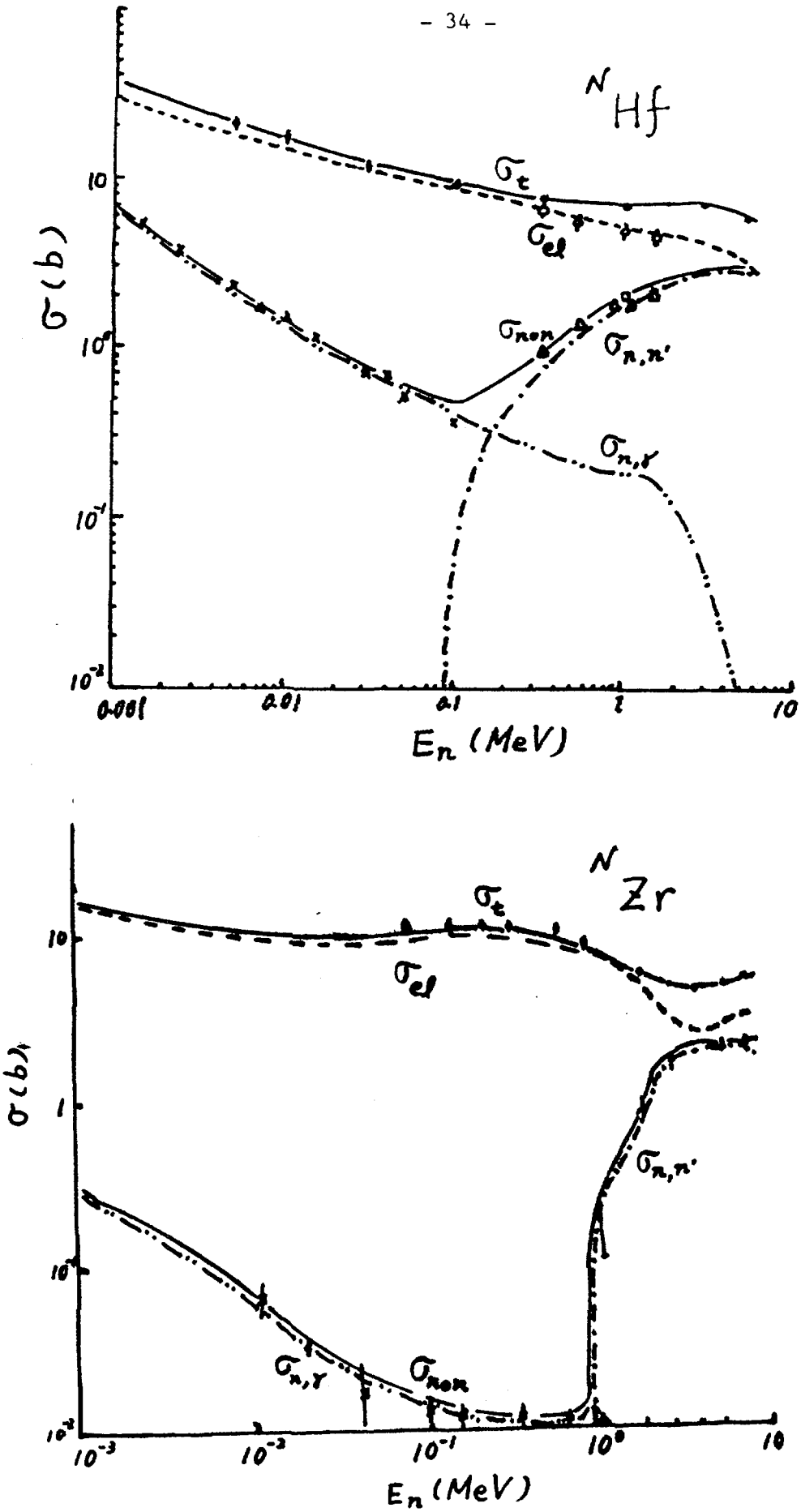
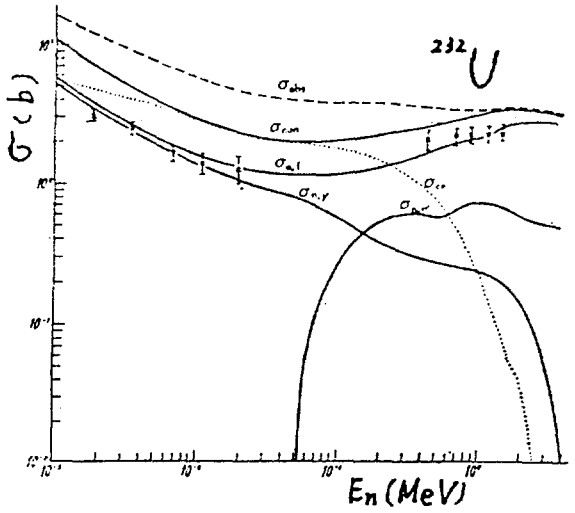
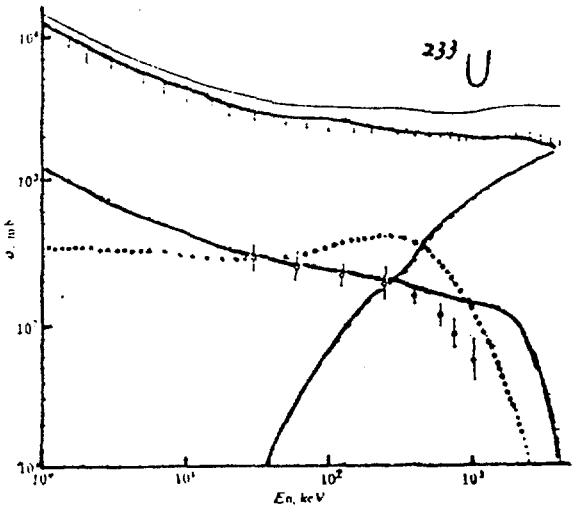


Fig 2. The comparison between the calculated cross sections and the experimental data for n+^{235}U, n+^{238}U and n+^{239}Pu reactions.



Fif 3. The comparison between the calculated cross sections and the experimental data for n+^{N}Hf, n+^{N}Zr reactions


232 U
σ (b)
En (MeV)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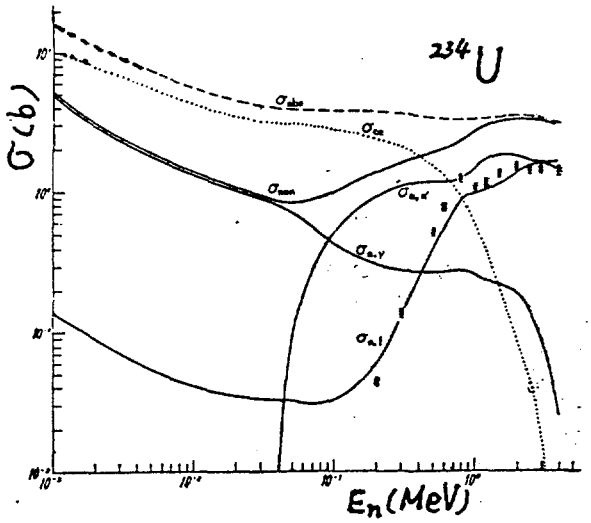
En, keV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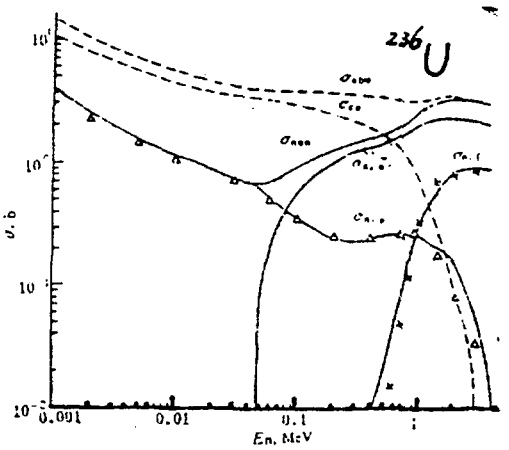
σ (b)
En (MeV)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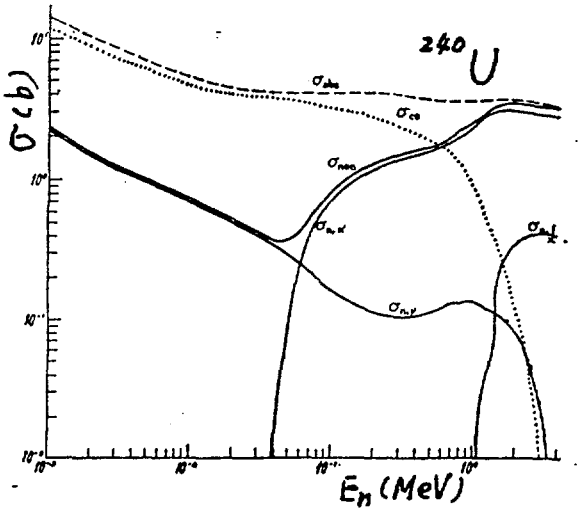
En, MeV


240 U
σ (b)
En (MeV)

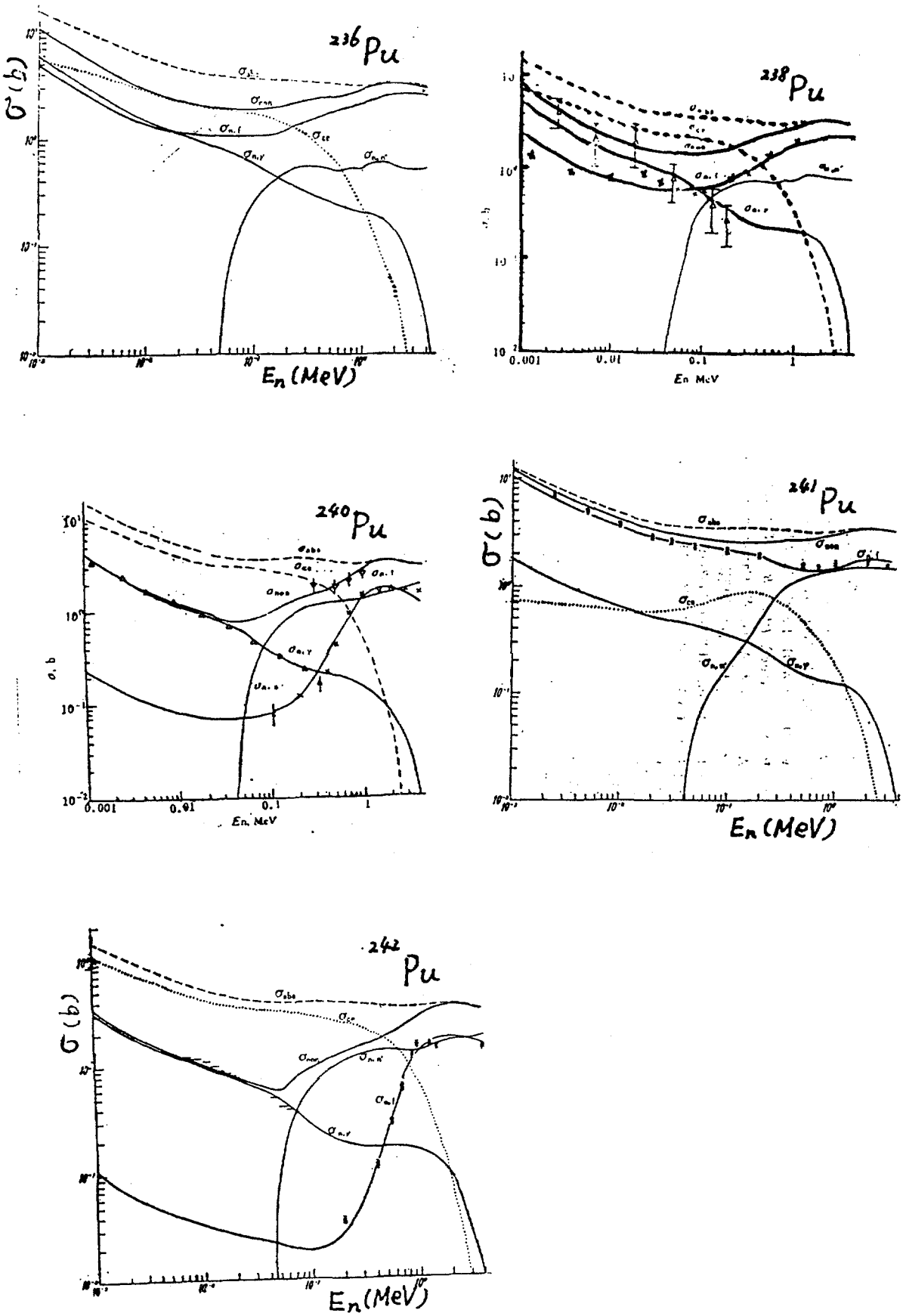


Fig 4. The theoretical calculations of neutron reaction cross sections for some U and Pu isotopes which are lacking in the experimental data

Table 3 the level density parameters of this work

N OR Z	PN	SN	PZ	SZ
11	0.00	6.80	0.00	-5.40
12	2.67	7.53	2.00	-3.80
13	0.00	7.55	0.00	-5.72
14	1.80	7.21	2.09	-7.80
15	0.00	7.44	0.00	-8.97
16	1.67	8.07	1.45	-9.50
17	0.00	9.10	0.00	-10.10
18	1.86	9.81	1.62	-10.70
19	0.00	10.60	0.00	-11.38
20	2.01	11.39	1.75	-12.00
21	0.00	13.85	0.00	-12.10
22	1.64	13.68	1.53	-12.80
23	-0.10	14.50	-0.26	-12.20
24	1.40	14.10	1.20	-14.30
25	-0.10	14.93	0.00	-14.00
26	1.36	13.70	1.30	-14.40
27	-0.20	14.55	-0.10	-14.75
28	1.20	12.50	1.20	-16.57
29	0.00	13.70	0.00	-17.10
30	1.15	13.45	1.06	-17.95
31	-0.20	15.45	0.00	-17.68
32	1.32	14.98	1.06	-16.78
33	-0.15	15.80	0.00	-16.65
34	1.30	16.38	1.35	-16.35
35	-0.18	17.25	0.00	-16.70
36	1.50	17.55	1.10	-15.20
37	-0.10	18.05	0.20	-16.20
38	1.90	17.65	1.24	-16.41
39	0.00	18.59	0.29	-17.05
40	1.43	18.71	1.35	-16.75
41	-0.28	18.95	0.00	-15.40
42	1.50	18.99	1.17	-15.85
43	-0.10	18.60	-0.15	-15.50
44	1.70	18.25	1.15	-17.29
45	-0.10	18.20	-0.10	-18.44
46	1.57	17.38	1.20	-17.82

N OR Z	PN	SN	PZ	SZ
47	0.00	16.72	0.34	-18.62
48	1.60	14.25	1.36	-18.58
49	-0.28	14.88	0.28	-19.65
50	1.20	12.88	1.47	-19.95
51	0.10	12.95	0.00	-19.44
52	0.75	13.65	1.00	-17.75
53	-0.30	14.80	0.00	-17.70
54	1.12	15.20	1.12	-16.72
55	0.00	15.89	0.26	-16.95
56	1.15	17.15	1.20	-14.37
57	0.00	17.00	0.10	-14.44
58	0.80	17.73	1.40	-14.00
59	-0.25	19.75	0.93	-12.30
60	1.35	18.80	1.36	-11.91
61	-0.32	19.45	0.36	-11.59
62	1.25	19.51	1.22	-10.78
63	-0.44	20.17	-0.20	-11.40
64	1.14	19.85	0.97	-10.21
65	0.08	19.98	-0.20	-10.00
66	1.32	20.05	0.78	-9.35
67	-0.11	20.28	0.00	-9.30
68	1.15	19.83	0.52	-8.85
69	-0.16	20.20	0.00	-8.91
70	1.06	19.44	0.68	-8.13
71	0.22	18.64	0.00	-7.90
72	1.65	17.31	0.68	-7.45
73	-0.20	17.08	0.00	-7.24
74	1.37	16.16	0.69	-7.30
75	-0.16	16.65	0.00	-7.05
76	1.20	15.33	0.58	-6.68
77	-0.54	15.35	0.28	-8.28
78	0.92	13.54	0.78	-7.57
79	-0.57	13.17	0.20	-7.80
80	1.17	10.75	0.73	-7.89
81	-0.30	10.40	0.20	-8.70
82	0.85	9.15	0.80	-8.50
83	-0.37	10.00	0.00	-7.71
84	1.40	10.07	0.89	-6.38

N OR Z	PN	SN	PZ	SZ
85	-0.11	12.50	0.00	-5.47
86	1.12	11.80	0.79	-4.78
87	-0.16	12.40	0.00	-4.37
88	1.09	12.35	0.80	-4.05
89	-0.35	13.60	0.00	-4.12
90	0.72	13.47	0.58	-4.00
91	-0.20	13.00	0.00	-5.00
92	0.92	12.11	0.61	-5.24
93	-0.30	12.15	0.00	-5.60
94	0.73	11.21	0.51	-6.15
95	0.30	11.25	0.00	-6.45
96	0.79	9.80	0.72	-6.93
97	0.00	10.43	0.00	-7.20
98	0.80	9.70	0.77	-7.74
99	0.00	9.75		
100	0.80	8.65		
101	0.00	8.72		
102	0.80	8.23		
103	0.00	7.80		
104	0.85	7.50		
105	0.00	7.40		
106	0.50	7.35		
107	0.00	7.15		
108	0.75	6.96		
109	0.00	6.94		
110	0.75	6.55		
111	0.00	6.72		
112	0.86	6.49		
113	-0.10	6.69		
114	1.10	6.00		
115	-0.26	5.60		
116	0.84	4.53		
117	-0.33	4.25		
118	0.72	2.60		
119	0.03	2.39		
120	0.96	1.58		
121	0.10	2.15		
122	0.52	0.46		

N OR Z	PN	SN	PZ	SZ
123	-0.05	-0.85		
124	0.41	-1.69		
125	-0.20	-2.63		
126	0.38	-3.16		
127	0.00	-1.37		
128	0.45	-0.41		
129	0.00	0.71		
130	0.61	1.66		
131	0.00	2.62		
132	0.78	3.22		
133	0.00	3.76		
134	0.67	4.10		
135	0.00	4.46		
136	0.67	4.83		
137	0.00	5.09		
138	0.79	5.18		
139	0.00	5.25		
140	0.80	4.75		
141	0.00	5.09		
142	0.60	4.95		
143	0.00	5.08		
144	0.49	4.87		
145	0.00	5.10		
146	0.52	4.88		
147	0.00	5.58		
148	0.58	5.18		
149	0.00	5.80		
150	0.39	5.50		