THE USE OF DATA-CONTAINING CODES FOR THE INTERPRETATION OF NUCLEAR EXPERIMENTAL RESULTS

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One of the trends of development of the approaches using for description of nuclear processes is creation and improvement of codes which, on the one hand, realize various standard theoretical approaches of the nuclear reactions and, on the other hand, contain a large bulk of nuclear data.

This development follows the direction of higher capability of the programs and, in addition, makes these codes user-friendly step by step.

Typical examples of such codes are EMPIRE and TALYS.

EMPIRE-II-19

Basic program content of the code package EMPIRE are:

1. The subdivision realizing Hauser-Feshbasch statistical model.

2.Optical-model code SCAT2.

3. Couple-channel model codes.

4. Pre-equilibrium, direct, and multi-step direct mechanisms are described by the approaches which are realized by four codes: ORION, TRISTAN TUL, DEGAS exciton model, and hybrid model HMS employing Monte-Carlo simulation methods.

At all stages of the calculation the discussed approaches allow one to take into account proton, neutron emission channels and the channel with other particles such as alphas etc.

Basing on a certain input the EMPIRE code either employs proper codes containing in it automatically, or makes it possible to address the codes chosen by a user, switch on and switch off some of them.

For example the schemes realizing the Hauser-Feshbasch and optical-model approaches look as follows.

In the Hauser-Feshbach model cross section of compound reaction takes the form:

$$\sigma(\varepsilon, U_{res}, J_{res}, \{\varepsilon_{f_i}, J_{f_i}\}) = \sum \sigma_c(U_c, J_c) \prod_i P_{b_i}(U_{f_{i-1}}, J_{f_{i-1}}, J_{f_i}, l_{f_i}, s_{f_i}),$$

where:

$$\sigma_c(U_c, J_c) = \pi \lambda\!\!\!^{-2} \frac{2J_c + 1}{(2I+1)(2i+1)} \sum_{s=|I-i|}^{I+i} \sum_{l=|J_c-s|}^{J_c+s} T_l(\varepsilon),$$

T_l – coefficients of penetrability and $P_b(\ldots)$ denotes emission probability of a particle *b*. The latter value depends on the level density of initial and final nuclide which is expressed as:

$$\rho(E, J) = \frac{(2J+1) \cdot \exp(2\sqrt{aE})}{24\sqrt{2}\ \sigma^3\ a^{1/4}\ E^{5/4}} \exp\left(-\frac{(J+1/2)^2}{2\sigma^2}\right)^2.$$

The optical-model potential is chosen in the form: $V(r) + iW(r)$

where:

$$\begin{aligned} V(r) = &-V_R f(r, R_R, a_R) \\ &+ V_{SO}(\mathbf{s} \cdot \mathbf{l}) \lambda_\pi^2 (1/r)(d/dr) \left[f\,(r, R_{SO}, a_{SO}) \right] \\ &+ \begin{cases} (Zze^2/2R_c) \left[3 - (r^2/R_c^2) \right] & (r \leqslant R_c)\,, \\ Zze^2/r \quad (r \geqslant R_c)\,, \end{cases} \end{aligned}$$

$$\begin{aligned} W(r) = &-W_V f\left(r, R_I', a_I'\right) \\ &+ W_{SF} \cdot 4a_I \,(d/dr) \left[f\,(r, R_I, a_I) \right]. \end{aligned}$$

Typical values of the parameters are also contained in the package EMPIRE. For example

Potential	r_R, fm	a_R, fm	V_R, MeV	W_{SF}, MeV	r_I, fm	a_I, fm	r_{SO}, fm	a_{SO}, fm	V_{SO}, MeV
Becchetti–Greenlees (p, n)	1.170	0.750	56.3	13.0	1.260	0.580	1.01	0.75	6.2
Becchetti–Greenlees (p, p)	1.170	0.750	54.0	11.8	1.320	0.510	1.01	0.75	6.2

or

Potential	r_R, fm	a_R, fm	V_R, MeV	W_{SF}, MeV	r_I, fm	a_I, fm	r_{SO}, fm	a_{SO}, fm	V_{SO}, MeV	W, MeV	a_W, fm
Wilmore–Hodgson optical potentials (p, n)	1.220	0.650	53.3	–	–	–	–	–	–	14.6	0.47
Koning–Delaroche (p, p)	1.162	0.665	62.4	15.2	1.29	0.510	1.00	0.58	6.0	–	–

Furthermore the package contains a large bulk of input information taken from nuclear data tables, among them:

1. Masses of nuclei.

2. Ground state deformation parameters of nuclei.

3. Nuclear spectra and decay schemes.

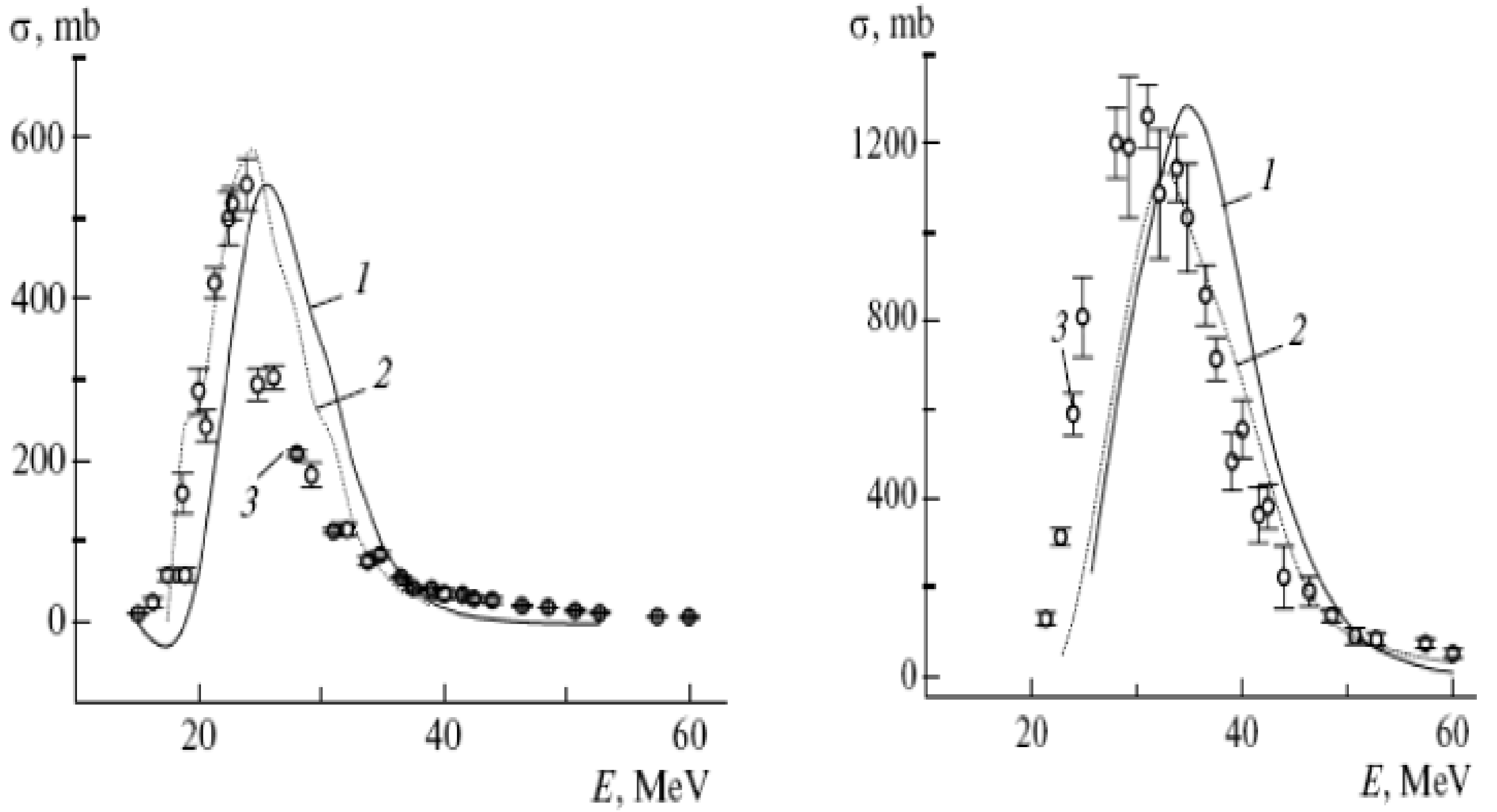
4. Level densities.

5. Fission-barrier parameters.

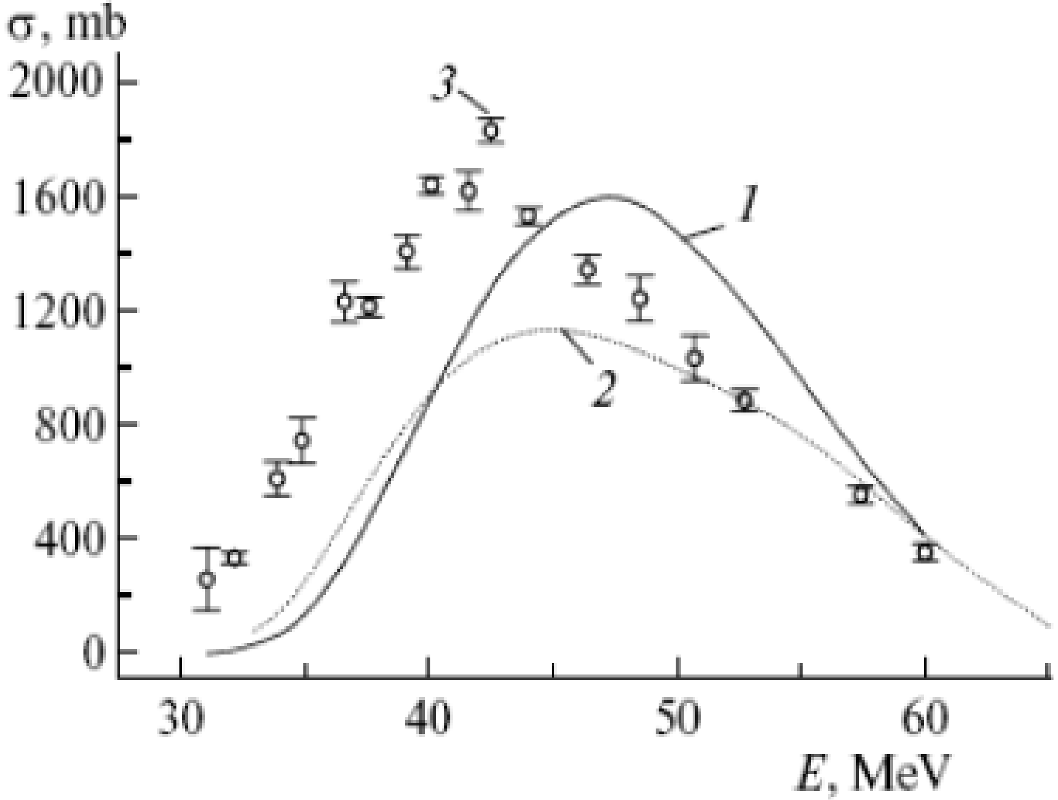
6. Full library of experimental data on nuclear reactions EXFOR.

7. Optical model parameters database RIPL-3.

SOME EXAMPLES



Experimental and calculated by EMPIRE-II-19 cross sections of the evaporation residuals formation for the reactions $^{6}He+{}^{197}Au \rightarrow {}^{200,199}Tl$

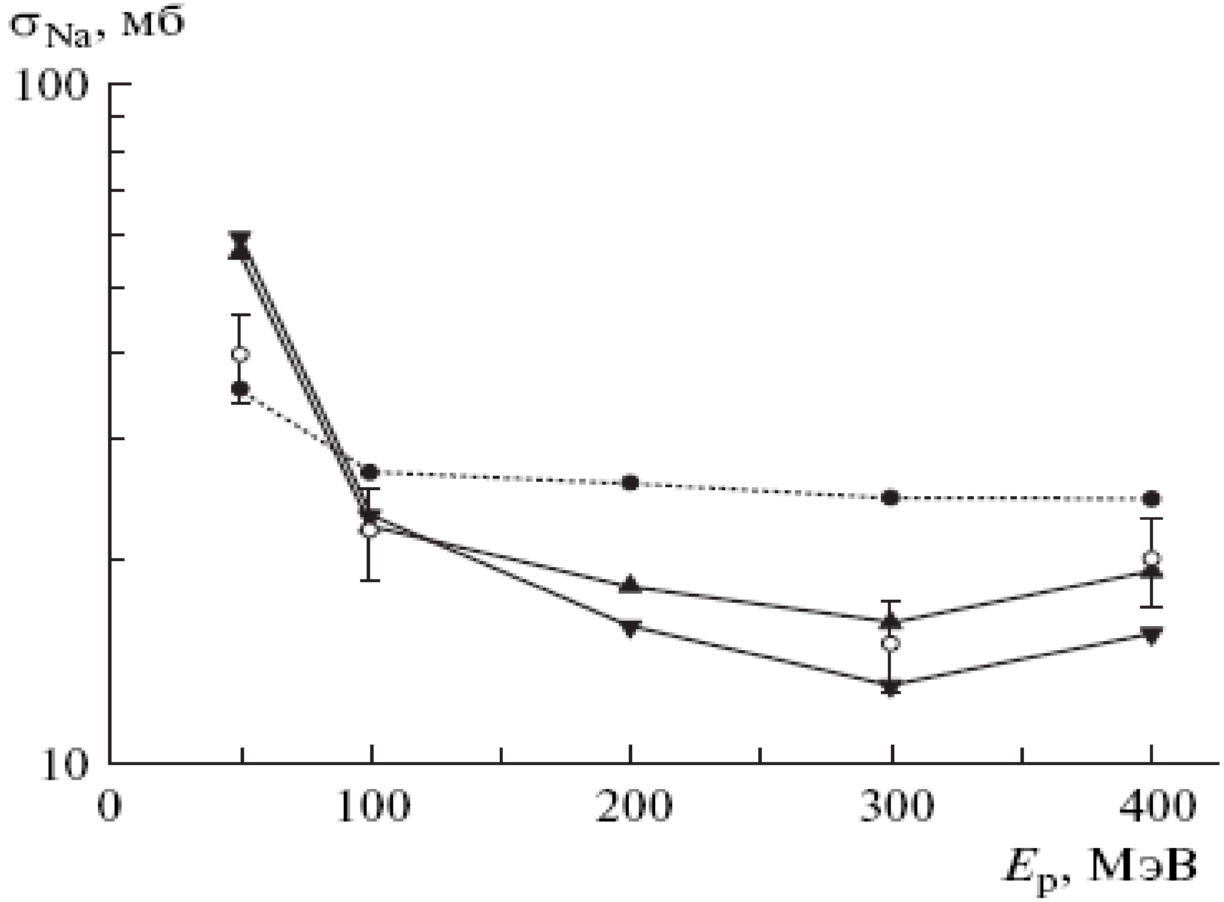


The same for 198Ta evaporation residual

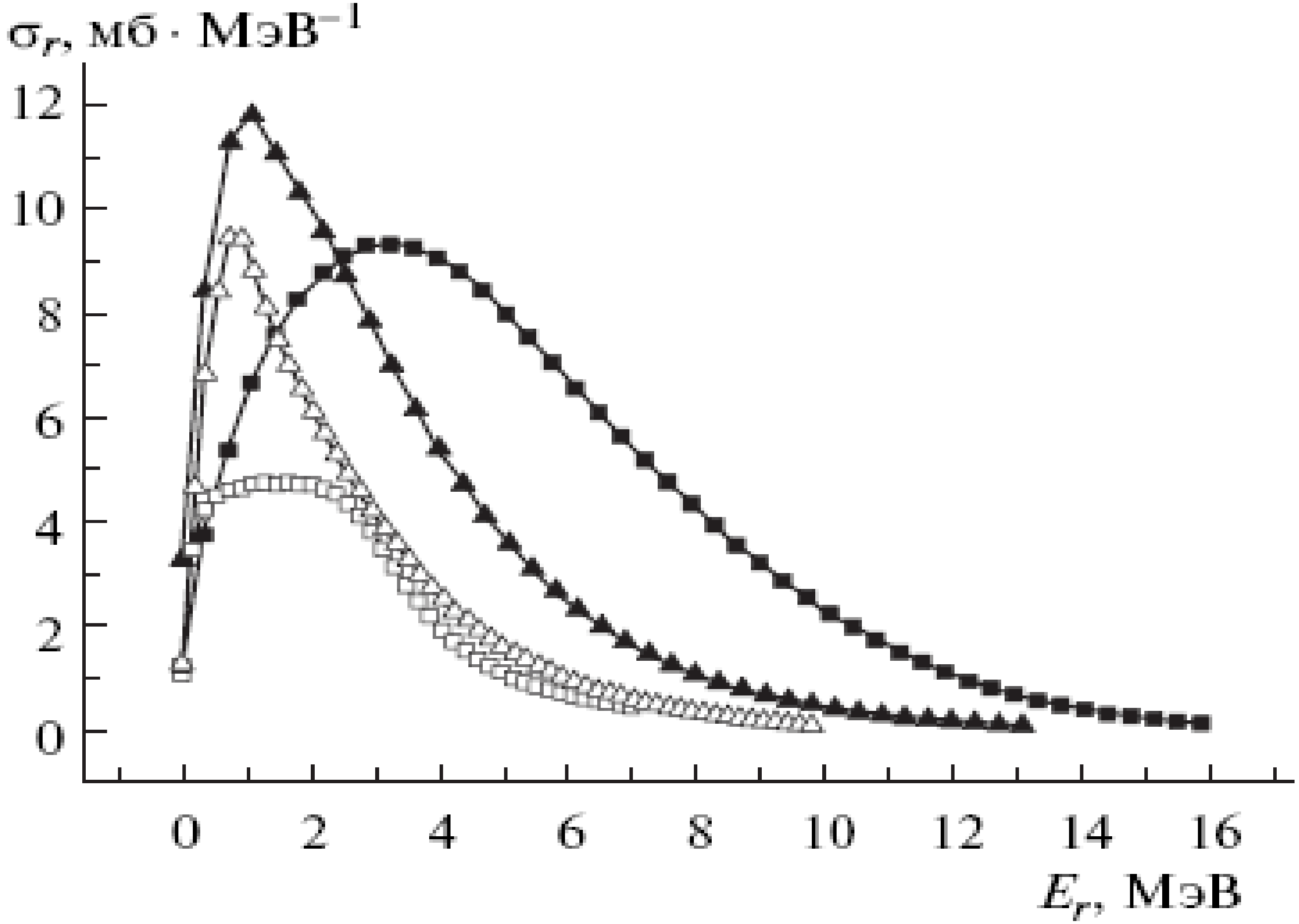
Calculated and measured cross sections of the evaporation residuals formation for the reactions $^{6}He + {}^{197}Au \rightarrow {}^{194,196}Au$.

$E_{Lab}(^{6}He)$ MeV	E_C	^{196} Au mb	$^{19\ 4}$Au mb
113.7	*122.5*		17.2
95.35	*104.7*	0.02	184.7
81.44	*91.2*	1.12	285
68	*78.2*	1.4	79.0
55	*65.6*	21..8	2.9
40.8	*51.8*	21..8	

E	*Au-196*	*Au-194*
113.7	307.4	122.8
95.35	404.3	89.19
81.44	455	54.21
68	357.6	45
55.5	274.5	21.5
40.8	168.3	7.5



Energy dependence of the yield of the evaporation residual 22Na in the reaction p+27Al for various optical-model potentials.



Spectra of the evaporation residuals (recoils) of the reaction p+28Si →24Mg + X (E=50 MeV – open symbols and E=100 MeV – solid symbols) for various optical-model potentials.

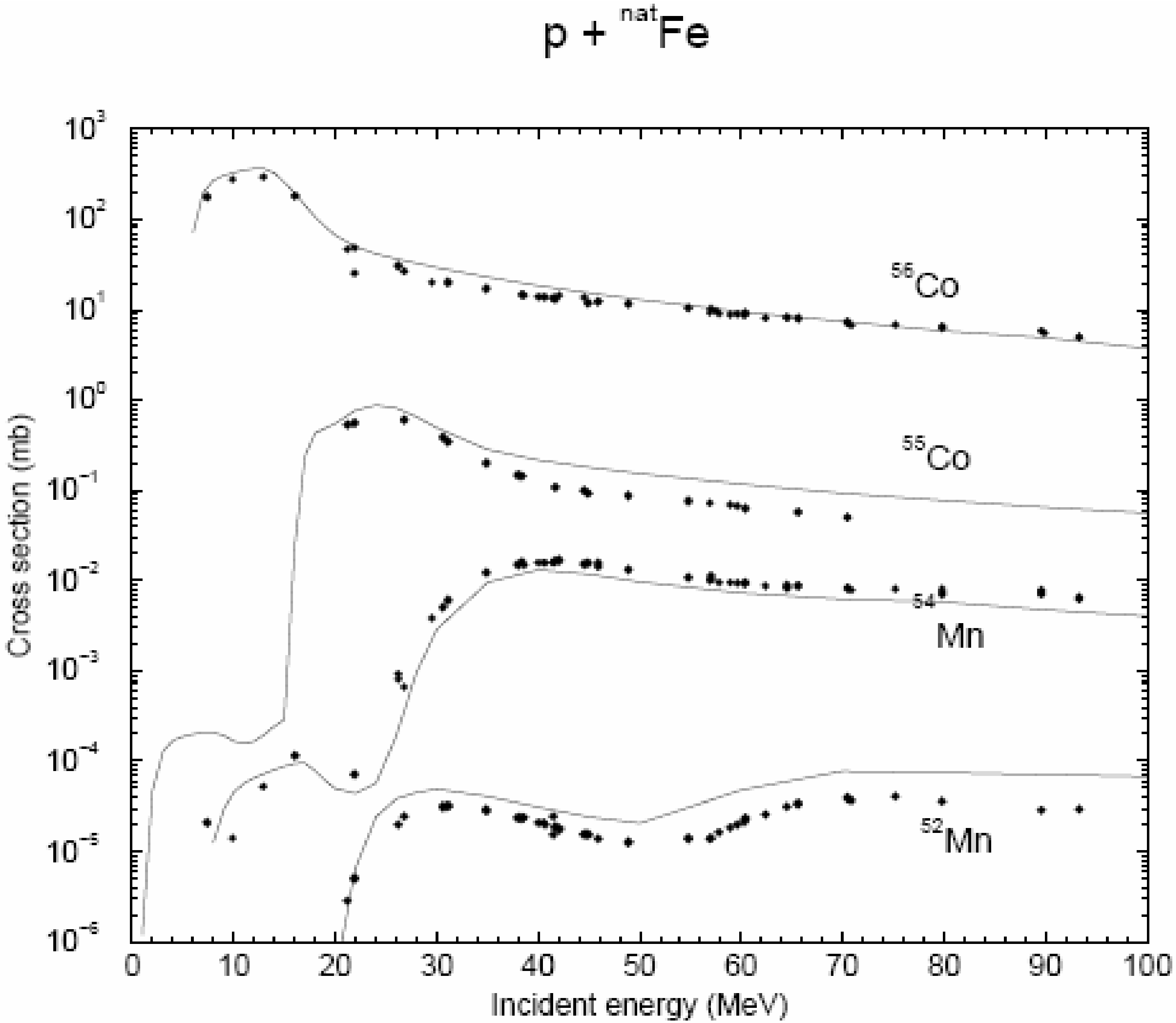
TALYS. NEW POSSIBIITIES

CONVENIENT INPUT

```
#
# General
#
projectile p
element si
mass 28
energy
energies
#
# Output
#
file residual      y
```

WELL-DEVELOPED TESTING BASIS

To test the code a large number of examples of the cross sections of various reactions are involved in the database of the code. In particular yields of evaporation residuals of the proton collision with the natural Fe is presented in the database.



p + natFe
Cross section (mb)
Incident energy (MeV)
56Co
55Co
54Mn
52Mn

USER-FRIENLY OUTPUT

p + 28Si Binary cross sections
#
#
energies = 24

# E	gamma	neutron	proton	deuteron	triton	helium-3	alpha
1.000E+00	1.7393E-04	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
2.000E+00	3.8505E-04	0.0000E+00	3.1145E-02	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
3.000E+00	6.8411E-04	0.0000E+00	1.6222E+01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
4.000E+00	9.7564E-04	0.0000E+00	1.3240E+02	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
5.000E+00	1.7007E-03	0.0000E+00	2.4358E+02	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
6.000E+00	3.2167E-03	0.0000E+00	3.2167E+02	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
8.000E+00	9.6375E-03	0.0000E+00	4.9617E+02	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
1.000E+01	4.7007E-02	0.0000E+00	6.9630E+02	0.0000E+00	0.0000E+00	0.0000E+00	1.3206E-03
1.200E+01	7.8837E-02	0.0000E+00	8.6175E+02	0.0000E+00	0.0000E+00	0.0000E+00	5.9323E+00
1.400E+01	1.2142E-01	0.0000E+00	8.5735E+02	0.0000E+00	0.0000E+00	0.0000E+00	4.2926E+01
1.600E+01	1.8815E-01	2.3666E+00	8.3717E+02	2.7371E-07	0.0000E+00	0.0000E+00	6.1531E+01
1.800E+01	2.8883E-01	1.0734E+01	8.1606E+02	1.3108E+00	0.0000E+00	0.0000E+00	6.1585E+01
2.000E+01	3.9675E-01	1.6745E+01	7.9575E+02	6.3829E+00	0.0000E+00	6.6885E-04	5.5128E+01
2.500E+01	5.5109E-01	2.9468E+01	7.4158E+02	1.8703E+01	3.1340E-03	8.8775E-01	3.9449E+01
3.000E+01	5.8548E-01	4.6378E+01	6.7767E+02	2.7551E+01	9.6897E-02	1.9612E+00	3.1277E+01
3.500E+01	5.6808E-01	6.1618E+01	6.1685E+02	3.4877E+01	1.6946E-01	3.2535E+00	2.6351E+01
4.000E+01	5.3591E-01	7.4130E+01	5.6360E+02	4.0857E+01	3.3173E-01	4.4747E+00	2.2610E+01
4.500E+01	5.1392E-01	8.3482E+01	5.2052E+02	4.4028E+01	5.8141E-01	5.5278E+00	1.9300E+01
5.000E+01	4.9479E-01	8.9990E+01	4.8460E+02	4.6961E+01	8.7988E-01	6.2138E+00	1.6325E+01
6.000E+01	4.8134E-01	9.8999E+01	4.2822E+02	5.1179E+01	1.4658E+00	6.6181E+00	1.1676E+01
7.000E+01	4.7870E-01	1.0377E+02	3.8677E+02	5.4013E+01	2.0233E+00	6.5562E+00	8.5875E+00
8.000E+01	4.7077E-01	1.0540E+02	3.5487E+02	5.6264E+01	2.5928E+00	6.4032E+00	7.2681E+00
9.000E+01	4.5911E-01	1.0568E+02	3.2955E+02	5.7479E+01	3.2616E+00	6.4616E+00	6.9508E+00
1.000E+02	4.4915E-01	1.0505E+02	3.0935E+02	5.8071E+01	4.0445E+00	6.6503E+00	6.9103E+00

p + 28Si Total cross sections
#
#
energies = 24

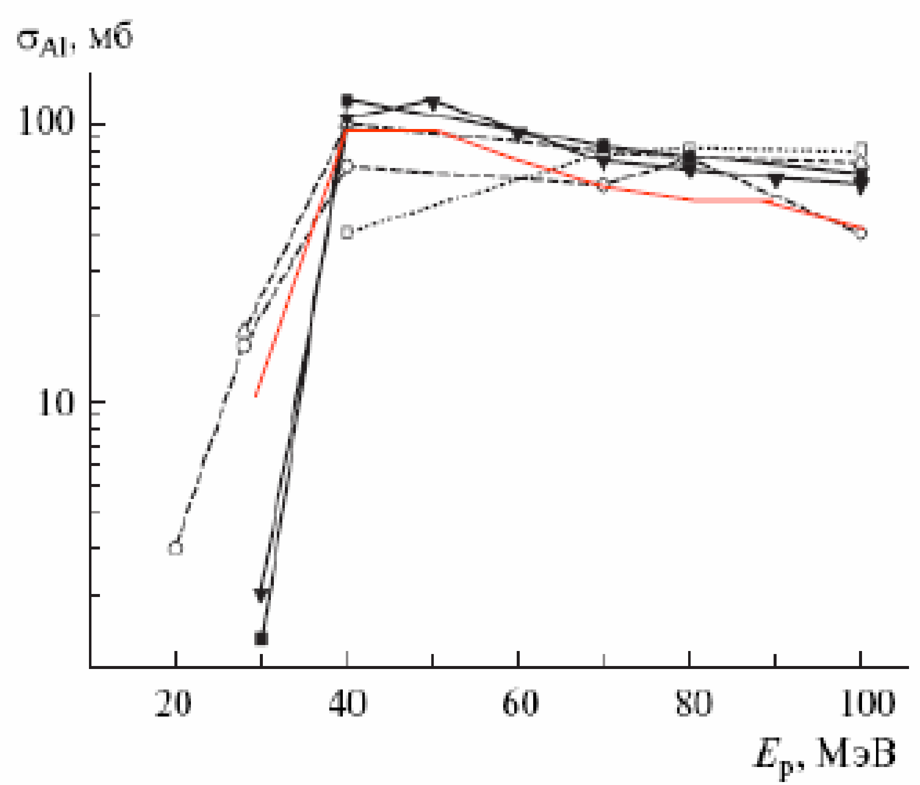
# E	Non-elastic	Elastic	Total	Comp. el.	Shape el.	Reaction	Comp. nonel	Direct	Pre-equil.
1.000E+00	2.6617E-03	9.0070E+00	0.0000E+00	9.0070E+00	0.0000E+00	9.0096E+00	2.6617E-03	0.0000E+00	0.0000E+00
2.000E+00	8.0017E-02	2.1114E+02	0.0000E+00	2.1114E+02	0.0000E+00	2.1122E+02	8.0017E-02	1.1959E-10	0.0000E+00
3.000E+00	1.6248E+01	4.2889E+02	0.0000E+00	4.2889E+02	0.0000E+00	4.4514E+02	1.5919E+01	3.2968E-01	0.0000E+00
4.000E+00	1.3241E+02	3.9164E+02	0.0000E+00	3.9164E+02	0.0000E+00	5.2405E+02	1.2471E+02	7.7030E+00	0.0000E+00
5.000E+00	2.4358E+02	3.4647E+02	0.0000E+00	3.4647E+02	0.0000E+00	5.9005E+02	2.1607E+02	2.7512E+01	0.0000E+00
6.000E+00	3.2167E+02	3.3629E+02	0.0000E+00	3.3629E+02	0.0000E+00	6.5796E+02	2.7709E+02	4.4578E+01	0.0000E+00
8.000E+00	4.9618E+02	2.9204E+02	0.0000E+00	2.9204E+02	0.0000E+00	7.8821E+02	4.3443E+02	6.1750E+01	0.0000E+00
1.000E+01	6.9634E+02	1.7041E+02	0.0000E+00	1.7041E+02	0.0000E+00	8.6675E+02	6.2131E+02	7.5023E+01	5.4362E-03
1.200E+01	8.6776E+02	3.7203E+01	0.0000E+00	3.7203E+01	0.0000E+00	9.0496E+02	7.7278E+02	8.4753E+01	9.9582E+00
1.400E+01	9.0039E+02	1.4545E+01	0.0000E+00	1.4545E+01	0.0000E+00	9.1493E+02	7.4889E+02	8.9138E+01	5.3821E+01
1.600E+01	9.0125E+02	5.5194E+00	0.0000E+00	5.5194E+00	0.0000E+00	9.0677E+02	6.7787E+02	9.2608E+01	1.1445E+02
1.800E+01	8.8998E+02	2.0405E+00	0.0000E+00	2.0405E+00	0.0000E+00	8.9202E+02	5.9284E+02	9.3852E+01	1.8406E+02
2.000E+01	8.7440E+02	7.4685E-01	0.0000E+00	7.4685E-01	0.0000E+00	8.7514E+02	5.0879E+02	9.4660E+01	2.5034E+02
2.500E+01	8.3064E+02	5.7607E-02	0.0000E+00	5.7607E-02	0.0000E+00	8.3070E+02	3.2024E+02	9.2042E+01	3.9707E+02
3.000E+01	7.8552E+02	4.6386E-03	0.0000E+00	4.6386E-03	0.0000E+00	7.8553E+02	2.1152E+02	8.3887E+01	4.6262E+02
3.500E+01	7.4368E+02	4.0675E-04	0.0000E+00	4.0675E-04	0.0000E+00	7.4368E+02	1.4509E+02	7.3908E+01	4.9294E+02
4.000E+01	7.0654E+02	4.1535E-05	0.0000E+00	4.1535E-05	0.0000E+00	7.0654E+02	1.0008E+02	6.5964E+01	5.0759E+02
4.500E+01	6.7395E+02	5.7553E-06	0.0000E+00	5.7553E-06	0.0000E+00	6.7395E+02	7.0646E+01	5.8148E+01	5.1105E+02
5.000E+01	6.4546E+02	1.6254E-06	0.0000E+00	1.6254E-06	0.0000E+00	6.4546E+02	4.9906E+01	5.1274E+01	5.0888E+02
6.000E+01	5.9864E+02	1.0128E-06	0.0000E+00	1.0128E-06	0.0000E+00	5.9864E+02	2.2135E+01	4.1158E+01	5.0258E+02
7.000E+01	5.6219E+02	1.0002E-06	0.0000E+00	1.0002E-06	0.0000E+00	5.6219E+02	5.5232E+00	3.3348E+01	4.9526E+02
8.000E+01	5.3325E+02	9.8515E-07	0.0000E+00	9.8515E-07	0.0000E+00	5.3325E+02	0.0000E+00	2.7158E+01	4.8275E+02
9.000E+01	5.0982E+02	9.6402E-07	0.0000E+00	9.6402E-07	0.0000E+00	5.0982E+02	2.8507E-06	2.2526E+01	4.6808E+02
1.000E+02	4.9048E+02	9.4638E-07	0.0000E+00	9.4638E-07	0.0000E+00	4.9048E+02	0.0000E+00	1.8635E+01	4.5608E+02

WIDE RANGE OF ACCESSIBLE REACTION EXIT CHANNELS

TALYS has the possibility to calculate the cross sections and spectra of recoils of the products of the nuclear reactions with the number ejectial up to 13 for neutrons and 9 for protons.

```
# p +  28Si: Production of  13N  - Total
# Q-value    =-2.93278E+01 mass=  13.005738
# E-threshold= 3.03837E+01
# # energies = 24
#    E          xs                E          xs
 3.500E+01 0.00000E+00      7.000E+01 2.03181E-03
 4.000E+01 0.00000E+00      8.000E+01 1.98600E-03
 4.500E+01 0.00000E+00      9.000E+01 5.97030E-03
 5.000E+01 0.00000E+00      1.000E+02 2.36762E-02
 6.000E+01 1.65502E-03
```

RESULTS OBTAINED IN EMPIRE AND TALYS CODES ARE CLOSE ONE TO ANOTHER BUT DO NOT COINCIDE COMPLETELY



E	σ
2.500E+01	6.41609E-01
3.000E+01	1.04302E+01
3.500E+01	5.78926E+01
4.000E+01	9.40607E+01
4.500E+01	1.03172E+02
5.000E+01	9.91911E+01
6.000E+01	8.00202E+01
7.000E+01	7.09261E+01
8.000E+01	6.29551E+01
9.000E+01	5.89405E+01
1.000E+02	5.14031E+01

Energy dependence of the yield of the evaporation residual 26Al in the reaction p+28Si for: EMPIRE calculations (various optical-model potentials) – closed symbols, TALYS calculations – red line (and the table), various databases – open symbols.

CONCLUSIONS

1. One of popular lines of the investigations of nuclear physics is processing of the experimental data by large-scale codes which are constructed as a synthesis of a number of more or less standard theoretical approaches and a large volume of nuclear data.

2. Codes of such a type are currently upgraded. New versions appear.

3. Handling of experimental data by these codes may result in a good or a mediocre description. The latter case provides reasons to perform more wide analysis of the bulk of related experiments and to create more accurate theoretical approaches.

THANK YOU FOR YOUR ATTENTION!

For the fusion reaction producing the Tl products at E ~ 20÷60 MEV a rather good agreement of experimental and calculation values takes place. For the transfer reactions producing the isotope ^{194}Au at this region of energies there is the shift of maximum of excitation function up to 20 MeV. In this case EMPIRE calculations form the basis of more developed theoretical approaches which would be capable to remove the discrepancy.

As for ^{196}Au isotope the discrepancy between experimental and calculated values of the cross section up to 10 times takes place. EMPIRE calculations provide an unambiguous evidence of the fact that there is another reaction producing this isotope.

3. At the same time it is very difficult to explain the large values of the subbarrier cross sections of Tl isotopes production within the standard approaches used for these purposes. Such large cross sections are most likely related to the unusual properties of the direct reactions induced by ^{6}He nuclei.

4. The analysis performed in this study showed that the problem of large experimental yield of ^{198,196}Au nuclei in a wide range of ^{6}He-ion energies (whereas the values of cross sections of other isotopes are usual for the discussed reactions) cannot be solved both within the standard approaches and in the case that direct reactions are taken into account. The large yield of these isotopes can be related to the presence of a great quantity of neutrons generated by the ^{6}He breakup in the ^{197}Au nucleus field in the multilayer target.

EMPIRE-II19. Calculated cross sections of the evaporation residuals formation for the reactions $^{6}He + ^{197}Au \rightarrow ^{198}Tl, ^{194,196}Au, ^{195,197}Hg$.

$E_L(^6He)$ MeV	E_C	^{198}Tl mb	^{196}Au mb	^{194}Au mb	^{197}Hg mb	^{195}Hg mb
113.7	*122.5*			17.2	12.1	
95.35	*104.7*	0..8	0.02	184.7	125	
81.44	*91.2*	18.7	1.12	285	259.6	4.4
68	*78.2*	65.8	1.4	79.0	101.4	0.05
55	*65.6*	969.4	21..8	2.9	25.4	
40.8	*51.8*	924.6	21..8			

The calculations of the products of the reactions induced by protons of energy region up to 100 MeV on isotope 28Si and Al were performed. The code TALYS was used for these purposes. This code has the possibility to calculate the cross sections and spectra of recoils of the products of the nuclear reactions with the number ejectial up to 13 for neutrons and 9 for protons. As a test of the code the reaction induced by protons on the natural Fe was used. Early by us calculations by code EMPIRE were carried out. The comparison of the obtained results was performed. The preliminary results for the reaction 28 Si(α,xn,yp) at E α energy region up to 100 MeV are presented.

The given results are important taken into account the interaction of the cosmic rays with the materials of the border electronic.

INPUT

```
#
# General
#
projectile p
element si
mass 28
energy energies
#
# Output
#
fileresidual     y
```

p + 28Si: Production of 13N - Total
Q-value   =-2.93278E+01 mass= 13.005738
E-threshold= 3.03837E+01
energies = 24
E   xs

1.000E+00	0.00000E+00
2.000E+00	0.00000E+00
3.000E+00	0.00000E+00
4.000E+00	0.00000E+00
5.000E+00	0.00000E+00
6.000E+00	0.00000E+00
8.000E+00	0.00000E+00
1.000E+01	0.00000E+00
1.200E+01	0.00000E+00
1.400E+01	0.00000E+00
1.600E+01	0.00000E+00
1.800E+01	0.00000E+00
2.000E+01	0.00000E+00
2.500E+01	0.00000E+00
3.000E+01	0.00000E+00
3.500E+01	0.00000E+00
4.000E+01	0.00000E+00
4.500E+01	0.00000E+00
5.000E+01	0.00000E+00
6.000E+01	1.65502E-03
7.000E+01	2.03181E-03
8.000E+01	1.98600E-03
9.000E+01	5.97030E-03
1.000E+02	2.36762E-02

p + 28Si: Production of 26Al - Ground state
Q-value   =   -17.00360
E-threshold=   17.61580
energies = 24
E   xs   Branching

E	xs	Branching
1.000E+00	0.00000E+00	
2.000E+00	0.00000E+00	
3.000E+00	0.00000E+00	
4.000E+00	0.00000E+00	
5.000E+00	0.00000E+00	
6.000E+00	0.00000E+00	
8.000E+00	0.00000E+00	
1.000E+01	0.00000E+00	
1.200E+01	0.00000E+00	
1.400E+01	0.00000E+00	
1.600E+01	0.00000E+00	
1.800E+01	0.00000E+00	
2.000E+01	0.00000E+00	
2.500E+01	6.41609E-01	0.71948
3.000E+01	1.04302E+01	0.79206
3.500E+01	5.78926E+01	0.76744
4.000E+01	9.40607E+01	0.72741
4.500E+01	1.03172E+02	0.71442
5.000E+01	9.91911E+01	0.71017
6.000E+01	8.00202E+01	0.71800
7.000E+01	7.09261E+01	0.72699
8.000E+01	6.29551E+01	0.72622
9.000E+01	5.89405E+01	0.72270
1.000E+02	5.14031E+01	0.73576

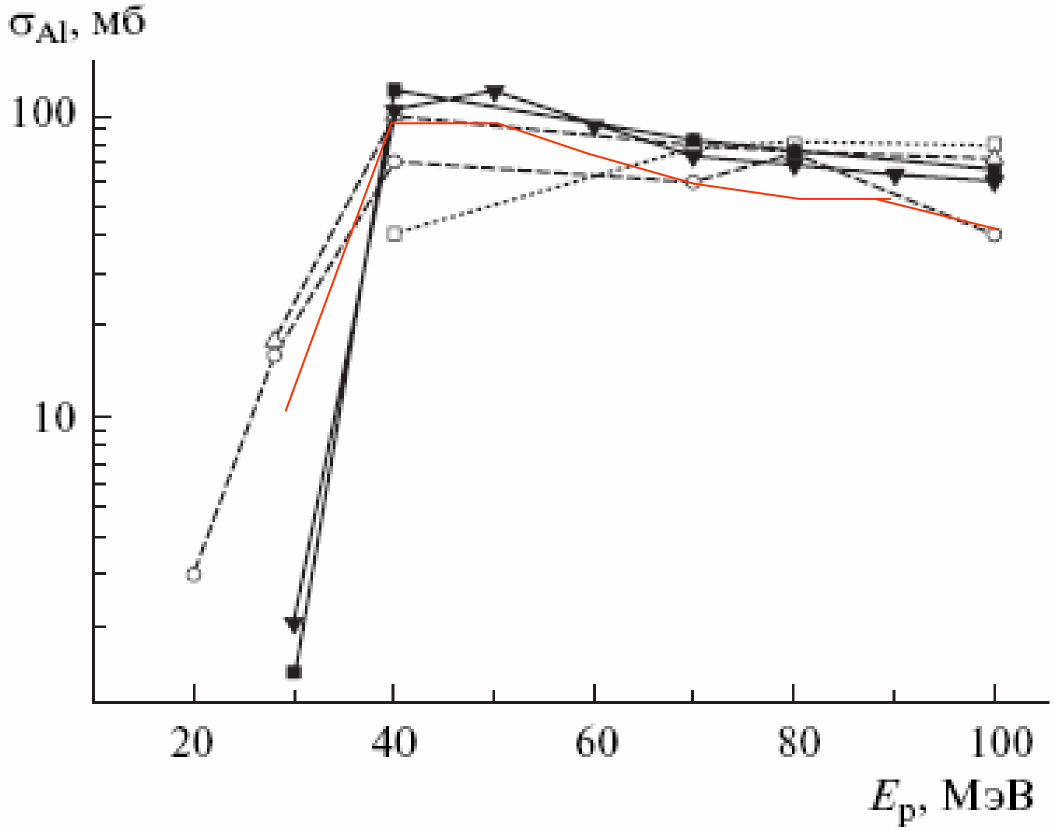
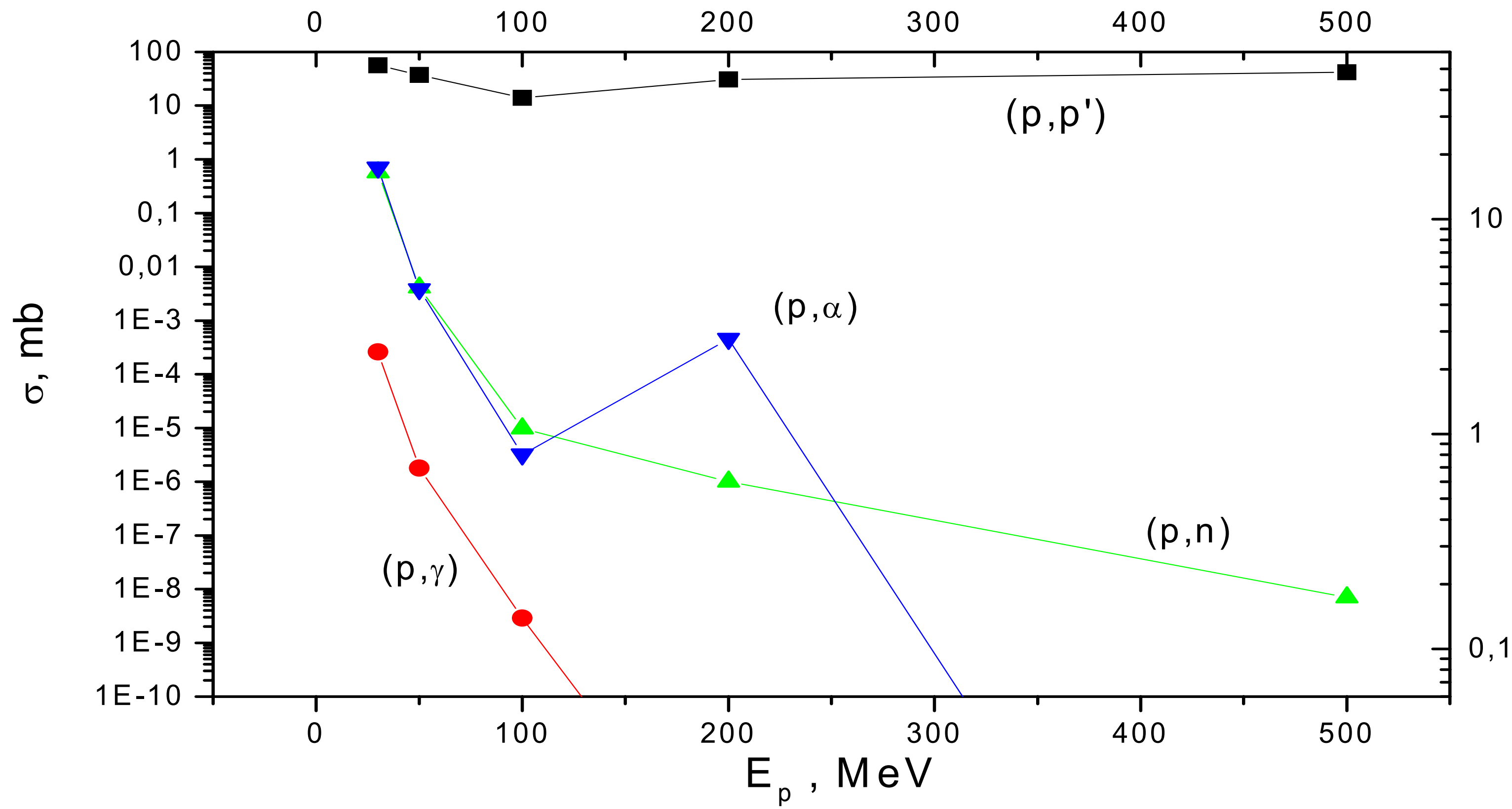
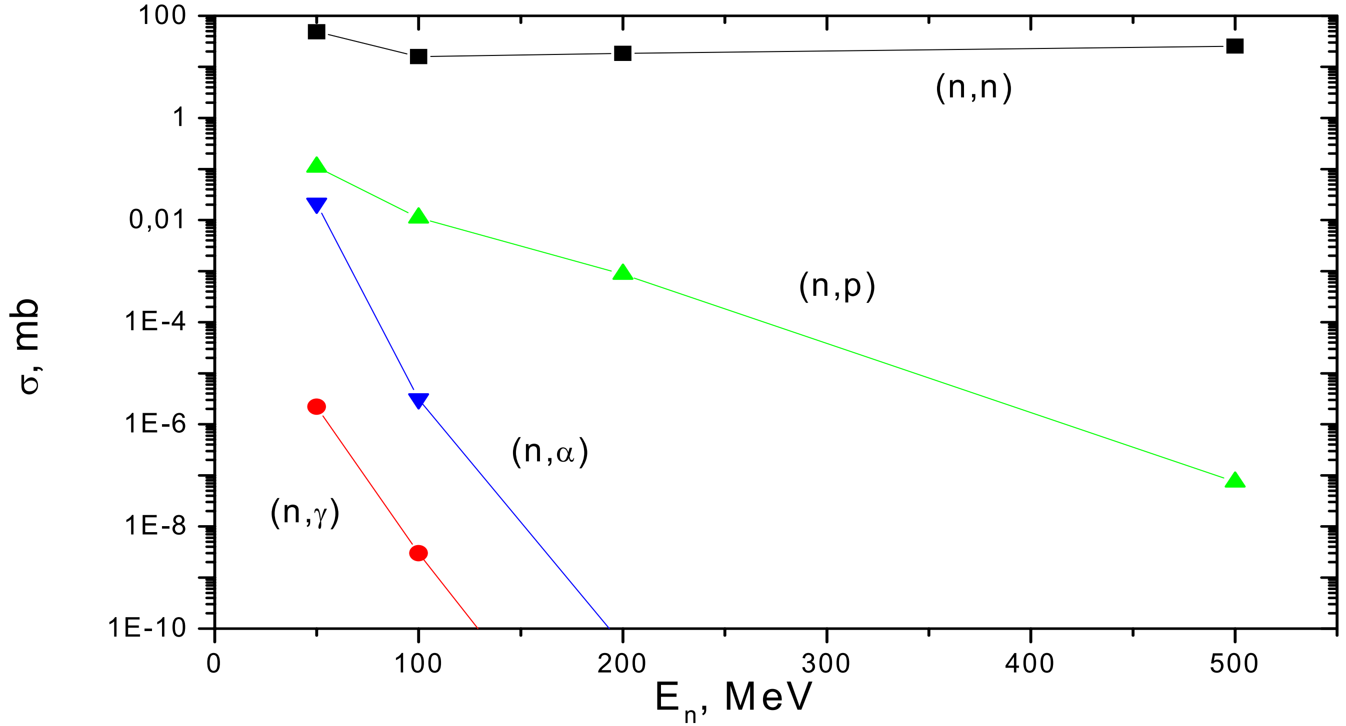


Рис. 4. Сечение образования конечного ядра ^{26}Al в реакции p + Si^{28} для различных наборов потенциалов: (пунктирная кривая со светлыми квадратами – omp1, сплошная линия с черными квадратами – omp2, сплошная линия с черными треугольниками вниз – omp3 – данные настоящей работы; пунктирная кривая со светлыми кругами – данные из базы данных [19]; пунктирная кривая со светлыми треугольниками вверх – компиляция данных работы [20]).

Расчеты сечений реакций $^{28}Si(p,p')^{28}Si$, $^{28}Si(p,\gamma)^{29}P$, $^{28}Si(p,n)^{28}P$, $^{28}Si(p,\alpha)^{25}Al$ в области энергий налетающих протонов E_p = 30, 50, 100, 200 , 500 МэВ.



Расчеты сечений реакций $^{28}Si(n,n')^{28}Si$, $^{28}Si(n,\gamma)^{29}Si$, $^{28}Si(n,p)^{28}Al$, $^{28}Si(n,\alpha)^{25}Mg$ в области энергий налетающих нейтронов E_p = 50, 100, 200 , 500 МэВ.



Расчеты спектра отдачи в реакции с максимальным выходом (n,n'), E(inc)=50 MeV