The Cross Section Calculation of ^{102,104,106}Mo below 20 MeV

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【abstract】 *The cross section calculation of ^{102,104,106}Mo below 20 MeV was carried out. Because there are no any experimental data for three unstable isotopes of element molybdenum, our results of ^{102,104,106}Mo are compared each other and with evaluated data of ^{92,94,96,98,100}Mo which are generally in good accordance with experimental data. In our final evaluation files, the most of the data are directly taken from our calculated values, which are reasonable in physics.*

1 Parameters Used in UNF and Direct Inelastic Contribution

For unstable isotopes of element molybdenum without any experimental data, we used the program APMN[1] to automatically search for a common optimal set of optical potential parameters in neutron channel based on the experimental data of total cross sections (with weight 8.0) and elastic scattering angular distributions (with weight 1.0) of 6 stable isotopes $^{92,94\sim96,98,100}$Mo, and natural element molybdenum. All these experimental data were taken from EXFOR. The code DWUCK4[2] was used to calculate the direct inelastic cross sections and the Legendre coefficients of their angular distributions. And our main tool for the calculation of complete cross section data below 20 MeV is the version 2001 of program UNF[3]. For five charged particle channels, we used the universal optical potential parameters[4].

The optical potential parameters given in Table 1 were used in our final calculations for all these unstable isotopes. The same set of optimal optical potential parameters in neutron channel were also used in calculations of the direct inelastic cross sections as well as the angular distributions with DWUCK4. Levels and their deformation parameters β_2 used are given in Table 2. We take β_2=0.11 for all levels.

In UNF, Gilbert-Cammeron formula was employed for calculation of the level density. The level density parameter a, the pair energy correction Δ and the two peak giant dipole resonance parameter for gamma emission were obtained from the Parameters Library in CNDC. The data of levels and their spin, parity were taken from the Parameters Library in CNDC and/or the Web site of the National Nuclear Data Center at Brookhaven National Laboratory. In order to make the calculated cross sections reasonable in physics, the level density parameters a and the pair energy corrections Δ were adjusted by hand in suitable range. The values of a and Δ used in our final calculations are given in Table 3.

For 3 unstable isotopes concerned, we took the adjustable Kulbach parameter in exciton model as CK=822.0, which is the average value of that of ^{92,94,96,98,100}Mo. The adjustable factor in (n,γ) cross section calculation CE1=8.3, which is the same value as ^{100}Mo .The adjustable parameter in direct (n,γ) calculation DGM=0.65.

2 Results and Discussion

With above mentioned parameters and the calculated direct inelastic data by DWUCK4 as the input data, we calculated the neutron nuclear data of ^{102,104,106}Mo with the code UNF. The calculated results were compared with each other and with evaluated data of ^{92,94,96,98,100}Mo which are presented in Fig. 1~9.

Our calculated values of σ_{tot} above resonance region are given in Fig.1, from which we can see that our σ_{tot} of ^{102,104,106}Mo are with in small differences in comparison with each other, within larger differences in comparison with σ_{tot} of ^{92,94,96,98,100}Mo. The reason is that a common optical potential parameters for ^{102,104,106}Mo were obtained on the basis of experimental σ_{tot} and angular distributions of elastic scattering of 6 stable isotopes (there are no any experimental data for ^{97}Mo) and natural element molybdenum, which are different from those for ^{92,94,96,98,100}Mo based on their own experimental σ_{tot} respectively.

Table 1 Optical potential parameters used in this work

channel	n	p	α	^{3}He	d	t
a_r	0.583 222 03	0.75	0.52	0.72	0.71	0.72
a_s	0.678 118 82	0.51	0.52	0.88	0.78	0.84
a_v	0.716 305 85	0.51	0.52	0.88	0.78	0.84
a_{so}	0.225 942 94	0.75	0.52	0.72	0.71	0.72
r_r	1.209 779 26	1.17	1.442	1.20	1.17	1.20
r_s	1.211 337 09	1.32	1.442	1.40	1.30	1.40
r_v	1.508 646 37	1.32	1.442	1.40	1.30	1.40
r_{so}	0.924 287 32	1.01	1.442	1.20	0.64	1.20
r_c	1.300 000 00	1.25	1.25	1.30	1.30	1.30
W_{v0}	−0.942 049 56	−2.70	22.4	0.0	0.0	0.0
W_{v1}	0.449 992 60	0.22	0.0	0.0	0.0	0.0
W_{v2}	−0.012 814 66	0.0	0.0	0.0	0.0	0.0
V_0	55.643 169 40	54.000 00	164.700 00	151.900 00	90.600 000	165.000 00
V_1	−0.507 165 31	−0.32	0.0	−0.17	0.0	−0.17
V_2	0.006 078 12	0.0	0.0	0.0	0.0	0.0
V_3	−22.314 836 5	24.0	0.0	50.0	0.0	−6.4
V_4	−0.139 821 89	0.4	0.0	0.0	0.0	0.0
V_{so}	4.858 808 04	6.2	0.0	2.5	7.13	2.5
W_{so}	0.249 576 23	11.8	0.0	41.7	12.0	46.0
W_{s1}	0.087 561 61	−0.25	0.0	−0.33	0.0	−0.33
W_{s2}	20.387 477 87	12.0	0.0	44.0	0.0	−110.0

And a_{s1}=0.7, a_{v1}=0.7 for p channel.

Table 2 levels and deformation parameters β_2 used in direct inelastic calculation

^{102}Mo				^{104}Mo				^{106}Mo			
Level/MeV	J	π	β_2	Level/MeV	J	π	β_2	Level/MeV	J	π	β_2
0.296 597	2.0	+1	0.11	0.192 19	2.0	+1	0.11	0.171 548	2.0	+1	0.11
0.743 74	4.0	+1	0.11	0.560 68	4.0	+1	0.11	0.522 29	4.0	+1	0.11
0.848 06	2.0	+1	0.11	0.812 36	2.0	+1	0.11	0.710 71	2.0	+1	0.11
1.245 58	3.0	+1	0.11	1.028 35	3.0	+1	0.11	0.885 60	3.0	+1	0.11
1.249 75	2.0	+1	0.11	1.079 98	6.0	+1	0.11	1.033 7	6.0	+1	0.11
1.327 92	6.0	+1	0.11	1.214 82	4.0	+1	0.11	1.068 2	6.0	+1	0.11
1.398 43	4.0	+1	0.11	1.275 19	4.0	+1	0.11	1.279 9	6.0	+1	0.11
				1.468 61	4.0	+1	0.11	1.435 77	6.0	+1	0.11
				1.475 67	5.0	+1	0.11				

Table 3 the a and Δ values used in the calculations

channel		(n,γ)	(n,n′)	(n,p)	(n,α)	(n,^{3}He)	(n,d)
^{102}Mo	a	17.889 04	17.131 92	18.119 28	16.671 60	16.004 00	17.363 92
	Δ	1.05	0.62	−0.32	−0.90	2.70	0.25
^{104}Mo	a	18.901 68	18.117 63	19.133 50	16.741 76	16.961 38	18.351 31
	Δ	1.13	0.67	−0.44	0.03	2.60	0.55
^{106}Mo	a	19.082 81	18.783 20	19.324 22	17.725 89	17.605 12	19.021 80
	Δ	0.88	0.31	0.08	0.91	2.49	0.84
channel		(n,t)	(n,2n)	(n,nα)	(n,2p)	(n,3n)	
^{102}Mo	a	18.028 00	16.808 32	14.761 15	16.741 76	15.854 40	
	Δ	−0.25	−0.70	2.45	1.03	−0.07	
^{104}Mo	a	18.119 28	16.889 04	16.004 00	17.725 89	17.131 92	
	Δ	−0.32	−1.00	2.70	0.91	1.02	
^{106}Mo	a	19.133 50	18.901 68	16.961 38	17.894 52	18.117 63	
	Δ	−0.44	0.73	2.60	1.43	2.42	

The calculated values of σ_{el} above resonance region are given in Fig.2, from which we can see that the values below 3 MeV are very divergent for different isotopes, and above 3 MeV the values of σ_{el} are almost the same for ^{102,104,106}Mo, however with small differences in comparison with ^{92,94,96,98,100}Mo respectively. The reason is that in lower energy region, the compound nucleus elastic scattering cross sections are obviously larger than zero, then the values of σ_{el} depend on both the set of optical potential parameters and the different level structure of each isotope. In higher energy region, the compound nucleus elastic scattering cross sections are almost zero, the values of σ_{el} only depend on the set of optical potential parameters.

All calculated $\sigma_{n,n'}$ are given in Fig.3, from which we can see that near threshold energy, the larger the mass number of certain isotope, the larger the values of $\sigma_{n,n'}$ of the corresponding isotope.

Our radiative capture cross sections of ^{92,94,96,98,100,102,104,106}Mo are given in Fig.4, from which we can see that the $\sigma_{n,\gamma}$ values for ^{100,102,104,106}Mo are with small differences below 0.15 MeV, and the $\sigma_{n,\gamma}$ values for all isotopes are very divergent in higher energy region.

Our calculated (n,p) reaction cross sections of all these isotopes are given in Fig.5, from which we can see that the $\sigma_{n,p}$ values are lower and lower, and the threshold energies of them are higher and higher when the mass number of corresponding isotope is larger and larger.

Our calculated (n,α),(n,d) reaction cross sections of all these isotopes are given in Fig.6,7 from which we can see that the (n,α) reaction cross sections become smaller, and the threshold energies of them become higher when the mass number of corresponding isotope becomes larger.

Our calculated (n,2n), (n,3n) reaction cross sections of all these isotopes are given in Fig.8,9 from which we can see that the threshold energy of (n,2n) and (n,3n) reactions becomes lower and lower when the mass number of corresponding isotope becomes larger and larger. In E_n>13 MeV energy region we find that $\sigma_{n,2n}$ values drop at lower energy for heavier isotope because (n,3n) reaction of heavier isotope has lower threshold energy and $\sigma_{n,2n}+\sigma_{n,3n}$ should keep about constant in this energy region.

In summary, in this work we give complete cross sections in the energy region from 1 keV to 20 MeV for all even unstable isotopes (102~106) of element molybdenum. In our calculation and evaluation, the common optimal set of optical potential parameters are automatically searched with the code APMN to suit all isotopes of element molybdenum, with which the calculated total cross sections and angular distributions of elastic scattering are in optimal accordance with experimental data for $^{92,94\sim96,98,100}$Mo. For calculations of the cross sections in different reaction channels, the total changing trend are considered being kept reasonable in physics.

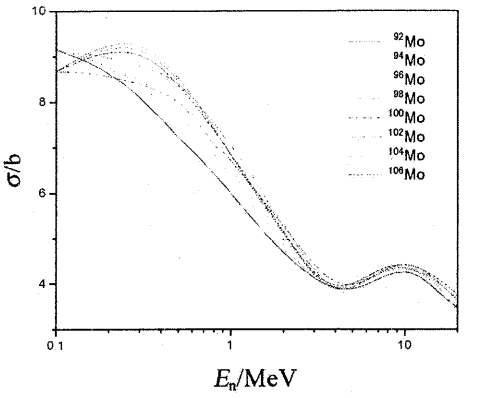

Fig.1 Total cross sections

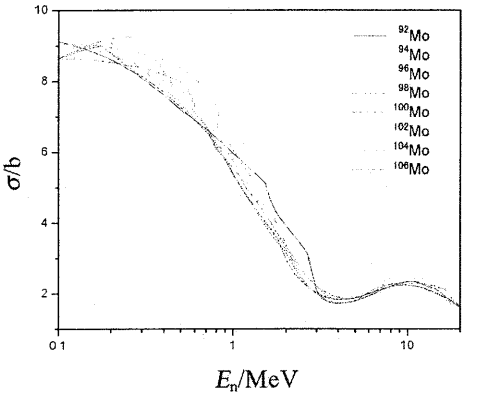

Fig.2 Elastic scattering cross sections

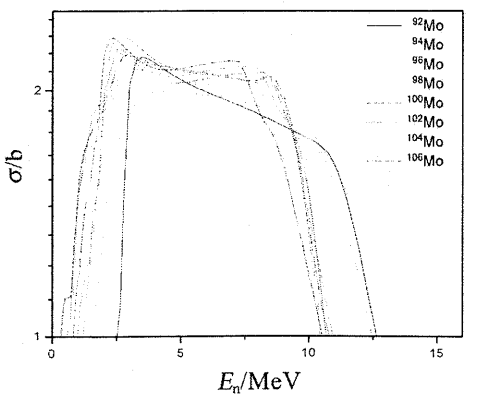

Fig.3 (n,n′) cross sections

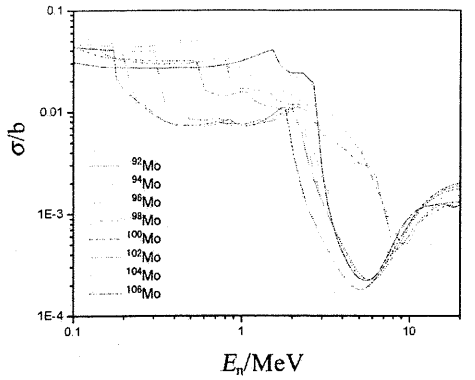

Fig.4 (n,γ) cross sections

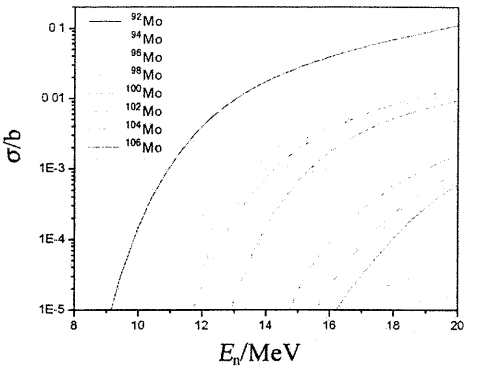

Fig.7 (n,d) cross sections

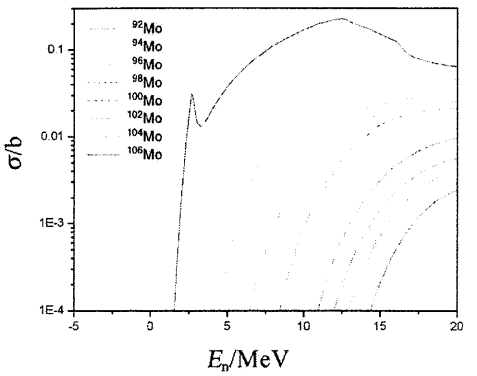

Fig.5 (n,p) cross sections

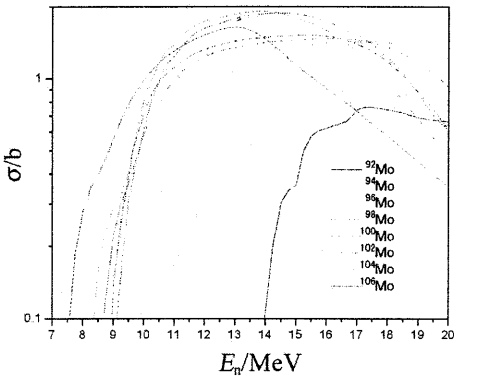

Fig.8 (n,2n) cross sections

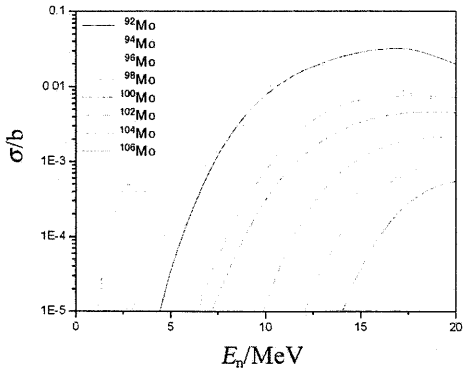

Fig.6 (n,α) cross sections

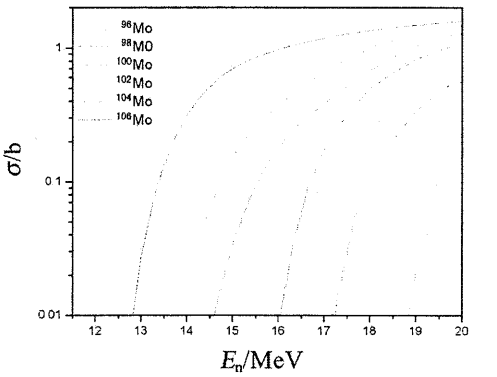

Fig.9 (n,3n) cross sections

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