Re-Evaluation of Neutron Data for ^{89}Y below 20 MeV

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【abstract】 *The neutron data, including all kinds of cross sections, especially the cross sections of the isomeric states in (n,γ) and (n,α) section channels, angular distributions of elastic scattering, energy spectra and/or double-differential cross sections of all emitted particles, gamma production data (production cross sections and multiplicity, energy spectra) in n+^{89}Y reaction below 20 MeV were calculated and evaluated. In most cases, except the channel of (n,p) reaction, the calculated cross sections are in good agreement with the measurements.*

^{89}Y is the only stable isotope of element yttrium, which is a fission production nucleus.

There are a few evaluated files for ^{89}Y, such as in ENDF/B-6 and JENDL-3.2 as well as in CENDL-3; all of them do not contain double-differential cross sections and gamma production data, meanwhile something still needs to be improved. The calculations of ^{89}Y for CENDL-3 in 1997, did not analyze the experimental data coming from different authors and different years carefully. Based on the newer and more reliable experimental data, as well as the data on isomeric states, the reevaluation of n+^{89}Y was performed to improve the neutron reaction data including double-differential cross sections and gamma production data in ENDF/B-6 format. In this paper the comparison with experimental data, the methods, parameters used in the model calculation and part of cross sections, secondary neutron energy spectra, angular distributions and double-differential cross sections are given. All the experimental data in figures were taken from EXFOR.

1 Direct Inelastic Contribution, Optical Potential and Other Parameters

Firstly, the program APMN[1] was used to search the optimal optical potential parameters of n+^{89}Y automatically by fitting the experimental data, such as total cross sections (C.Budtz-Jorgensen in 1984, W.P.Poenitz in 1983, D.G.Foster in 1971 and J.F.Whalen in 1968), elastic scattering cross sections (F.G.Perey in 1970, J.H.Towle in 1969, N.A.Bostrom in 1959) and their angular distributions on 60 energy points distributing from 0.889 to 21.6 MeV (G.Schreder in 1989, S.Mellema in 1987, R.D.Lawson in 1986, G.M.Honore in 1986, C.Budtz-JOrgensen in 1984, Y.Yiming in 1982, F.D.Mcdaniel in 1977, V.I.Trykova in 1975, S.A.COX in 1972, M.E.Gurtovoj in 1971 and F.G.Perey in 1970). In order to make the calculated (n,p), (n,d) and (n,α) reaction cross sections in good agreement with experimental data. We also need adjusting some optical potential parameters in proton, deuteron and alpha channels by hand. The optical potential parameters as the input parameters in the main code UNF[2] are given in Table 1.The meaning of all the optical potential parameters can be found in Ref. [1]. The same neutron optical potential parameters are also used in the calculations of the direct inelastic cross sections as well as the Legendre coefficient of their angular distributions with Dwuck4[3]. Levels and their deformation parameters β_2 used in direct inelastic calculation are given in Table 2.

Besides the optical potential parameters, the direct inelastic cross sections as well as the Legendre coefficients of angular distributions are also the input data for the main code UNF. In UNF code, Gilbert-Cammeron formula is employed for calculation of the level density. The level density parameter a, the pair energy correction Δ and the two peak giant resonance parameter for gamma emission were obtained from the Parameters Library in CNDC by using PREUNF code[4]. The data of levels and their spin, parity and the branch ratio of gamma emission were taken from the Parameters Library in CNDC and/or the Web of NNDC at BNL, USA. In order to make the calculated cross sections in good accordance with experimental data, some of the level density parameters a and the pair energy corrections Δ need to be adjusted. The a and Δ's values used in the final calculations are given in Table 3.

Besides parameters mentioned above, Kulbach parameter in exciton model CK=5500.0 the adjustable factor in (n,γ) cross section calculation CE1=5.5, and the adjustable parameter in direct (n,γ) calculation DGM=0.35 were used.

Table 1 Optical potential parameters of ^{89}Y used in this work

channel	n	p	alpha	^{3}He	d	t
a_r	0.6493890	0.47	0.52	0.72	0.71	0.72
a_s	0.4711004	0.45	0.55	0.88	0.70	0.84
a_v	0.6243670	0.45	0.55	0.88	0.70	0.84
a_{so}	0.6493890	0.47	0.52	0.72	0.71	0.72
r_r	1.2497820	1.16	1.40	1.20	1.30	1.20
r_s	1.3129580	1.14	1.39	1.40	1.35	1.40
r_v	1.2393860	1.14	1.39	1.40	1.35	1.40
r_{so}	1.2497820	1.01	1.40	1.20	0.64	1.20
r_c	1.3000000	1.25	1.30	1.30	1.30	1.30
W_{v0}	-0.1708760	-2.70	22.4	0.0	0.0	0.0
W_{v1}	0.1160180	0.22	0.0	0.0	0.0	0.0
W_{v2}	-0.0338120	0.0	0.0	0.0	0.0	0.0
V_0	52.776480	54.0	164.7	151.9	90.6	165.0
V_1	-0.5965391	-0.32	0.0	-0.17	0.0	-0.17
V_2	0.01366303	0.0	0.0	0.0	0.0	0.0
V_3	-24.00000	24.0	0.0	50.0	0.0	-6.4
V_4	-0.01222399	0.4	0.0	0.0	0.0	0.0
V_{so}	6.200000	6.2	0.0	2.5	7.13	2.5
W_{s0}	7.310210	11.8	0.0	41.7	12.0	46.0
W_{s1}	0.1593175	-0.25	0.0	-0.33	0.0	-0.33
W_{s2}	-12.00000	12.0	0.0	44.0	0.0	-110.0

And a_{s1}=0.7, a_{v1}=0.7 for proton.

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

Level / MeV	J	π	β_2
1.50741	1.5	-1	0.085
1.74474	2.5	-1	0.085
2.88153	1.5	-1	0.085
3.06776	1.5	-1	0.085
3.10726	2.5	-1	0.085
3.13890	2.5	-1	0.085

Table 3 The *a* and *Δ*'s values used in our final calculations

channel	(n,γ)	(n, n')	(n, p)	(n,α)	(n,^{3}He)	(n,d)
a	9.53280	10.37206	8.78813	12.75302	9.81221	10.46237
Δ	-0.9000	+0.4000	-3.0500	-1.1400	+1.4000	-2.65
channel	(n, t)	(n, 2n)	(n, nα)	(n, 2p)	(n, 3n)	
a	11.18263	11.75555	10.61140	9.97920	9.61023	
Δ	+0.3000	-2.2000	+0.2000	-1.3000	-1.0000	

2 Calculated Results, Evaluation and Discussion

By using the input parameters mentioned above, all kinds of the files were calculated with the code UNF firstly. The resonance parameters below 0.15 MeV were taken from ENDF/B-6. The values of σ_{tot} and σ_{el} below 0.65 MeV were also taken from ENDF/B-6, which are fluctuated rapidly. In order to make our calculated values smoothly connecting with those in resonance region, the values of σ_{tot} and σ_{el} within 0.65~1.1 MeV were adjusted, which are shown in Figs 1,2, respectively.

The evaluated σ_{tot} , σ_{el} and those of ENDF/B-6 and CENDL-3 are all in good agreement with experimental data, while those of JENDL-3.2 are not in good accordance with experimental data in $E_n > 8$ MeV energy region. The angular distributions of elastic scattering at 8 energy points are given in Fig. 3a, 3b and 3c, respectively. The results show that our calculated values are in good accordance with experimental data for every energy points, the angular distributions at other 52 energy points not given in Fig. 3, which are also in same good agreement with experimental data as in Fig. 3.

The continuous inelastic neutron spectra are shown in Fig. 4, from which one can see that the calculated values and CENDL-3 are in good accordance with experimental data. The comparisons of the calculated double-differential cross sections of inelastic scattering with their experimental data at E_n=9.1, 7.94 and 7.02 MeV for 5 angles (30, 60, 90, 120 and 150 degree) are shown in Figs. 5a, 5b and 5c, respectively. At higher emitted neutron energies corresponding to discrete levels, we cannot make the calculated values in very good agreement with experimental data. There are no data of double-differential cross sections given in the ENDF/B-6, JENDL-3.2 and previous CENDL-3.

The (n,γ) reaction cross sections are shown in Fig. 6, which indicate that our evaluation values (basically the calculated values are adopted, only increase a little within 1.7~3.5 MeV based on experimental data and decrease a little within 0.15~0.18 MeV to connect with ENDF/B-6) are in very good accordance with experimental data; the calculated $\sigma_{n,\gamma}$ cross section of the isomeric state (0.6817 MeV, $J^{\pi}=7^{+}$, $T_{1/2}$=3.19 hour) is also in good agreement with experimental data except in 0.97~1.5 MeV energy region, where the calculated values are lower than experimental data.

The (n,n') reaction cross sections are shown in Fig. 7. the evaluation values (basically the calculated values are adopted, but in $E_n < 1.53$ MeV region they are lower than the experimental data given by C.P.SWANN in 1955, so we took the values from CENDL-3 to replace the calculated values).

The (n,2n) reaction cross sections are shown in Fig. 8. In E_n<16 MeV region, our calculated values are not in good agreement with experimental data as ENDF/B-6, JENDL-3.2 and CENDL-3, so we took the values from CENDL-3 as the reevaluation data. In E_n>16 MeV energy region, considering the newer and more reliable experimental data given by HUANG Jianzhou in 1989, our calculated values are reasonable.

Fig. 9 shows the (n,p) reaction cross section. One can see that the data given by H.A.Tewes in 1960 are lower than that given by B.P.Bayhurst in 1961. The later is more reliable because near 14.5 MeV with about equal values given by N.I.Molla in 1998, so all 3 evaluated files ENDF/B-6, JENDL-3.2 and CENDL-3 gave their recommend values based on these 2 sets. Our calculated $\sigma_{n,p}$ is not in reasonable shapes, which with a small peak near 3.5~4.0 MeV, drop rapidly and form a turning line segment near 17 MeV and rise much faster in 5~11 MeV energy region than all 3 evaluated files. The reason is not yet clear at this moment, the UNF code usually gives correct and reasonable calculation results for most cases, the (n,p) channel of ^{89}Y is a special exception case. Considering the physical reasonableness, the evaluated values for $\sigma_{n,p}$ are based on the experimental data given by N.I.Molla et al. in 1998 and by B.P.Bayhurst et al. in 1961, and give the evaluation values for inclusive $\sigma_{n,p}$(=$\sigma_{n,p}$ +$\sigma_{n,,np}$) based on the experimental data given by Haight in 1981, then the evaluation values for $\sigma_{n,np}$(= inclusive $\sigma_{n,p}$ - $\sigma_{n,p}$) were obtained.

Fig. 10 gives the (n,α) reaction cross sections, in which the data given by H.A.Tewes in 1960 is apparently lower than other experimental data, the three data near 14.5 MeV given by E.T.Bramlitt in 1963, by F.STROHAL in 1962 and by E.B.Paul in 1953, respectively, are very divergent, all of them should be given up. JENDL-3.2 and CENDL-3 have their recommended values based on the data given by B.P.Bayhurst in 1961 and other three data near 14.5 MeV given by A.Grallert in 1993 and by L.R.Greenwood in 1987, respectively. But they did not use the newest measured data given by A.A.Filatenkov in 1999. Both of our calculated (i.e. evaluated) $\sigma_{n\alpha}$ and that corresponding to residual nucleus in isomeric state (0.55605 MeV, $J=6^{-}$, $T_{1/2}$=1.017 min) are in very good agreement with experimental data given by A.A.Fllatenkov in 1999.

Fig. 11 gives the (n,d) reaction cross sections, all of ENDF/B-6, CENDL-3 and our calculated (i.e. evaluated) values pass the only one experimental data given by R.C.HAIGHT in 1981 with the different shape.

The version 2001 of the code UNF have many improved functions, with which and based on some newer experimental data, the recalculations for neutron reaction data of n+^{89}Y below 20 MeV were performed and improved. For some special cases, such as the ascending segment of $\sigma_{n,2n}$ in E_n < 16 MeV energy region and $\sigma_{n,n'}$ below 1.53 MeV, our calculated values is not so good as in CENDL-3, so the recommend values in CENDL-3 were adopted in our evaluation. For $\sigma_{n,p}$, $\sigma_{n,np}$ and $\sigma_{n,2n}$ in E_n<16 MeV energy region we did not take the calculated results but performed the new evaluation; in order to keep the consistency in σ_{non}, we also did the corresponding changes in σ_{in}. Because there are also some changes in $\sigma_{n,\gamma}$, $\sigma_{n,n'}$ and σ_{el}, we also did corresponding changes in σ_{tot} to keep the consistency. All these consistency corrections in σ_{in} and σ_{tot} are small in comparison with the cross sections themselves.

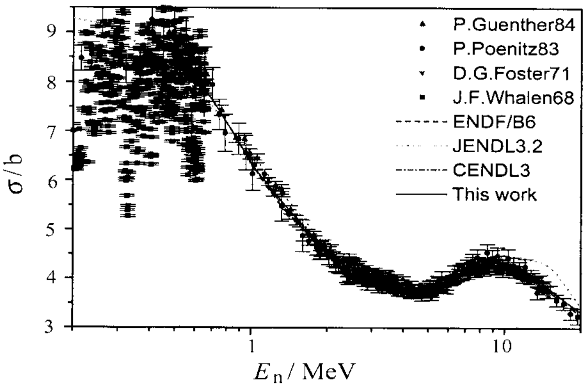

Fig. 1 Total cross section for n+^{89}Y

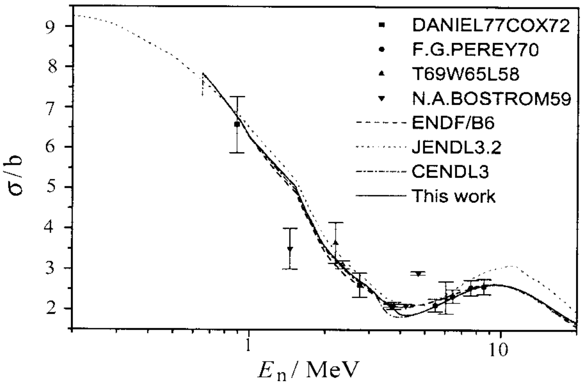

Fig. 2 Elastic scattering cross section for n+^{89}Y

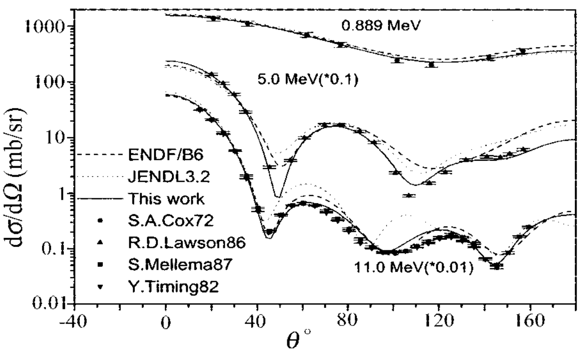

Fig. 3(a) Elastic scattering angular distributions for n+^{89}Y

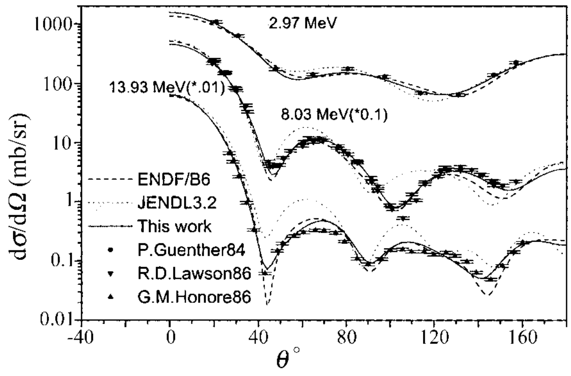

Fig. 3(b) Elastic scattering angular distributions for n+^{89}Y

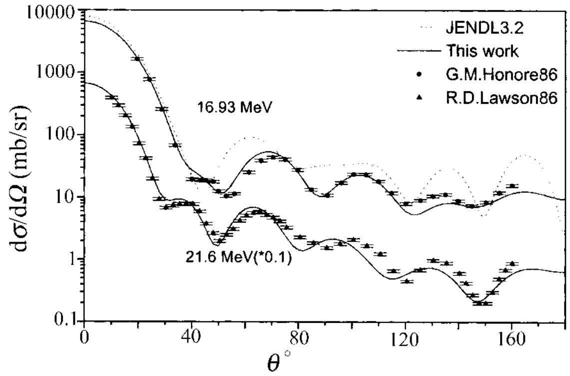

Fig. 3(c) Elastic scattering angular distributions for n+^{89}Y

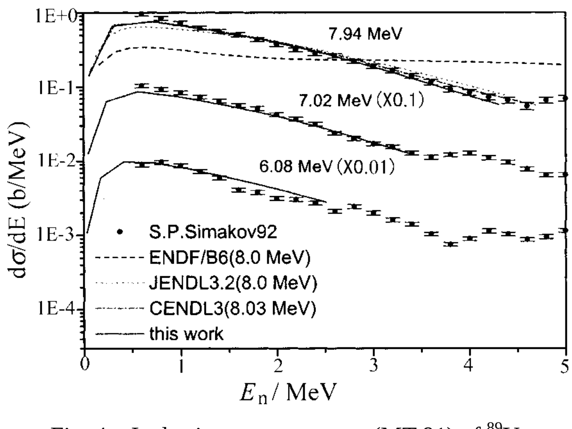

Fig. 4 Inelastic neutron spectra (MT-91) of ^{89}Y

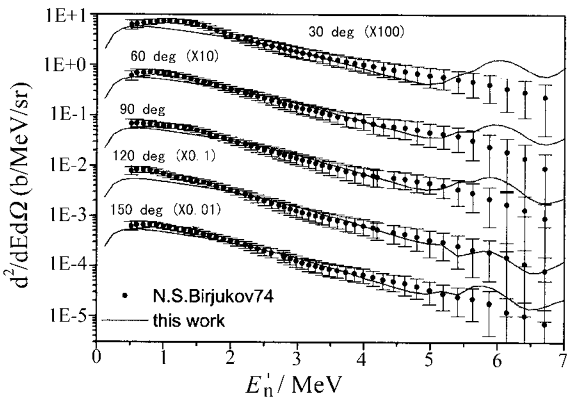

Fig. 5(a) DDCS of inelastic neutron of ^{89}Y at E_n= 9.1 MeV

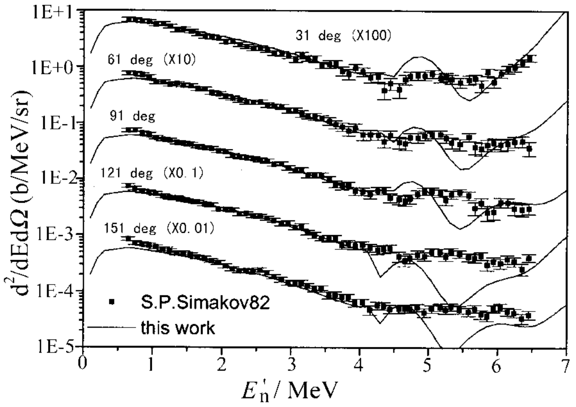

Fig. 5(b) DDCS of inelastic neutron of ^{89}Y at E_n= 7.94 MeV

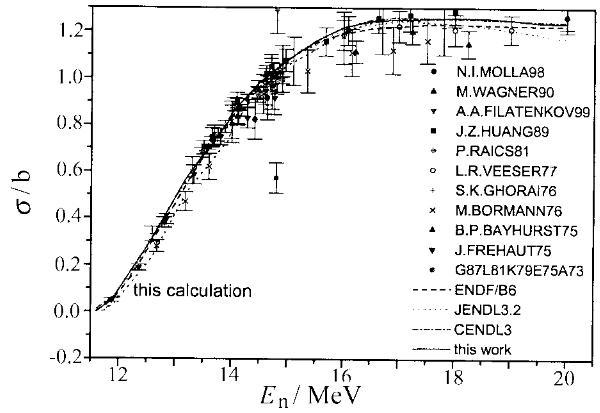

Fig. 8 (n,2n) reaction cross sections of ^{89}Y

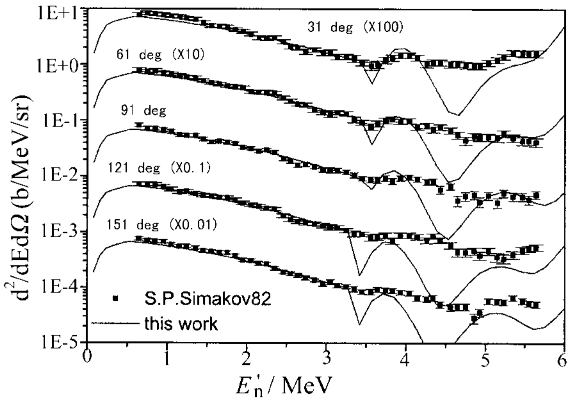

Fig. 5(c) DDCS of inelastic neutron of ^{89}Y at E_n= 7.02 MeV

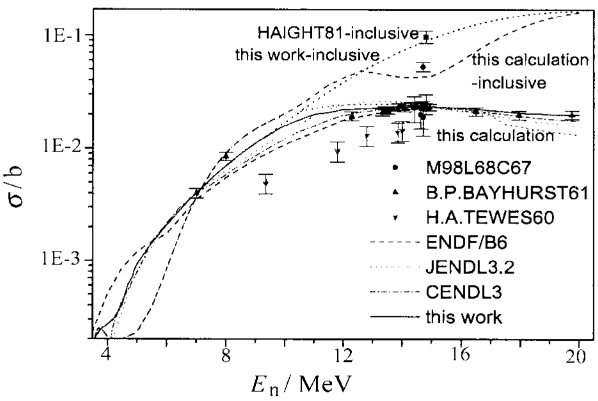

Fig. 9 (n,p) reaction cross sections of ^{89}Y

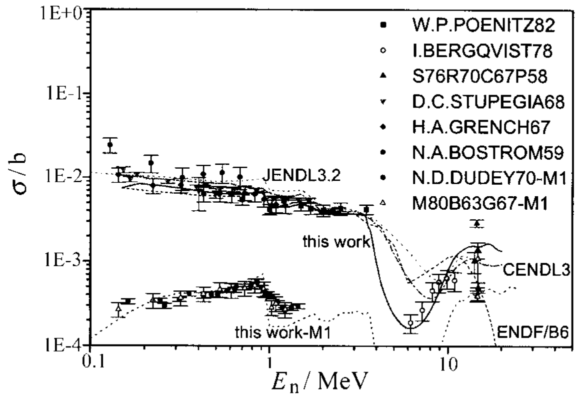

Fig. 6 (n,γ) reaction cross sections of ^{89}Y

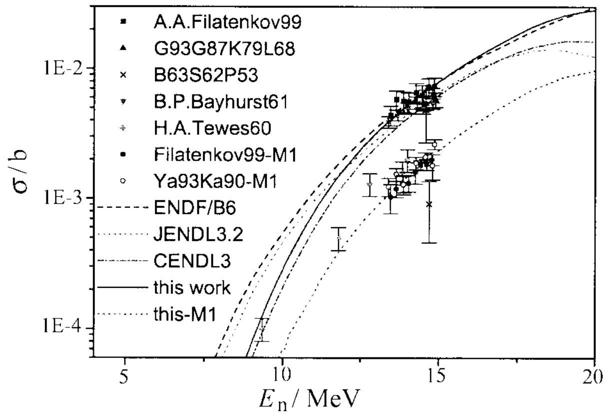

Fig. 10 (n,α) reaction cross sections of ^{89}Y

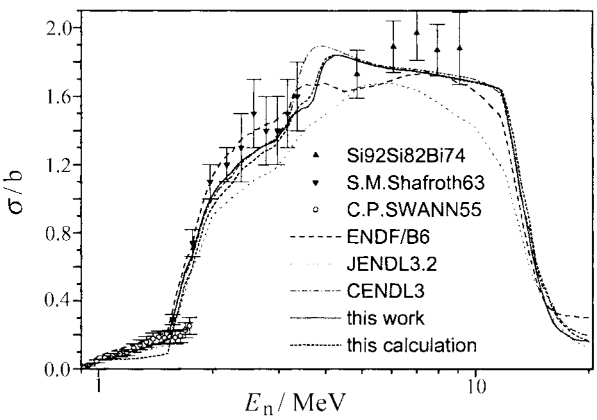

Fig. 7 (n,n′) reaction cross sections of ^{89}Y

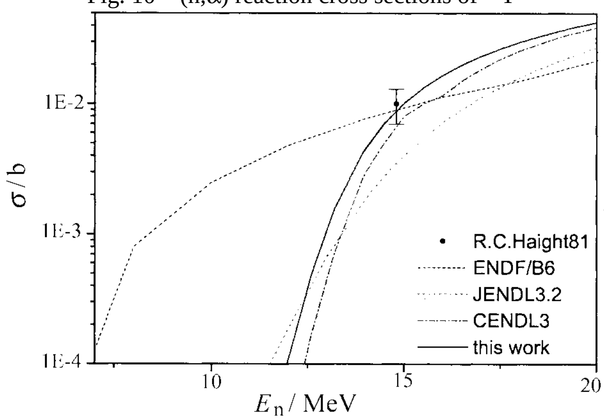

Fig. 11 (n,d) reaction cross sections of ^{89}Y

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