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A SYNOPSIS OF THE ACTIVITIES ON NEUTRON STANDARD REFERENCE DATA  
AT THE INSTITUTE OF ATOMIC ENERGY

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A Synopsis of the Activities on Neutron Standard Reference Data  
at the Institute of Atomic Energy

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The activities of neutron standard reference data including neutron standard cross section measurements,  $^{252}\text{Cf}$  spontaneous fission nubar and neutron energy spectrum measurements, neutron flux measurements, neutron source strength calibrations and neutron standard data evaluations carried out at the Institute of Atomic Energy, Beijing are presented. Some experimental results and recommended values are given.

The activities of neutron standard reference data at the Institute of Atomic Energy, Beijing (AEP) were begun at the beginning of the sixties. The main works were divided into two parts at that time: one was the measurements of thermal neutron standard cross sections including the measurement of thermal neutron absorption cross section of natural boron (by transmission method)<sup>1</sup>, the absolute measurement of thermal neutron fission cross section of  $^{235}\text{U}$ <sup>2</sup>, the relative measurement of slow neutron fission cross section of  $^{235}\text{U}$ <sup>3,4</sup>, the measurement of thermal neutron absorption cross section of gold<sup>5</sup> and the measurements of thermal neutron absorption cross sections of natural boron and lithium (by neutron life time method)<sup>6</sup>; and the other was the absolute calibration of Ba-Be standard neutron source<sup>7,8</sup>. In the meantime a  $4\pi\beta\text{-r}$  coincidence device was set up for measuring the absolute thermal neutron flux.

In the later stage of the sixties, some techniques for measuring the neutron flux in the fast neutron energy region were developed. They are the  $^7\text{Be}$  radioactivity method, the

gaseous proportional counter method, the proton recoil telescope method, the semiconductor telescope method, the scintillator telescope method and the associated particle method<sup>9</sup>.

In the seventies, in addition to improving the techniques of neutron flux measurement, some measurements of neutron standard reference data were carried out further. For example, the fission cross section and fission cross section ratio measurement for  $^{233}\text{U}$ ,  $^{235}\text{U}$  and  $^{239}\text{Pu}$  in the thermal neutron region<sup>10,11</sup>, the fission cross section measurement for  $^{233}\text{U}$  and  $^{235}\text{U}$  in fast neutron energy region<sup>12</sup>, the fission cross section ratio measurement for  $^{239}\text{Pu}$  and  $^{235}\text{U}$  in fast neutron energy region<sup>13</sup>, the measurement of the average number of prompt neutrons and the distribution of prompt neutron numbers for  $^{252}\text{Cf}$  spontaneous fission<sup>14</sup>, the cross section measurement for  $^{27}\text{Al}(\text{n},\text{r})$  and  $^{56}\text{Fe}(\text{n},\text{p})$  reactions<sup>15,16</sup>, etc. In the other side the neutron beam filter facility has been installed at the horizontal beam channel of the light water swimming pool reactor at AEP<sup>17</sup>.

In recent years, in the field of neutron standard reference data, the following experimental works at AEP have been done: the measurement of prompt neutron energy spectrum for spontaneous fission of  $^{252}\text{Cf}$ <sup>18,19</sup>, the measurement of fission cross section for  $^{238}\text{U}$  induced by fast neutrons<sup>20</sup>, the absolute measurement of fission cross section for  $^{235}\text{U}$  and  $^{239}\text{Pu}$  in the fast neutron energy region<sup>21,22</sup>, the measurement of  $^{197}\text{Au}$  neutron capture cross section between 100-1500keV and at 30keV<sup>23,24</sup>, and the measurement of scattering cross section of carbon<sup>25-27</sup>, etc.

The main points of the measurements of neutron standard reference data carried out at AEP are shown in table 1.

Some experimental results of absolute measurements of neutron standard reference data obtained at AEP are shown in table 2.

Fig.1 shows the relation between  $^{235}\text{U}$  fission cross section and the neutron energy in the slow neutron energy region (Yuan Hanrong et al; 1964).

Fig.2 shows the relation between  $^{197}\text{Au}(\text{n},\text{r})$  cross section and the neutron energy in the 100-1500keV region (Chen Ying et al; 1981).

Fig.3 shows the scattering cross section of 11.6 MeV neutrons from carbon (Sa Jun et al; 1981).

Fig.4 shows the comparison of AEP value with ENDF/B-V and some reported values of  $\sigma_f(^{235}\text{U})$  in the 14 MeV range.

In the respect of neutron flux measurement, besides making some comparisons among the different methods<sup>28-30</sup>, AEP participated in the international comparison of 14 MeV neutron flux measurement organized by BIPM in 1983. One part used the  $^{115}\text{In}(n,n')$  $^{115m}\text{In}$  reaction (co-ordinated by Dr. H.Liskien) and the other used the Nb/Zr transfer technique (co-ordinated by Dr. V.E.Lewis). In this year AEP participated in a bilateral comparison with NPL using the  $^{56}\text{Fe}(n,p)$  $^{56}\text{Mn}$  reaction also. At present, the neutron flux standards and their uncertainties for various neutron energy region used at AEP are shown in table 3.

As for the neutron source strength measurement and neutron energy standard, a new Am-Be standard source has been calibrated with a neutron emission rate of  $7.3 \times 10^6$  n/s. Now it is being compared with the  $^{252}\text{Cf}$  standard source from NPL, Using the Si detector method, the 14 MeV neutron energy standard has been set up. Its uncertainty is  $\pm 30$  keV.

It is worth to point out that the Radiometrology Center set up at AEP will undoubtely make its contributions to the work of radio-metrology standards in China.

In 1975 the Chinese Nuclear Data Center (CNDC) was founded at AEP. Since then a co-operation network consisting of a number of Institutes and Universities has been organized under the co-ordination of Chinese Nuclear Data Center. The nuclear data activities in China including nuclear data measurement, nuclear data evaluation, nuclear data theoretical calculation and nuclear data test are now being unfolded under the co-ordination of CNDC. During the past ten years, the evaluations of neutron nuclear data for all reactions including the standard reference data in the energy range from thermal up to 20 MeV have been carried out for about 30 nuclei. The evaluations of neutron standard reference data which have been accomplished at AEP are

listed in table 4. Namely, evaluation of  $^1\text{H}(\text{n},\text{n})$  cross section<sup>31</sup>, evaluation of  $^3\text{He}(\text{n},\text{p})$  cross section<sup>32</sup>, evaluation of  $^6\text{Li}(\text{n},\text{t})$  cross section<sup>33,34</sup>, evaluation of  $^{10}\text{B}(\text{n},\alpha)$  cross section<sup>35-38</sup>, evaluation of  $^{12}\text{C}(\text{n},\text{n})$  differential cross section<sup>39</sup>, evaluation of  $^{27}\text{Al}(\text{n},\alpha)$  cross section<sup>40</sup>, evaluation of  $^{55}\text{Mn}(\text{n},\text{r})$  cross section<sup>41</sup>, evaluation of  $^{56}\text{Fe}(\text{n},\text{p})$  cross section<sup>42</sup>, evaluation of  $^{59}\text{Co}(\text{n},\text{r})$  cross section<sup>43</sup>, evaluation of  $^{197}\text{Au}(\text{n},\text{r})$  cross section<sup>44-49</sup>, evaluation of  $^{235}\text{U}(\text{n},\text{f})$  cross section<sup>50-53</sup>, evaluation of  $^{238}\text{U}(\text{n},\text{f})$  cross section<sup>54</sup>, evaluation of  $^{239}\text{Pu}(\text{n},\text{f})$  cross section<sup>55,56</sup>, evaluation of  $^{252}\text{Cf}$  spontaneous fission  $\bar{\gamma}$  value<sup>57</sup> and the evaluation of prompt neutron energy spectrum for spontaneous fission of  $^{252}\text{Cf}$ <sup>58</sup>, etc. Besides, a review on the thermal neutron constants for the fissile nuclei was made<sup>59</sup>.

In table 5 some recommended values of thermal neutron standard cross sections are listed.

Fig.5 and 6 show the CNDC recommended curves of  $^{10}\text{B}(\text{n},\text{n})$  cross section and  $^{197}\text{Au}(\text{n},\text{r})$  cross section in the interested neutron energy regions separately.

In addition, in order to coordinate the evaluations of nuclear standard reference data, some relevant theoretical calculations were carried out. Among them the optical model, statistical theory, pre-equilibrium theory and the R-matrix theory were used.

To sum up it can be seen, a number of works on nuclear standard reference data have been completed at the AEP. But owing to the limitation of experimental condition (considering the accelerator neutron source, there is only a 600 kV Cockcroft-Walton accelerator, a 2.5 MeV Van de Graaff accelerator and a diameter 1.2 m cyclotron at the AEP), quite a lot of works couldn't be done. Now a new tandem accelerator of type HI-13 purchased from HVEC is being installed and a 100 MeV high current short pulse electron linac is under construction in AEP. Once these new accelerators and relevant experimental equipments are completed, the experimental work at AEP will be improved to some extent. It can be predicted that with the improving of experimental condition and the developing of international co-

operation, the activities of nuclear standard reference data at AEP will be improved.

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Table 1 Main points of measurements of neutron standard reference data of AEP

Nuclei	Quantity	Neutron energy	Comments	Accuracy	Ref.
B	$\sigma_a$	0.0253eV	transmision	0.65%	1
$^{235}\text{U}$	$\sigma_f$	0.0253eV	nucl. emulsion	1.5%	2
$^{235}\text{U}$	$\sigma_f$	0.01-1.6eV	scint. chamber	2.0%	3
$^{235}\text{U}$	$\sigma_f$	0.04-100eV	fiss. chamber	2-6%	4
$^{197}\text{Au}$	$\sigma_r$	0.0253eV	$4\pi$ -detector	1.7%	5
Li, B	$\sigma_a$	0.0253eV	neutron life time	0.4-0.8%	6
$^{233}\text{U}, ^{235}\text{U}, ^{239}\text{Pu}$	$\sigma_f$	0.02-0.3eV	semic. detector	1.2-3%	11
$^{233}\text{U}, ^{235}\text{U}$	$3\sigma_f/5\sigma_f$	0.03-5.6, 14-18MeV	fiss. chamber	2.4-2.9%	12
$^{239}\text{Pu}, ^{235}\text{U}$	$9\sigma_f/5\sigma_f$	0.03-5.6, 14-18MeV	fiss. chamber	2.0-2.6%	13
$^{235}\text{U}, ^{239}\text{Pu}$	$\sigma_f$	14.7MeV	TCAP, TOF	1.9%	21
$^{238}\text{U}$	$\sigma_f$	4.0-5.5MeV	PRT, fiss.chamber	2.6%	20
$^{239}\text{Pu}$	$\sigma_f$	1.0-5.6MeV	PRT, fiss.chamber	2.3%	22
$^{252}\text{Cf}$	$\bar{\nu}_p$	spont.fiss.	liq. scint.	0.48%	14
$^{252}\text{Cf}$	en.spec.	spont.fiss.	TOF, liq. scint.	1.6-2.8%	18,19
$^{56}\text{Fe}$	$\sigma_{n,p}$	12.8-18.2MeV	activation	3-5%	16
$^{27}\text{Al}$	$\sigma_{n,\alpha}$	12-18MeV	activation	3.3-4.8%	15
$^{197}\text{Au}$	$\sigma_r$	0.1-1.5MeV	activation	3.8-5.8%	23
$^{197}\text{Au}$	$\sigma_r$	30.45keV	activation	3.0%	24
$^{12}\text{C}$	$\sigma_s$	11.6MeV	TOF	7%	26

Table 2 Some experimental results of absolute measurements obtained at AEP

Nuclei	Quantity	Neutron energy	Exper.result	Date	Ref.
B	$\sigma_a$	0.0253eV	$764 \pm 5$ b	1964	1
$^{235}\text{U}$	$\sigma_f$	0.0253eV	$582 \pm 9$ b	1964	2
$^{197}\text{Au}$	$\sigma_r$	0.0253eV	$98.8 \pm 1.7$ b	1965	5
Li	$\sigma_a$	0.0253eV	$70.9 \pm 0.6$ b	1968	6
B	$\sigma_a$	0.0253eV	$760.3 \pm 3.2$ b	1968	6
$^{235}\text{U}$	$\sigma_f$	0.5 MeV	$1.148 \pm 0.058$ b	1975	12
$^{235}\text{U}$	$\sigma_f$	1.0 MeV	$1.243 \pm 0.063$ b	1975	12
$^{235}\text{U}$	$\sigma_f$	14.7 MeV	$2.098 \pm 0.040$ b	1983	21
$^{238}\text{U}$	$\sigma_f$	4.0 MeV	$0.566 \pm 0.011$ b	1983	20
$^{238}\text{U}$	$\sigma_f$	4.5 MeV	$0.565 \pm 0.011$ b	1983	20
$^{238}\text{U}$	$\sigma_f$	5.0 MeV	$0.562 \pm 0.011$ b	1983	20
$^{238}\text{U}$	$\sigma_f$	5.5 MeV	$0.553 \pm 0.014$ b	1983	20
$^{239}\text{Pu}$	$\sigma_f$	14.7 MeV	$2.532 \pm 0.050$ b	1983	21
$^{252}\text{Cf}$	$\bar{\nu}_p$	Spont. fiss.	$3.743 \pm 0.018$	1979	14
$^{27}\text{Al}$	$\sigma_{n,\alpha}$	14.61 MeV	$117.5 \pm 3.9$ mb	1975	16
$^{56}\text{Fe}$	$\sigma_{n,p}$	14.63 MeV	$108.0 \pm 2.9$ mb	1977	15
$^{197}\text{Au}$	$\sigma_r$	1.49 MeV	$62.0 \pm 2.6$ mb	1981	23
$^{197}\text{Au}$	$\sigma_r$	1.19 MeV	$77.4 \pm 2.9$ mb	1981	23
$^{197}\text{Au}$	$\sigma_r$	0.99 MeV	$78.2 \pm 3.0$ mb	1981	23
$^{197}\text{Au}$	$\sigma_r$	0.46 MeV	$149.4 \pm 5.7$ mb	1981	23
$^{197}\text{Au}$	$\sigma_r$	30.45 keV	$592 \pm 18$ mb	1984	24

Table 3 Neutron flux standards used at AEP

Neutron energy, MeV	Method	Uncertainty
0.1-1.5	proportional counter	3.0%
1-5	semiconductor telescope	2.5%
2.5	associated particle method	2.5%
14	associated particle method	1.0%
12 - 20	proton recoil telescope	2.5%

Table 4 Evaluations of neutron standard reference data  
accomplished at CNDC

Nuclei	Quantity	Neutron energy region	Reference
$^1\text{H}$	$\sigma_{n,n}$	thermal-20 MeV	31
$^3\text{He}$	$\sigma_{n,p}$	thermal-20 MeV	32
$^6\text{Li}$	$\sigma_{n,t}$	thermal-20 MeV	33, 34
$^{10}\text{B}$	$\sigma_{n,\alpha}$	thermal-20 MeV	35-38
$^{12}\text{C}$	$d\sigma_{n,n}/d\omega$	0.05-18 MeV	39
$^{27}\text{Al}$	$\sigma_{n,\alpha}$	threshold-20 MeV	40
$^{55}\text{Mn}$	$\sigma_{n,r}$	thermal	41
$^{56}\text{Fe}$	$\sigma_{n,p}$	threshold-20 MeV	42
$^{59}\text{Co}$	$\sigma_{n,r}$	thermal	43
$^{197}\text{Au}$	$\sigma_{n,r}$	thermal-20 MeV	44-49
$^{235}\text{U}$	$\sigma_f$	thermal-20 MeV	50-53
$^{238}\text{U}$	$\sigma_f$	threshold-20 MeV	54
$^{239}\text{Pu}$	$\sigma_f$	thermal-20 MeV	55, 56
$^{252}\text{Cf}$	$\bar{\gamma}_p$	spontaneous fission	57
$^{252}\text{Cf}$	energy spectrum	spontaneous fission	58

Table 5 Comparison of recommended values of some thermal neutron standard cross sections

source	$\sigma_{a,b}$	$\sigma_a(^{10}\text{B})$	$\sigma_r(^{197}\text{Au})$	$\sigma_a(^{59}\text{Co})$	$\sigma_r(^{55}\text{Mn})$	$\sigma_f(^{235}\text{U})$
Yuan(81-83)		$3837 \pm 5$	$98.67 \pm 0.09$	$37.20 \pm 0.06$	$13.30 \pm 0.16$	$585.5 \pm 1.7$
Holden(81)		$3838 \pm 6$	$98.65 \pm 0.09$	$37.18 \pm 0.06$	$13.30 \pm 0.20$	
Axtom(84)						$584.7 \pm 1.7$

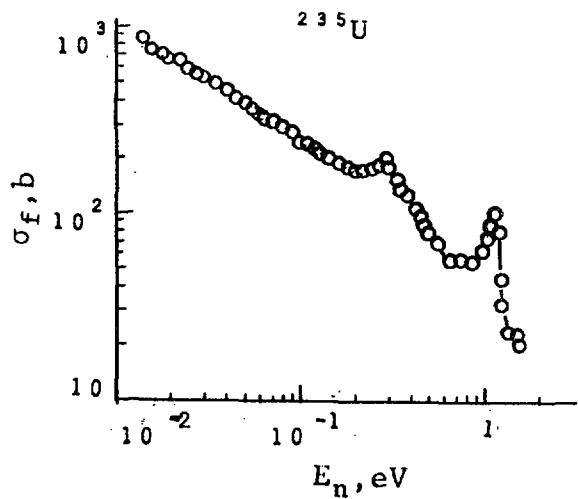
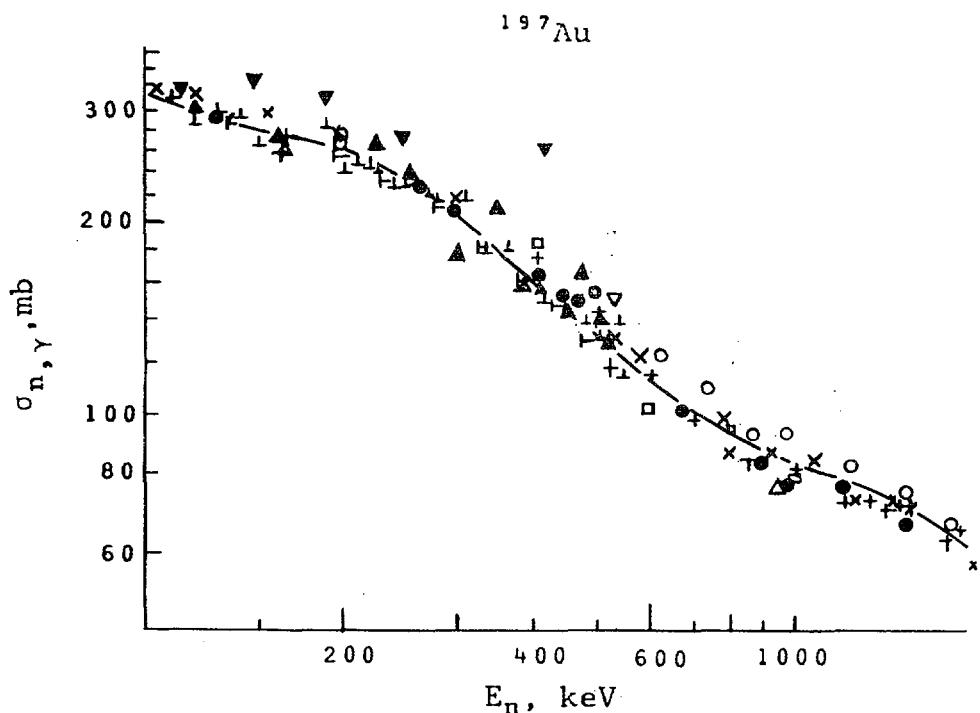


Fig.1 Relation between  $^{235}\text{U}$  fission cross section and  
neutron energy in the slow neutron energy region  
• Yuan Hanrong (1964)



**Fig.2** Relation between  $^{197}\text{Au}(n,\gamma)$  cross section and neutron energy in the 100---150 keV region

- Cen Ying (1981);    ✕ Liddner (1976);    ○ Paulsen (1975);
- + Poenitz (1975);    □ Pricke (1970);    ▲ Fort (1975);
- † Macklin (1975);    △ Joly (1979);    — ENDF/B-IV
- ▼ Czirr (1973);    ↴ Le Rigolear (1973);    τ Gwin (1976).

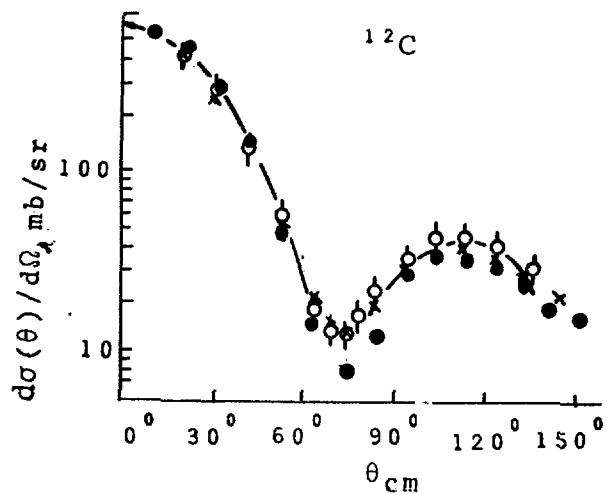
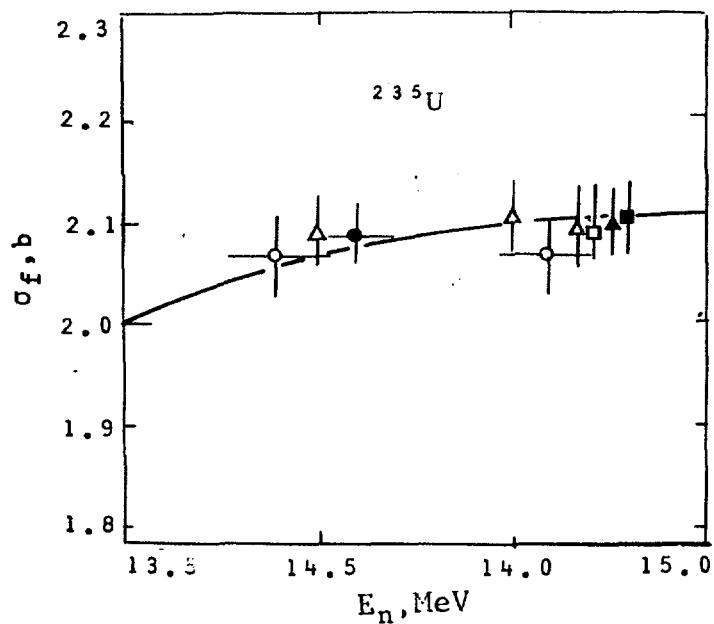


Fig.3 Scattering cross section of 116 MeV neutrons  
from carbon

- \* Glasgow (1976);
- Haouat (1975);
- Sa Jun (1981).



**Fig.4** Comparison of the AEP value of  $^{235}\text{U}$  fission Cross section with ENDF/B-V and some reported values obtained by TCAP method in the 14 MeV region

- Li Jingwen, 1983;
  - Wasson, 1981;
  - Arlt, 1979;  
Cance, 1976;
  - ENDF/B-V, 1978.
- Adamov, 1979

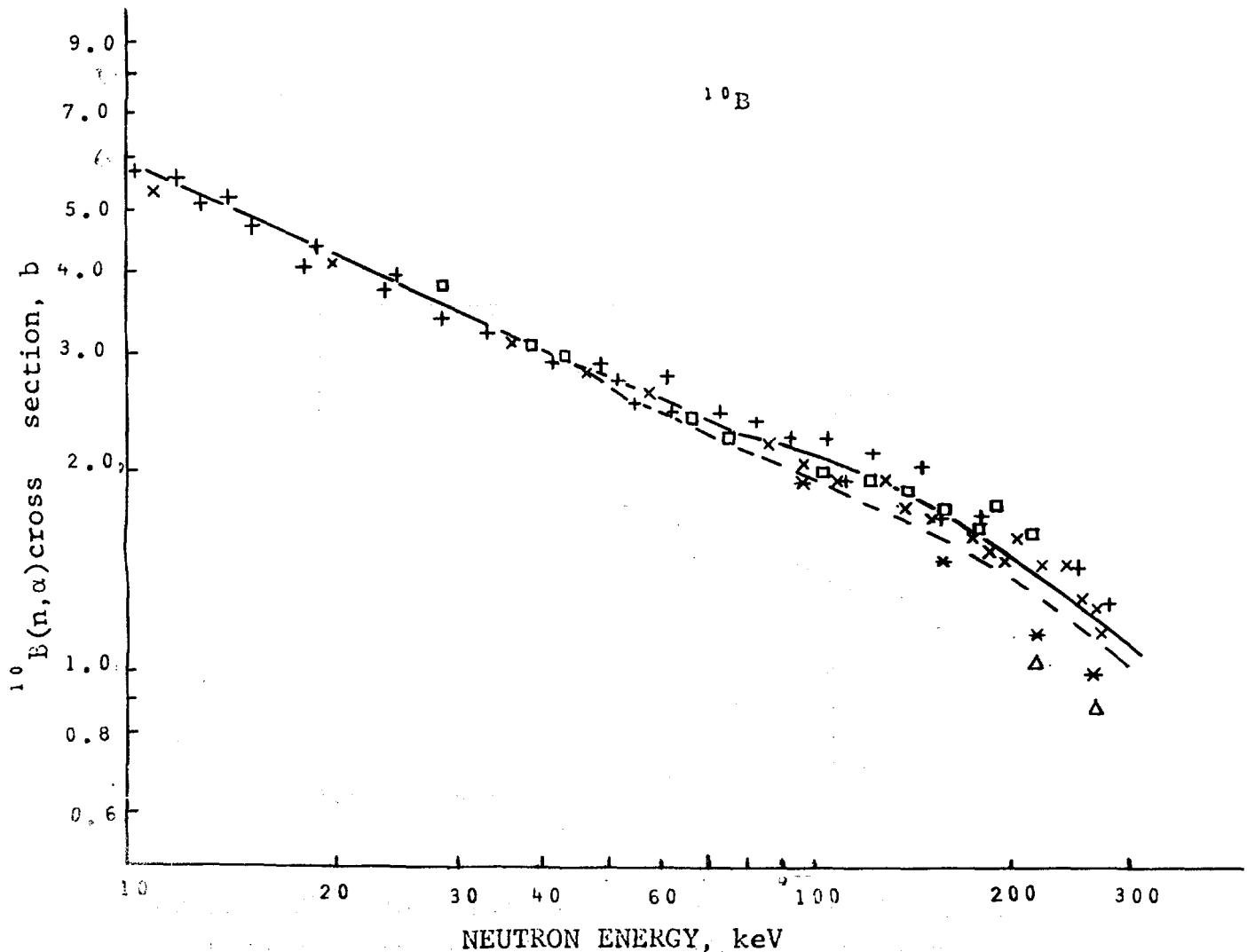


Fig.5 The CNDC recommended curve of  $^{10}\text{B}(\text{n}, \alpha)$  cross section in the interested neutron energy region

- Qi Huiquan (1983); ----ENDF/B-V;
- + Friesenhahn (1975); × Mooring (1966);
- \* Macklin (1968); ▲ Davic (1961);
- ◻ Bogart (1969).

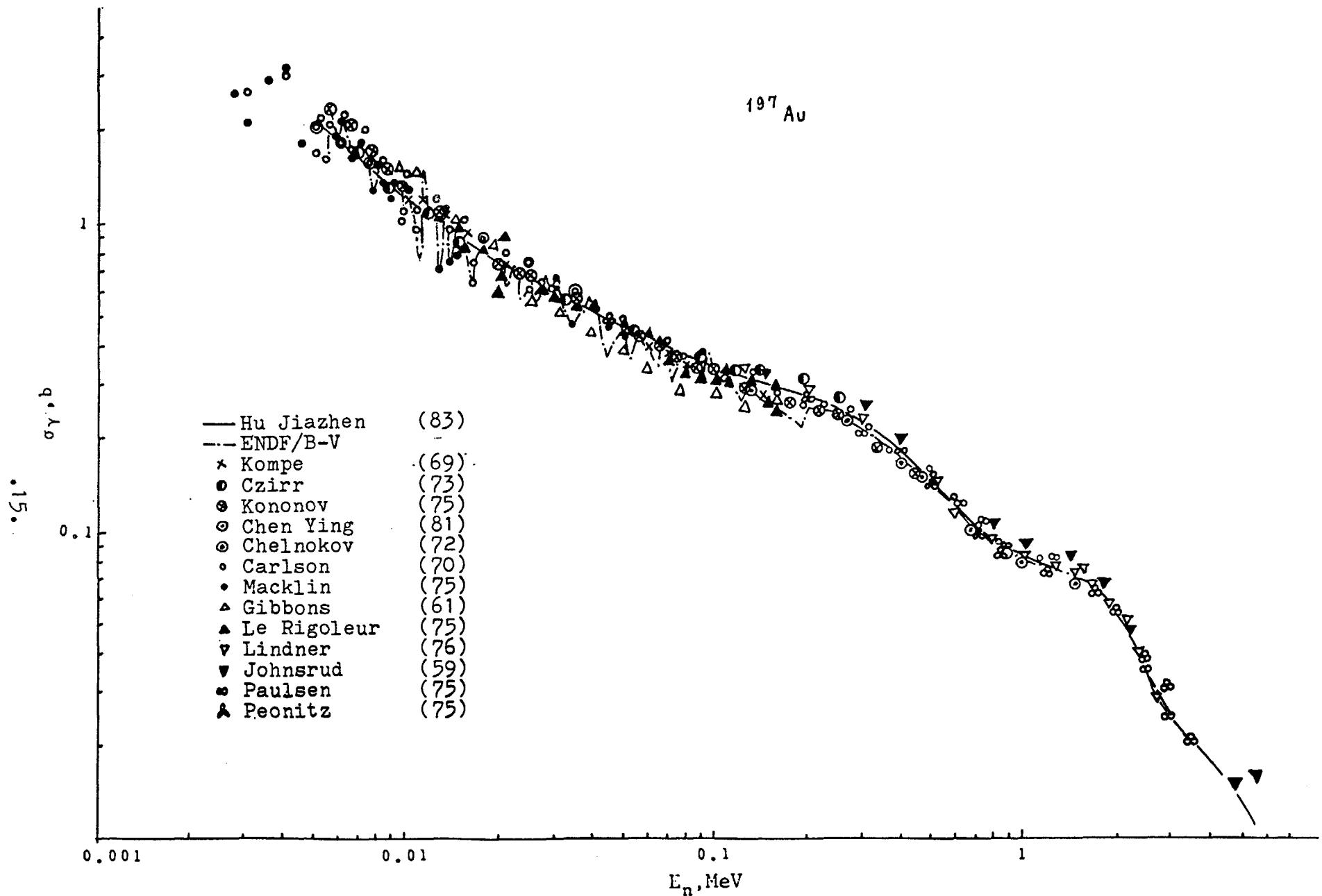


Fig.6 The CNDC recommended curve of  $^{197}\text{Au}(n,\gamma)$  cross section in the interested neutron energy region