III DATA EVALUATION

Evaluation of ^{235}U Fission Product Yield Data and Study of the Dependence of Fission Yield Data on Neutron Energy

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The $^{235}U(n,f)$ fission product yield data were evaluated for some important product nuclides ^{95}Zr, ^{99}Mo, ^{144}Ce and ^{147}Nd. The dependence of fission yield data on incident neutron energy was studied.

1 Data Collection

At first, the experimental data for these product nuclides were retrieved from master EXFOR data library by using EXFOR management system and some supplementary codes, as described in Fig.1. Then the data were taken from the EXFOR file, where the fission yield data measured in China were compiled and haven't been sent to the EXFOR master library. The data were also collected from some publications.

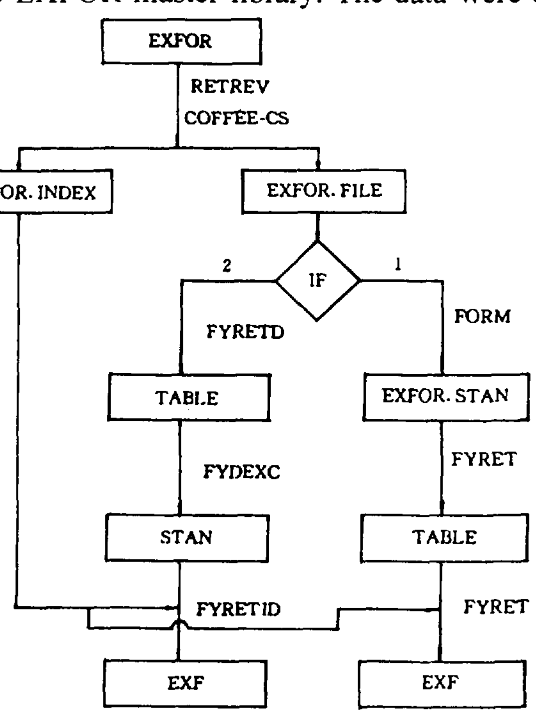

Fig.1 The flow chart of FY EXFOR data retrieval

1 Less than or equil to 6 column; 2 More than 6 column.

All together 83 EXFOR entries and papers were collected, they are listed in Table 1.

In general, the fission yield data can be retrieved according to the target, incident neutron energy, products by using EXFOR retrieval system. But when a product is given under the heading "ELEM/MASS", it could not be found. To solve this problem, the following programs were developed, and they can be used following the retrieving with EXFOR management system "RETREV", "COFFEE-CS" in the option "P" and default to the reaction field 4 (reaction product):

1) FORM Exchange the column position and make the data table standardization. Also change all the "DATA-ERR" into absolute error.

2) FYRET Extract the data table from EXFOR file.

3) FYRET1 Retrieve fission yield data according to the special Z and A, and read the reaction quantity, neutron energy, EXFOR entry number from the index file and write into the file.

If the quantities under the "HEADING" are over 6 (occupy two rows), instead of above, the corresponding programs FYRETD, FYEXC, FYRET1D can be used.

2 Evaluation of Experimental Data

The EXFOR BIB information and papers concerned were read carefully and were analysed in physics. The data were decided to be taken or abandoned according to the measurement date, method, facility, detector, monitor and discrepancy situation with others. In general, the following data were abandoned (marked by (×) in Table 1):

1) The quantity measured is not required;

2) Measured in 50's or earlier;

3) Large discrepancy with others and measured method is not reliable or no information in detail;

4) Incident neutron energy or other important quantities are not able or difficult to be known;

5) Something is wrong in the measurements or data processing.

The necessary corrections were made for the acceptable data:

1) Renormalization using new standards for decay data, standard fission yield, and fission cross section. The new standard data were taken from the Zhou's evaluation at CNDC[2] for decay data, the present evaluation for standard yield or Wang's evaluation (if there is no evaluation in this work) for thermal standard

yield[3], and ENDF/B for fission cross section.

2) Make the neutron energy standardization: 1.95 MeV for ^{235}U fission spectrum, 2.13 MeV for ^{252}Cf spontaneous fission spectrum. Some fast reactor spectra were also changed if they are considerably unreasonable.

3) Enlarge errors, if they were too small given by authors or the corresponding data are discrepant with those of others or even themelves and could not find the reason.

3 Data Processing

In general, the data were processed with the following codes:

1) AVERAG arithmetical average and weighted average and calculating the corresponding error for measured data more than two sets at same energy point, for example, thermal energy, 14.7 MeV, etc.

2) ZOTT developed by D.Muir[1], transplanted and modified. Used for simultaneously evaluating fission yield data at different energy points or for different products and their ratios. The covariance matrix can be calculated for the evaluated data. Concretely, the data were treated as follows:

a. Nuclides Zr, Mo, Ce, thermal yield: Only the absolute measured data were taken, averaging for each and their ratios. Simultaneous evaluation for fission yield and ratio.

b. Nuclide Zr: Averaging for data at fission spectrum, 14.8 MeV, 8.0 MeV. Simultaneous evaluation at thermal energy points, fission spectrum, 8.0 MeV.

c. Nuclide Mo: Averaging for fission yield at fission spectrum, 14.8 MeV, 0.5 MeV. Simultaneous evaluation at thermal energy, fission spectrum, ^{252}Cf fission spectrum.

d. Nuclide Ce: Averaging for fission yield at fission spectrum, 14.8 MeV, 0.5 MeV; Simultaneous evaluation at thermal energy, 14.8 MeV.

e. Nuclide Nd: Averaging for fission yield at thermal energy, fission spectrum, 14.8 MeV. Simultaneous evaluation at thermal energy, 8.0 MeV, 14.8 MeV.

4 Data Fitting and Dependence on Neutron Energy

After treating above, the data, including averaged and simultaneously evaluated ones instead of original measured data, were first fitted with linear fit program LIFIT, which is based on least square method, with a option for $Y=aE+b$ or $\ln(Y)=aE+b$, and the reduced chi-square is calculated. If the χ^2 is larger than about 1.5 (it means that the data could not be fitted with linear function), then the data were fitted with general spline fit program SPF[2], which is with knot optimization and spline order selection and for multi-sets of data of any shape curve, depending on the knots and order selection.

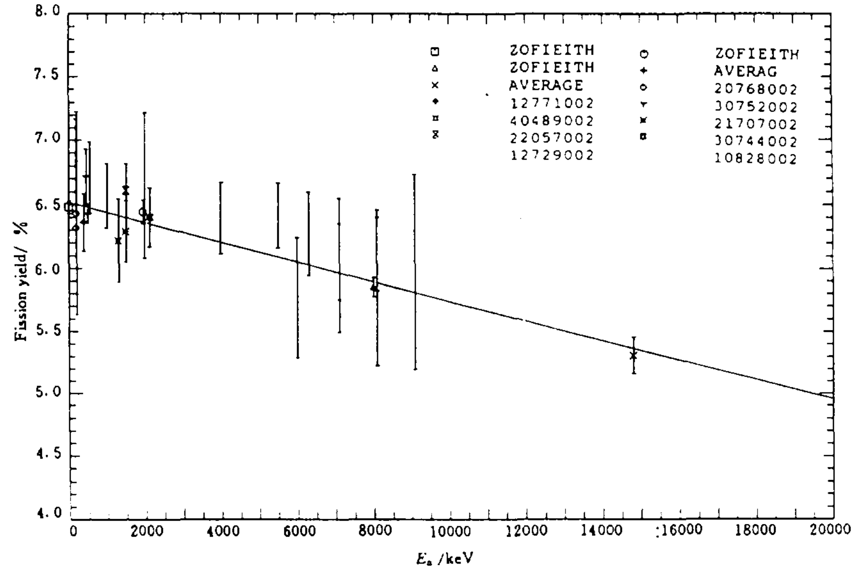

Fig.2 ^{235}U(N,F)^{95}Zr Cummu. Fission yield

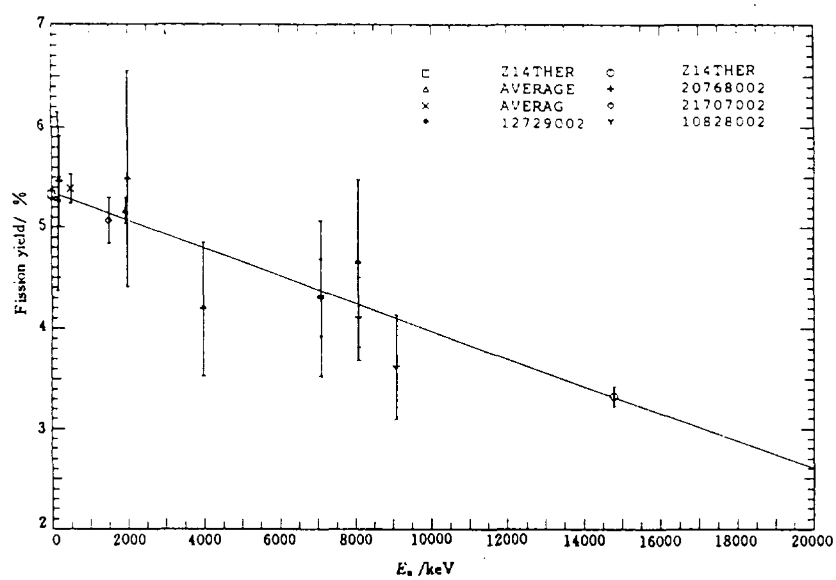

Fig.3 ^{235}U(N,F)^{144}Ce Cummu. Fission yield(processed)

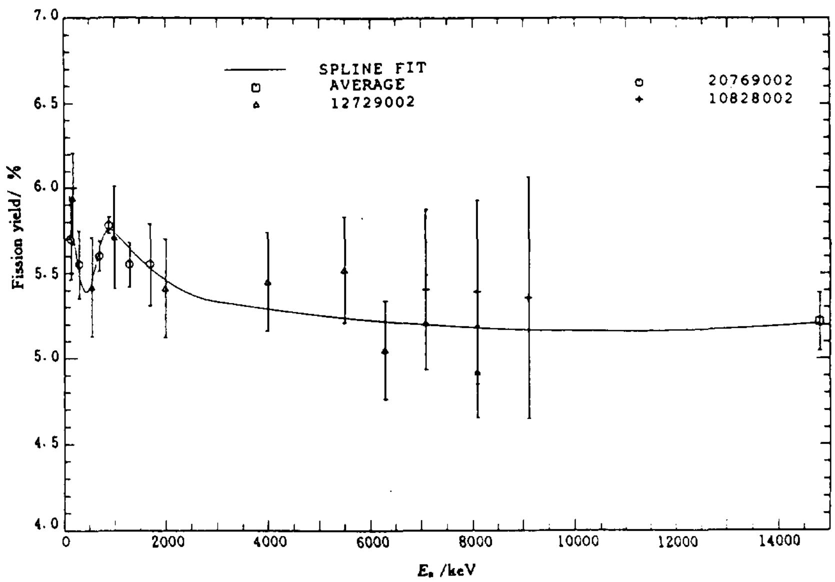

Fig.4 $^{235}U(N,F)^{99}Mo$ Cummu. FY (Mono energy)

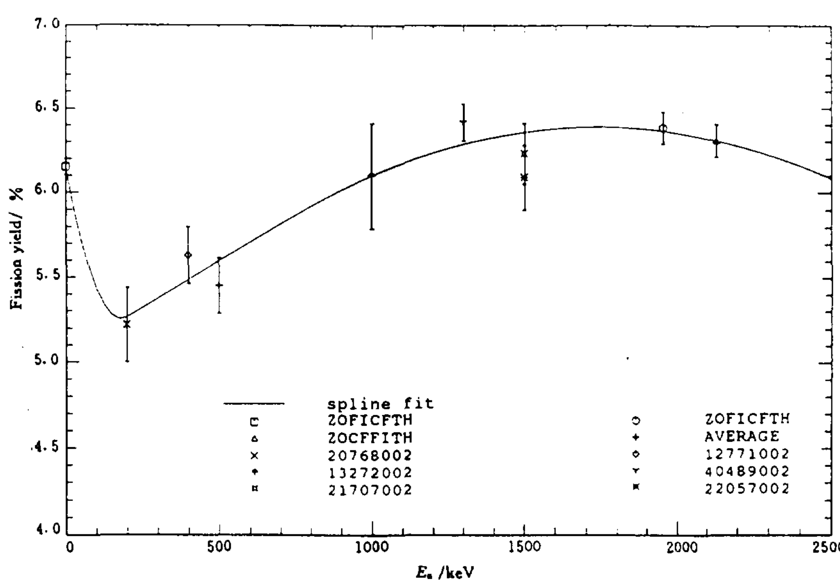

Fig.5 $^{235}U(N,F)^{99}Mo$ Cummu. FY (Spectrum average)

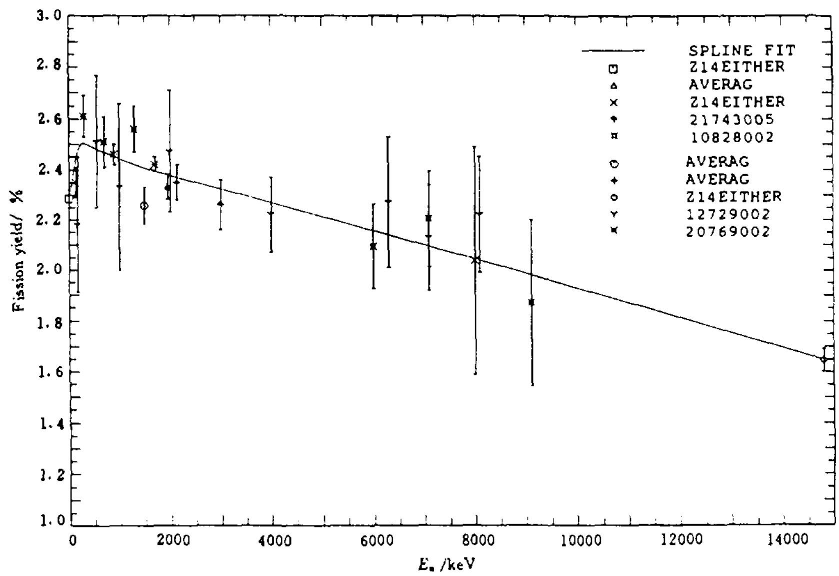

Fig.6 $^{235}U(N,F)^{147}Nd$ Cummu. FY

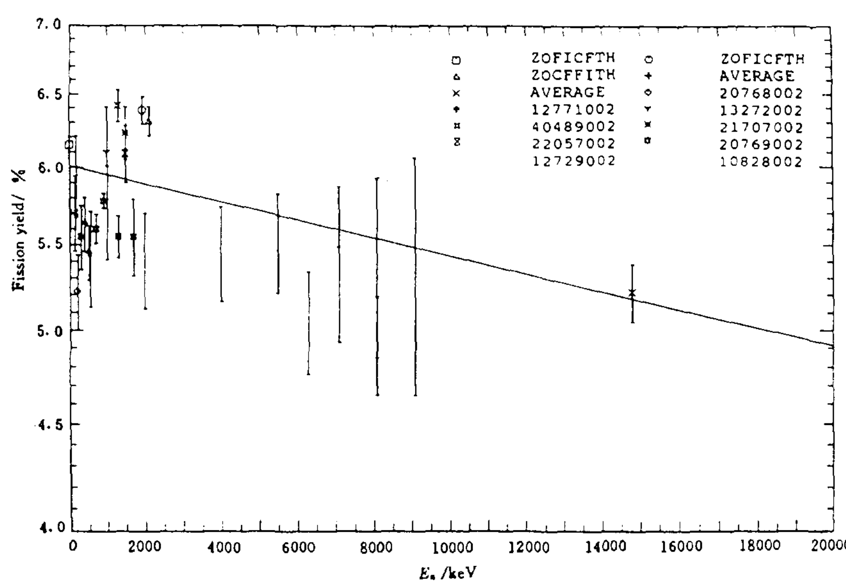

Fig.7 $^{235}U(N,F)^{99}Mo$ Cummulative Fission Yield

The results show that the dependencies of fission yield on incident neutron energy are simply linear for product nuclides Zr, Ce(Figs.2,3), but are quite complicated for Mo(Figs.4,5) and Nd(Fig.6), especially in the keV resonance region and for Mo. They could not be described by a straight line (in this case, χ^2=6.19 for Mo(Fig.7), and 2.07 for Nd). The deviation from linear line is over the experiment error and shown by several sets of data.

It should be pointed out that the fit values were obtained at the "optimum" condition, it's true in whole, but it's not true for some special energy points, for example, for thermal or 14.8 MeV points. Therefore, the recommended fission yield for some special data points, where there are more measured data are the data got through averaging or simultaneous evaluation instead of fit one.

5 Discussion

Dependence of fission yield on energy is a quite complicated problem, due to the complicated fission mechanism. So far it is not very clear but some trends can be seen from the available experimental data.

For studying the dependence of fission yield on incident energy, the measurement with monoenergetic neutron, like using Van de Graaff, Cockcroft-Walton, Tandem accelerator, is more valuable. The typical, important measurements at monoenergetic points were made by G.P.Ford et al. (Los Alamos Scientific Lab.)[3], L.E.Glendenin et al. (Argone National Lab.)[4], and T. C. Chapman et al. (Lawrence Livermore Lab.)[5].

Analyzing these data, the following trends have been found.

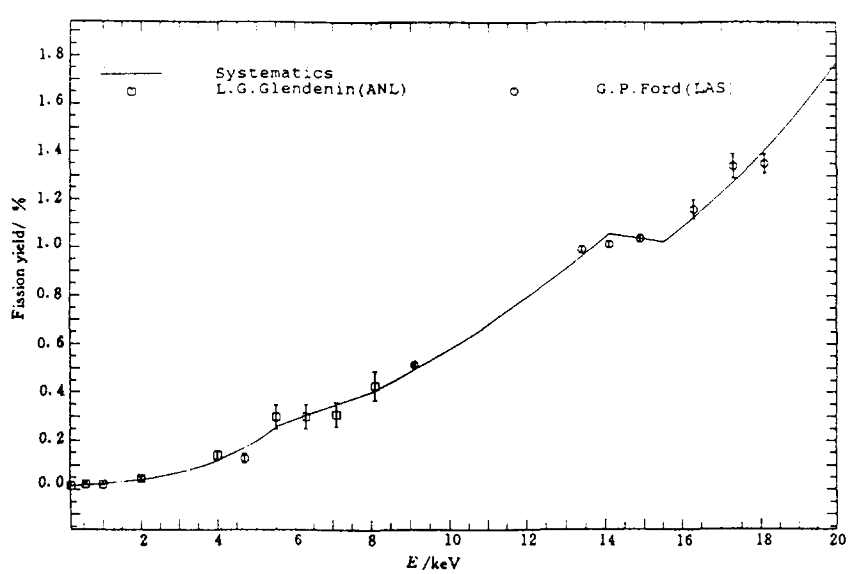

Fig.8 Fission yield measured at monoenergy for ^{111}Ag

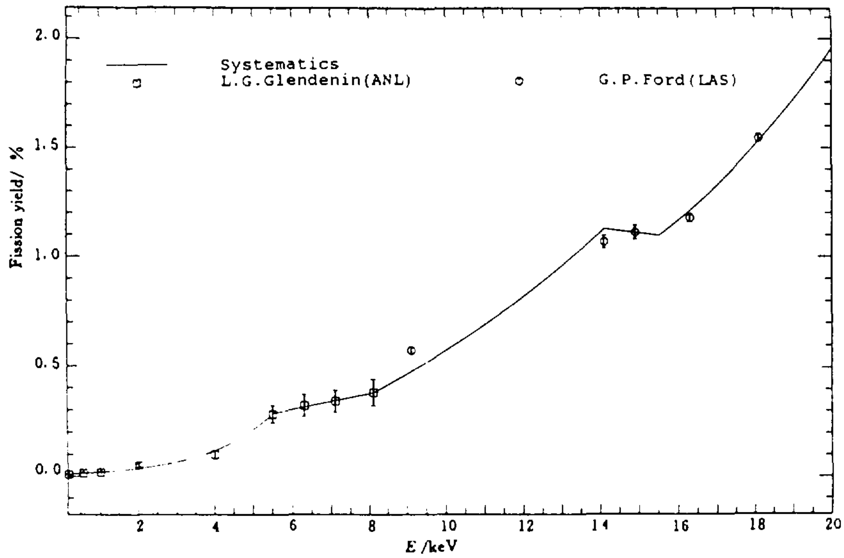

Fig. 9 Fission yield measured at monoenergy for ^{115}Cd

For symmetric fission, the yield increases with incident neutron energy in two steps. First, exponentially increase in the energy region up to about 5.5 MeV, then first step, a drop comparing the exponential increasing, from about 5.5 to 8.0 MeV, then again exponentially increase up to about 14.0 MeV, then second step from about 14.0 MeV to 15.5 MeV, at last, again exponentially increase up to 20.0 MeV. The two steps are approximately corresponding to the onsets of (n,n'f) and (n,2n'f) respectively, which make the excitation energy lower for the corresponding compound nucleus. These features are shown for fission products A=109−125, and some typical examples are given in Figs.8, 9.

For asymmetric fission, it is certain that the yield decreases slowly with increasing neutron energy, and roughly linearly (not exponentially). However if the dependence is studied carefully, it was found that the linear relation on energy is true for some products, for example for ^{95}Zr, ^{144}Ce, but not for others, for example for ^{99}Mo.

The dependence of fission yield on energy should be studied further in experimental measurement and theory investigation.

References

[1] D. Muir, Nucl. Sci. & Eng., 101,88(1989)
[2] Liu Tingjin, CNDP,2,58(1989)
[3] P. Ford et al., Phys. Rev., 137, 4B, 826(1965)
[4] E. Glendenin et al., Phys. Rev., C24(6) 2600(81)
[5] C. Chapman et al., Phys. Rev., C17(3), 1089(1978)

Table 1　Collected experimental FY data

EXFOR	$^{95}_{40}$Zr	$^{99}_{42}$Mo	$^{144}_{58}$Ce	$^{147}_{60}$Nd	EXFOR	$^{95}_{40}$Zr	$^{99}_{42}$Mo	$^{144}_{58}$Ce	$^{147}_{60}$Nd
10722002,3	√				20768002	√	√	√	
10994002				√(×)	21562002	√	√		
12729002	√	√	√	√	21590002	√	√	√	√
12771002	√	√			21605002	√	√		
12771005	√				21689002,4,6	√	√		
13059002-13				√(×)	21689012,19	√	√		
13064003			√		21707002	√	√	√	√
13064004				√	21708002			√	√
13065004	√				21743005		√		√
13086002					22054002	√			
13091002	√(×)		√(×)	√(×)	22057002	√	√		√
13116002					22066002	√	√	√	√
13174002					30495002		√		√
13211002,3	√				30496002				
13233006				√(×)	30504002		√		
13246002			√(×)		30744002	√	√		√
13251003				√	30752002	√			
13270017			√		30947002	√(×)		√(×)	√(×)
13272002		√			40206003			√(×)	√
13273003	√				40489002	√	√		
13283002	√			√	(Double Line heading)				
13283003			√		10828002	√	√	√	√
13286002	√		√	√	12919004	√(×)	√(×)	√(×)	√(×)
3306002,5	√		√		13054003	√(×)	√(×)	√(×)	
13335002	√				1307702				
13335008			√		13093002		√(×)		
13337002	√	√			13255002,4			√	√
13378002					13295002	√(×)	√(×)	√(×)	√(×)
13380002					13444003			√	
13339002	√				13445004			√	
13342002	√				20769002		√		√
13362002			√(×)		(Measured in China)				
13372003		√(×)			32628002			√(×)	√(×)
13374002,3		√(×)			32629002	√(×)	√(×)		√(×)
13382002		√(×)			32636002	√(×)	√(×)	√(×)	√(×)
13395002					32631002	√	√	√	√
13395003	√	√	√		32632002,3		√		
13403002	√(×)	√(×)			32633002,3	√	√	√	√
13425002					32634002-4	√(×)	√(×)		
13427003		√			32635002-5	√	√		
13428002	√(×)		√(×)		32636002	√(×)	√(×)		√
13448002	√(×)			√(×)	32638002,3	√	√	√	
13478002	√				32639002	√(×)	√(×)		
13478003			√		QiLinkun+(88)	√	√	√	√
13479002	√				Lize+(95)	√			√
13479003			√		H.R.Von Guntin(67)		√		