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STATUS of FISSION YIELD DATA

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Abstract: In this paper first we summarize the current status of the US evaluation for 34 fissioning nuclides at one or more neutron incident energies and for spontaneous fission. Currently there are 50 yields sets, and for each we have independent and cumulative yields and uncertainties for approximatively 1100 fision products. When finalized the recommended data will become part of the next version of the US ENDF/B VI.In a second part we review the different models developped to derive independent yields sets.The Zp and empirical models have been extensively studied by A.C Wahl/1,2/for 6 fissioning nuclides.Comparison of model estimates with experimental data will be presented.The parameters for other fissioning systems will be derived by th use of systematic trends.A comparison of model estimates with some recent experimental data, obtained from Lohengrin (249Cf T) will be given.

(Fission,Fragment yields,Fragment charge distribution,Evaluation)

Introduction

Next year will be the 50th anniversary of the discovery of fission.Since the begining physicists and chemists have measured the distribution in masses and charges of the fragments and products following fission .Generally these distributions are called "yields". The definitions of the different types of yields are now reasonably standardized. Their definitions can be found in the review paper of Wahl/ 1,2/.
The most recent review papers on yields by major evaluators in the US, UK, France, and China are in Ref./2/. This is a source of much of the material in our paper.Most of the chain yields for the more important fissioning systems have been measured. For the independent yields the situation is not the same, so models have been developed for estima ting the many hundreds of independent yields that have not been measured.

Because of space limitations, we will not include a discussion of isomeric yields except to note that some evaluations use the simple model in Ref./3/ and others simply assume equal division among isomer

Libraries of Evaluated Fission Yields

JAMES /2/ has recently reviewed the existing libraries of fission yields. He considers 4 libraries:

1. The UK unajusted and adjusted libraries UKFYU1 and UKFYA1, respectively. Adjustment refers to the inclusion of several conservations directly in the evaluation such as total prompt delayed neutrons,charge, etc. The UK libraries include 15 yield sets for ten fission nuclides. Fractional independent yields were not re-evaluated from CROUCH/4/, but did have some readjustment by least squares. The UK evaluations are again in progress and will include a more detailed treatment of uncertainties than previous evaluat ions.These libraries were started by CROUCH /4/,and include an independent evaluation of chain yields.

2. The US evaluation effort now resides at LOS ALAMOS. This library was first started by RIDER and MEEK of the General Electric Company and RIDER continues to update the data and assist in the evaluation. The 1988 version contains independent and cumulative yields and uncertainties for about 1100 products for each of 34 fissionable nuclides at one or more energies (50 sets). Independent yields that are unmeasured are based on the Gaussian Zp model with parameters based on an older U-235 analysis by Wahl except for the six recently studied systems/1/; other exceptions are pairing effects/3/, isomeric yields/5/, and the detailed treatment of decay, including direct use of DN precursors. Except for six systems, the Zp(A) values for many systems are based on Ref./6/. A description is given by RIDER /2/. Model parameters are not well known for many systems.
The compiled list of measured yields and related data is retained with the evaluations along with a list of about 1400 publications from 1939 through 1987. A listing of these data (April, 1988) will be supplied to members of the IAEA CRP and to others

by request. A complete listing requires about 1200 pages and distribution will be limited until issued as a Los Alamos report. It retains the format of the last widely distributed version /7/.
U235 Mass yields (Version G) and sum of direct yields by charge (Version G) are shown in figure 1 and 2.
The chain yields of thislibrary are used by other libraries (Wahl,French, Chinese).
3) A French library (1987)/2,8/.It is more a working file with the chain yields from the US, but with different parameters for the charge distribution. This file was mainly used for the decay heat calculations

4) A Chinese library (1987)/2/
Currently the Chinese evaluation contains ten yield sets for six fission ing nuclides. The methodology of evaluation, parameters, and chain yields are based on the US publications, but their data are now being expanded and there is an effort to improve estimated yields.
JAMES /2/ gives a summary of the methods of evaluation and comparisons of data,he had available. These older evaluations did not account for the systematics near symmetry/9,10/, and the charge distribution parameters were developed before the new experimental results from Lohengrin were available, but most of his analysis still applies.

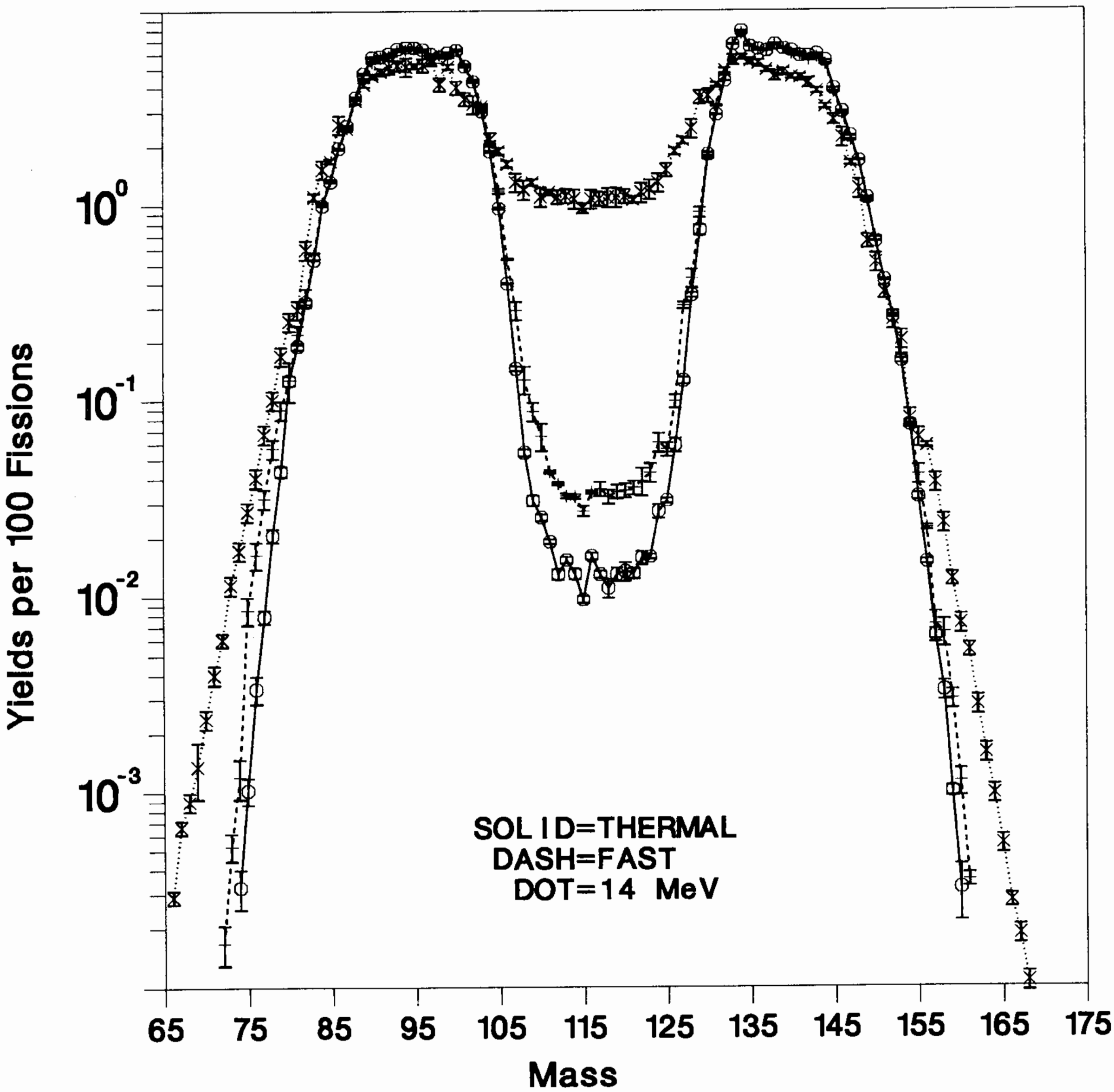

Fig. 1 U-235 Mass Yields (Version G) Los Alamos

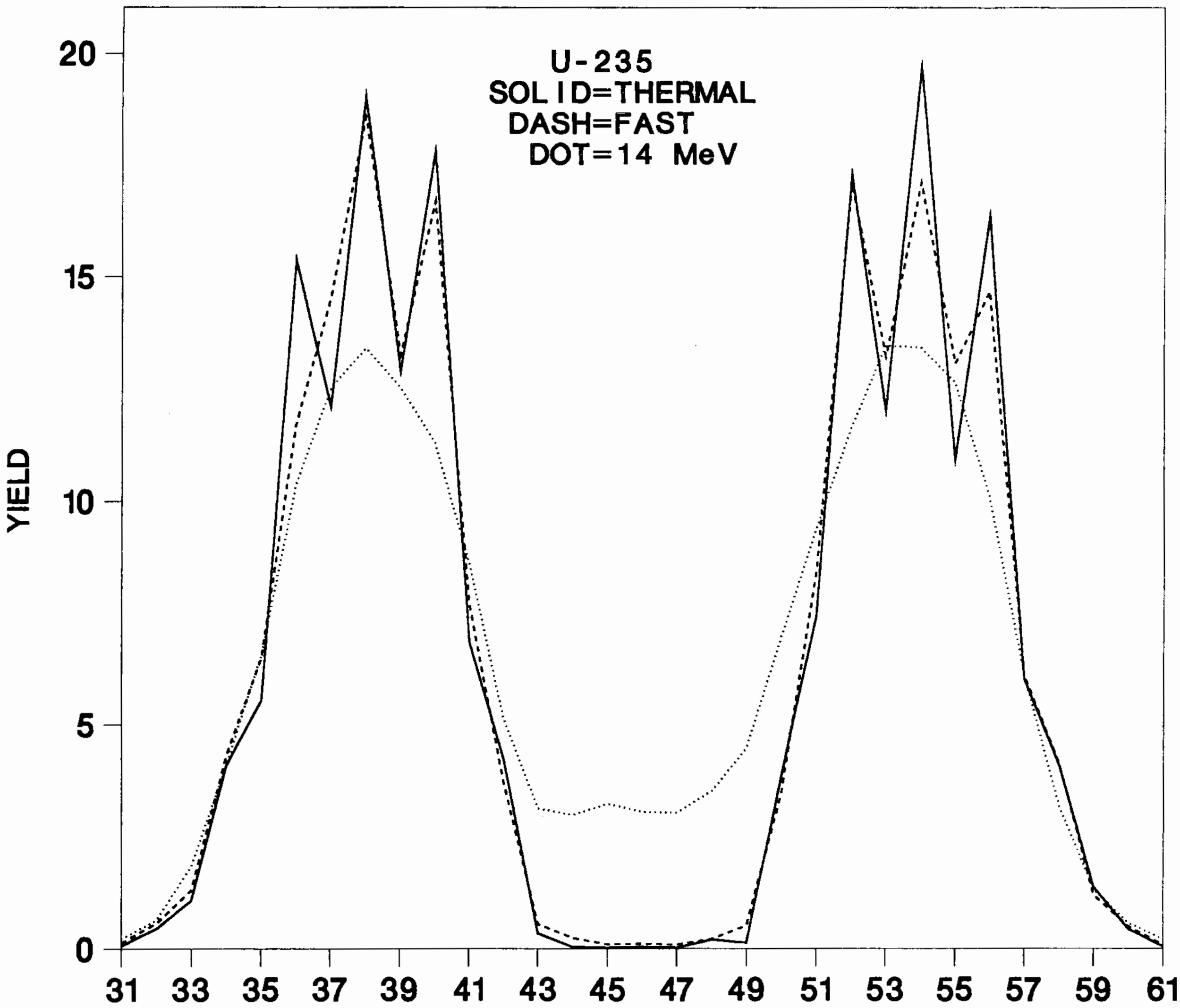

FIG 2 SUM OF DIRECT YIELDS BY CHARGE (VER. G)

Models for charge distribution.

Two empirical models, the Zp and the A'p models have been developed. Both models need to establish the complementarity of mass numbers

$$A'l + A'h = A'f \qquad (1)$$

$$A' = A + vA \qquad (2)$$

l for light and h for heavy products, f for the fissioning nuclide .
The vA values are calculated from Y(A) values by a program "NUTP8" It is based on a method first proposed by TERRELL/11 / .The number of neutrons emitted for symetric fission must be assumed.For U235T the observed kinetic energy deficit support value of 4 neutrons and this value is assumed for other fission reactions. The total average number of neutrons (vT) are divided between heavy and light products by multiplying vT by an estimated ratio . This ratio have to give reasonable agreement with experimental values .The plots of experimental vA(A) values and the smoothed functions derivated from the "NUTP8"program can be found in the WAHL papers/1,2/ for 4 systems (U235T, U233T, PU239T, CF2521)

Both the Zp AND Ap' models assume that the distribution of yields is Gaussian . Yields are modulated by proton and neutron pairing effects. The effects are applied by multiplication or division of Gaussian yields by Fz and Fn,the average even odd proton, neutron factors .The Gaussian width parameters for the 2 models are equal to the root mean square (RMS) values for Gaussian dispersions corrected for grouping:

$$\sigma = (RMS^2 - 1/12)^{1/2} \qquad (3)$$

It is convenient to compare the maxima in dispersion curves, Zp and A'p with values for unchanged charge division (UCD)

$$Zucd = A'(Zf / Zf) \qquad (4)$$

$$A'ucd = Z\ (Af/Zf) \qquad (5)$$

The parameters which are used to represent the 2 functions

$$\Delta Z = (Zp - Zucd) \qquad (6)$$

$$\Delta A' = (A'p - A'p\ ucd) \qquad (7)$$

are given in the Wahl paper and a summary is given in table A for the Zp model.They have been derived from available data by the method of least squares.A modification of the general leastsquares program ORGLS is used.

The figure 3 taken from ref. /1/ shows the variation of RMS and ΔZ for U235T. The parameters used with the model are given in Table A

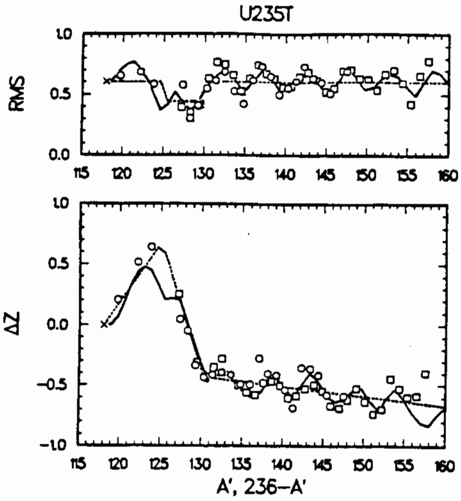

Fig.3 Z and RMS versus A'

Complementary element yields: Y(Zl)= Y (Zh) are required to be equal for the A'p model.When too few data exist to derive parameters, the U235T data are assumed be valid for all systems. The parameters for the A'p model can be found in ref/ 1/

Uncertainties in model calculation.

Estimates of per cent uncertainties in model calculated yields are made with the following equations similar to those proposed by SPINRAD /11/

$$Sest = 100(\exp(d)^2 - 1)^{1/2} \quad (8)$$

$$\delta\mu = \alpha + \gamma(\Delta)^4 \quad (9)$$

with

$$\Delta = (Z - Zp) \text{ or } (A' - A'p) \quad (10)$$

$$|\mathrm{Ln}(Ycal/Yexp)| = \alpha + \gamma(\Delta)^4 \quad (11)$$

generally α=0.1, γ=0.05 (Zp)and γ=001(A'p)

Recommended Independent yields derived from Zp and Ap' models for the six systems: U235T,U233T,PU239T,PU241T,U238F,Cf252 are now available on tape from Wahl. The procedure, which produces these complete data sets, gives detailed charge balance, equal yields for complementary elements.Detailed charge balance is not achieved for the other

TABLE A - PARAMETERS FOR THE Zp MODEL*

PARAMETER	235U	233U	239PU	252CF	238U	241PU
$\Delta Z(A'=140)$	-0.511	-0.519	-0.544	-0.420	-0.380	-0.503
$\partial\Delta Z/\partial A'$	-0.008	-0.015	-0.015	-0.015	-0.014	-0.012
$\bar{\sigma}z$	-0.531	-0.555	-0.546	-0.589	-0.542	-0.544
$\sigma z(50)$	0.33	0.36	0.35	0.35	0.35	0.35
$\bar{F}z$	1.27	1.27	1.14	1.05	1.18	1.10
$\bar{F}n$	1.07	1.07	1.05	1.0	1.0	1.0
$\Delta A'_Z$	0.9	0.9	0.9	0.7	0.9	0.9
$\Delta Zmax$	0.7	0.7	0.7	0.7	0.7	0.7

* Uncertainties can be found in ref/1/

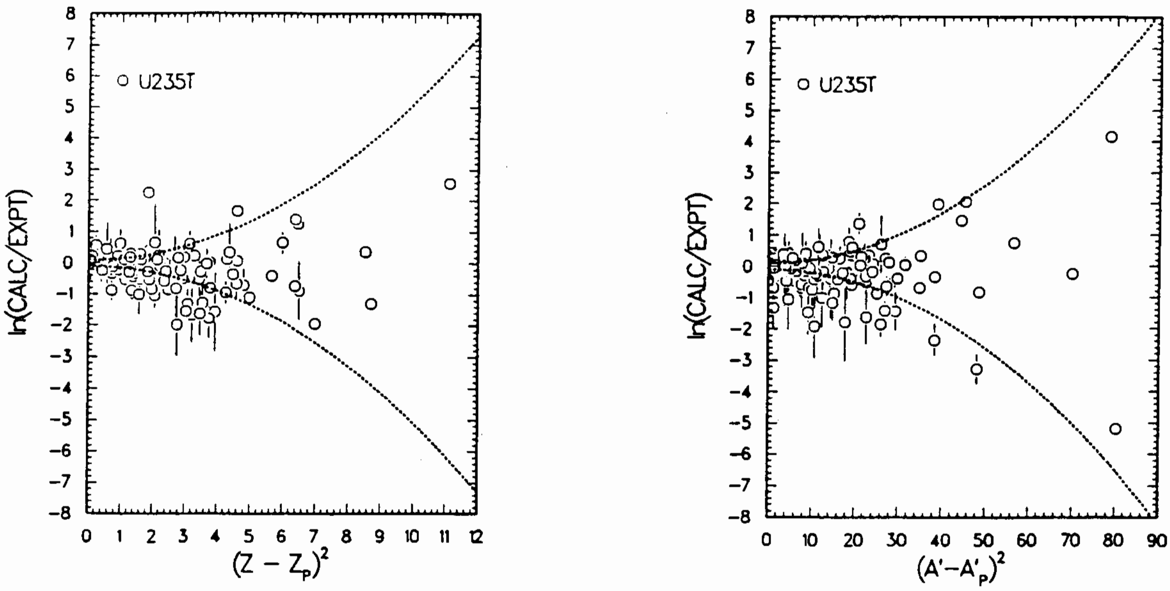

Fig.4 Uncertainty estimates for Zp and A'p model calculated yields.

Dashed lines represents $+\delta\mu$ and $-\delta\mu$ functions used for estimation of uncertainties.

complete independent yields sets,(US, UK,CHINESE) as it is shown in figure 4 of /2/ .
It is important to keep in mind that empirical model predictions tend to be increasingly uncertain as measured data become sparse as, e.g., with very small yields. Parameters are averaged over large mass ranges and different evaluators use different parameters.The models are not consistently used by all evaluators. For example, DICKENS/13/ notes that the Gaussian sigma depends on the even-odd character of Zp apart from the modulation by pairing; for cumulative yields, some use Sheppard's correction, etc.
Wahl's analysis, being the most recent for fractional yields and the most detailed, is presented above. His parameters are used in six of the 50 sets in the US evaluation and in the French calculations.

Delayed neutron yields :

Emission of neutrons following beta decay changes the initial mass distributions of both independent and mass number yields. 271 precursors have now been measured or calculated by ENGLAND /14/. With the sets of fission yields and the delayed neutron emission probabilities of the total delayed neutron yields can be derived .

New experimental Techniques :

Various methods to measure fission yields have been used since the discovery of the fission . These include radiochemical and mass spectrometric measurements, gamma spectrometry with or without radiocheical separations,
on line isotopic separations (OSIRIS, SOLIS,COSI et...) recoil separators, HIAWATHA and LOHENGRIN.
DENSCHLAG /15/ has done a survey of all these methods.

The LOHENGRIN spectrometer :

The fission product spectrometer "Lohengrin" at the high flux reactor of the ILL (GRENOBLE FRANCE) has been many times described /16/.
The masses are identified through a combination of electric and magnetic fields. Fission fragments are focussed onto parabola inside a reaction chamber. Each parabola is characterized by a fixed ratio A/q of mass number A to ionic charge q.Different points on a parabola correspond to different kinetic energies E of the fragments. Mass resolving powers $A/\Delta A$ of about 1000. are routimely available. To determine nuclear charges Z ,the method is based on the specific ionization, along the particle trajectory .We have to decompose the total fragment energy E into $E = \Delta E + E_{res}$ with ΔE being the energy loss in absorber of fixed thickness and Eres being the residual energy.The spectrometer gives E from the field settings, while Eres is measured with a ionization chamber.

Since each measurement applies to an individual ionic charge state (q) and to an individual kinetic energy of the fragments, a complete distribution has to be carried out over the whole range of kinetic energies and over most of the ionic charges produced .

The figure 5 shows residual energy spectra decomposed into charge components.It'clear from this figure that the uncertainty on low FI is high. See charge 37.

Physical results :

Up to now U235T, U233T, Pu239T have been measured at Lohengrin and used by Wahl /1,2/ in his evaluation. The large range of measurements allow to determine the proton Odd Even effect with the same method.The values now in the evaluations are derived from LOHENGRIN for 235,233UT,239PUT.

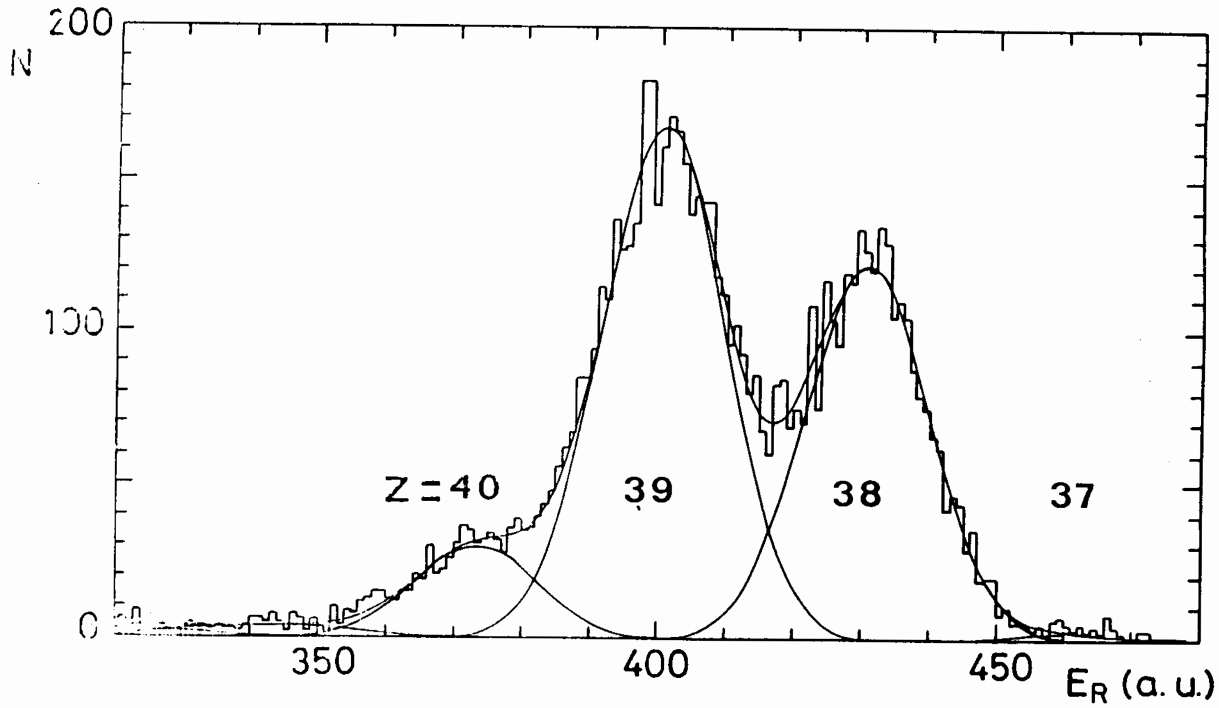

Fig.5 Residual energy spectra taken at LOHENGRIN.

Application of Wahl's model to new LOHENGRIN measurements .

CF249T has been recently measured at Lohengrin /17/. Fractionnal independent yields are given from masses 85 to 120. Following the method described in /1/, we have first calculated the vA. A complete data set of chain yields is in the US library/5 /. The agreement between these values and those measured at Lohengrin is good . Only chain yields for masses 94,95 have higher values at Lohengrin.To establish the vA(A) calculation, a vT value of 4.1 /18/ and the same ratio as in CF252 are taken The figure 6 compare the vA of CF252, with CF249T .

The parameters to calculate ΔZ are average values of 252CF and 241Pu in Table A .
Fz and Fn are taken from /17/
The Fn deduced from the work of Djebara /17/ is larger than values of table A. Most of it ought to be linked to the evaporation of prompt neutrons from the fragments since vT increases from 2.4 for 235U to 4.1 for Cf249T.
Now it is possible to calculate all independent yields in CF249T using the program "EFPYA" of ref /1/
The Table B is a part of the comparison of calculated and experimental charge distribution data. YI> 0.01 are in good agreement.
We have already seen the very large experimental uncertainty for the low yields. So it is worthless to try to compare these low data.

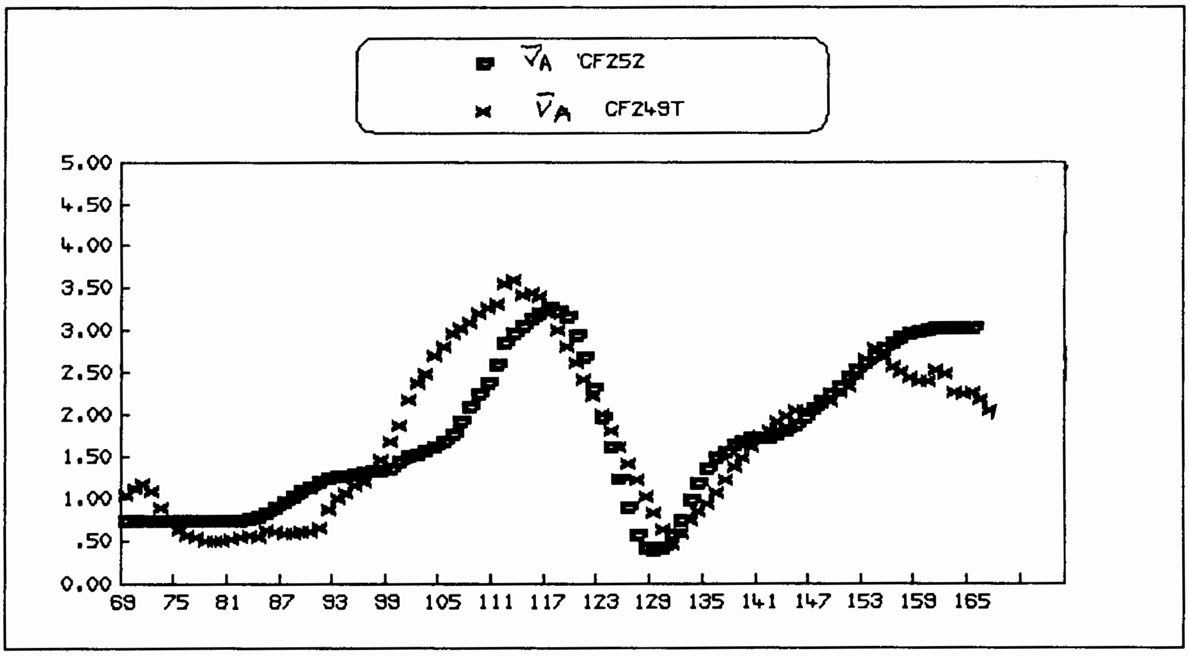

Fig.6 Average number of prompt neutrons emitted vA to form products with mass A

Table B

Comparison between experimental/17/ and calculated independent yields.

Nuclides			Experim.	Calculated
35	Br	91	1.403E-02	2.862E-02
36	Kr	91	3.020E-01	3.700E-01
37	Rb	91	5.530E-01	5.341E-01
38	Sr	91	1.310E-01	6.637E-02
36	Kr	92	1.200E-01	1.836E-01
37	Rb	92	5.130E-01	5.339E-01
38	Sr	92	3.680E-01	2.719E-01
36	Kr	93	1.400E-02	4.022E-02
37	Rb	93	3.880E-01	4.619E-01
38	Sr	93	5.400E-01	4.475E-01
39	Y	93	5.900E-02	4.960E-02
37	Rb	94	1.690E-01	1.940E-01
38	Sr	94	6.860E-01	6.596E-01
39	Y	94	1.450E-01	1.334E-01
37	Rb	95	5.900E-02	8.364E-02
38	Sr	95	4.780E-01	5.183E-01
39	Y	95	4.050E-01	3.747E-01
40	Zr	95	5.700E-02	2.225E-02
37	Rb	96	1.300E-02	1.686E-02
38	Sr	96	3.010E-01	3.866E-01
39	Y	96	5.510E-01	4.884E-01

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Conclusions

Evaluated yields through 1987 are now available for 50 fissioning systems. Six systems have had a recent, detailed analysis for distribution parameters. A similar effort is needed for other systems. Evaluation and modeling continues in the US, UK, China, and France. The new IAEA CRP may assist in resolving differences, and in defining needed experimental and evaluation support. Space has not permitted a discussion of problems and detailed differences in evaluations such as energy dependence, treatment of decay processes, and use of data measured before and after delayed neutron emission. We have chosen to summarize the most recent evaluations and modeling and to provide some recent Lohengrin data and its modeling.

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