INDC(IND)-29/G

1137

B.A.R.C.-1126

NOT FOR PUBLICATION

B.A.R.C.-1126

सत्यमेव जयते

भारत सरकार

GOVERNMENT OF INDIA

परमाणु ऊर्जा आयोग

ATOMIC ENERGY COMMISSION

PROGRESS REPORT ON NUCLEAR DATA ACTIVITIES IN INDIA

for the period from January, 1980 to June, 1981

Compiled by

R. P. Anand and Rekha Govil

Nuclear Physics Division

भाभा परमाणु अनुसंधान केन्द्र

BHABHA ATOMIC RESEARCH CENTRE

बंबई, भारत

BOMBAY, INDIA

1981

B. A. R. C. -1126

NOT FOR PUBLICATION

B. A. R. C. -1126

PROGRESS REPORT ON NUCLEAR DATA ACTIVITIES IN INDIA

for the period from January, 1980 to June, 1981

Compiled by

R.P. Anand and Rekha Govil
Nuclear Physics Division
Bhabha Atomic Research Centre
Bombay, India.

INDIAN NUCLEAR DATA GROUP

1.	B.B. BALIGA	SAHA INSTITUTE OF NUCLEAR PHYSICS, CALCUTTA.
2.	M.R. BHIDE	PHYSICS DEPARTMENT, UNIVERSITY OF POONA, PUNE.
3.	V.C. DENIZ	BHABHA ATOMIC RESEARCH CENTRE, BOMBAY.
4.	A.S. DIVATIA	VEC PROJECT, BHABHA ATOMIC RESEARCH CENTRE, CALCUTTA.
5.	S.K. GUPTA	BHABHA ATOMIC RESEARCH CENTRE, BOMBAY.
6.	S. GANGADHARAN	BHABHA ATOMIC RESEARCH CENTRE, BOMBAY.
7.	S.B. GARG	BHABHA ATOMIC RESEARCH CENTRE, BOMBAY.
8.	M.C. JOSHI	DEPARTMENT OF PHYSICS, UNIVERSITY OF BOMBAY, BOMBAY.
9.	S.S. KAPOOR (CONVENER)	BHABHA ATOMIC RESEARCH CENTRE, BOMBAY.
10.	M.K. MEHTA	BHABHA ATOMIC RESEARCH CENTRE, BOMBAY.
11.	G.K. MEHTA	PHYSICS DEPARTMENT, INDIAN INSTITUTE OF TECHNOLOGY, KANPUR.
12.	S.K. MITRA	TATA INSTITUTE OF FUNDAMENTAL RESEARCH, BOMBAY.
13.	M.P. NAVALKAR	BHABHA ATOMIC RESEARCH CENTRE, BOMBAY.
14.	J. RAMA RAO	PHYSICS DEPARTMENT, BENARAS HINDU UNIVERSITY, VARANASI.
15.	B.P. RASTOGI	BHABHA ATOMIC RESEARCH CENTRE, BOMBAY.
16.	SATYA PRAKASH	BHABHA ATOMIC RESEARCH CENTRE, BOMBAY.
17.	M. SRINIVASAN	BHABHA ATOMIC RESEARCH CENTRE, BOMBAY.
18.	R. SHANKAR SINGH	REACTOR RESEARCH CENTRE, KALPAKKAM, TAMIL NADU.
19.	P.N. TREHAN	PHYSICS DEPARTMENT, UNIVERSITY OF CHANDIGARH, CHANDIGARH.

CONTENTS

Page

PREFACE

Although in some previous years the progress reports on Indian nuclear data activities were not brought out separately, the nuclear data related work carried out in these years can still be desseminated from the proceedings of the annual Nuclear Physics and Solid State Physics Symposia, and other symposia held periodically on related topics. From this year, we have again started the practice of bringing out a separate progress report of the Nuclear Data activities in the country, and the present progress report covers the period Jan.80-June 81.

Bulk of the nuclear data related work in the country is being carried out at B.A.R.C. Trombay and R.R.C. Kalpakkam. The concerned divisions and sections of these research centres were requested to submit contributions for this report of their nuclear data related work, both published and unpublished, carried out during the above period. However, the nuclear data contributions of the other institutions and universities were taken from the proceedings of the nuclear physics and solid state physics symposium held in Dec.80. I hope this procedure has not caused omission from this report of any other nuclear data related work from these institutions and universities. I would like to take this opportunity to extend invitation to all the researchers in the country to also send their nuclear data contributions separately for inclusion in future progress reports, irrespective of whether or not these are submitted for publication in a journal or to symposia/conferences etc.

During the period 4-5 Aug.1981, a workshop on Nuclear data evaluation, processing and testing was held at Reactor Research Centre, Kalpakkam. As this period falls beyond the scope of this report, the contributions to the workshop are not included in the present progress report. But just to give an idea of the scope of the workshop, the topics which were discussed were Evaluation of Neutron Nuclear Data, Processing of Nuclear Data and Generation of Multigroup Constants, Nuclear Data Validation and Testing through Analyses of Integral Measurements,etc. In order to give future directions to our nuclear data related work, the workshop concluded with a panel discussion.

In this report, nuclear data activities are presented according to subject. Only those nuclear physics activities are included which have a direct relationship with nuclear data. For example, charged particle induced nuclear reactions of importance for understanding nuclear structure or nuclear reaction mechanism are not covered in the report. As the proceedings of the annual nuclear physics and solid state physics symposia give full coverage of the nuclear physics activities in the country, this report is limited to the compilation of nuclear data related activities only.

(S.S. Kapoor)
Convener
Indian Nuclear Data Group.

I. NUCLEAR FISSION

I.1 Multiparameter Study of the Long Range Alpha Particles emitted in the Thermal Neutron Induced Fission of ^{235}U*.

R.K. Choudhury, S.S. Kapoor, D.M. Nadkarni and P.N. Rama Rao

The correlations between the various parameters in the thermal neutron induced fission of ^{235}U accompanied by long range α particles (LRA) have been measured employing a back-to-back gridded ionization chamber. Semiconductor detectors were placed symmetrically along the electric field direction of the chamber behind the thin windows of the collector plates for the measurement of the LRA energies. A distinguishing feature of the present method is that the angle between the fission fragments and the electric field direction (hence the direction of α-particle emission) is also determined electronically by the analysis of the coincident collector and grid pulses of the ionization chamber. About 5×10^3 LRA accompanied fission events and about 2×10^6 binary fission events were recorded and analyzed to obtain a number of correlations of interest between the fragment mass, total kinetic energy, LRA energy and fragment LRA angle. These experimental results give some insight into the emission mechanism of the LRA.

---

*Published in Nucl. Phys. A 346 (1980) 473-496.

I.2 Multiparameter Study of ^{1}H, ^{3}H and ^{4}He in Fast Neutron Induced Fission of ^{235}U*.

S.C.L. Sharma*, G.K. Mehta*, R.K. Choudhury+, D.M. Nadkarni+ and S.S. Kapoor+.

The emission probabilities per fission of α-particles, tritons and protons have been measured in fast neutron induced fission of ^{235}U. The measurements were carried out at neutron energies of 120, 180, 230 and 500 keV. A ΔE-E semiconductor detector telescope was used to identify different light charged particles and fission fragments were detected with an ionization chamber. The three parameter data corresponding to the pulse heights from ΔE-E detectors and the ion-chamber were recorded event by event on magnetic tape and were analysed off-line by computer. No significant variation in the most probable energy ($\bar{E}$) and the standard deviation (σ_E) of the energy spectra of different light charged particles with incident neutron energy was observed, although $\bar{E}_\alpha$ was seen to have a slightly higher value beyond $E_n \sim 230$ keV. The yield of α-particles in fission induced by neutrons of $E_n \sim 200$ keV was found to be higher by about 20% than that in thermal neutron induced fission. The yields of tritons and protons were found to increase significantly with neutron energy.

*Published in Nuclear Physics A 355 (1981) 13-24.

---

*Physics Department, IIT, Kanpur.

+Nuclear Physics Division, BARC, Trombay, Bombay.

I.3 Macroscopic Systematics of Nuclear Level Densities.*

S.K. Kataria and V.S. Ramamurthy
Nuclear Physics Division
Bhabha Atomic Research Centre
Trombay, Bombay-400 085
India.

In a number of recently proposed semi-empirical nuclear level density formulae, a macroscopic-microscopic approach similar to that used in nuclear potential energy calculations has been successfully used. While the underlying macroscopic part in these formulae is the well-known Bethe expression, these formulae differ in the treatment of the microscopic part, namely the shell and pairing effect. In the present work, we have carried out a study of the macroscopic features of the nuclear level densities on the basis of the independent-particle model of the nucleus. It was found that even after taking into account shell and pairing effects, large deviations from the predictions of the Bethe expression with a level density parameter 'a' smoothly dependent on the mass number ($a = \alpha A$) are present. In particular, the level density parameter 'a' was found to be strongly dependent on the last nucleon separation energies. A simple parametrisation of 'a' including its dependence on the separation energies is proposed. The experimental data on the neutron resonance spacings of spherical nuclei have been analysed on the basis of this parametrisation. It is shown that the predicted isospin dependence of 'a' is consistent with the available experimental data. The deformation dependence of 'a' is also discussed.

*Published in Nucl. Phys. A349 (1980) 10-28.

I.4 Analysis of prompt neutron anisotropies in thermal neutron fission of ^{235}U+.

Rekha Govil and R.K. Choudhury
Nuclear Physics Division
Bhabha Atomic Research Centre
Trombay, Bombay-400085.

The analysis of experimental results on prompt neutron anisotropy have led to the conclusion that a small fraction of the total number of neutrons is emitted isotropically, prior to the full acceleration of the fission fragments. In this work prompt neutron anisotropies have been calculated as a function of total fragment kinetic energy E_k in the thermal neutron induced fission of ^{235}U. These calculations are made on the basis of evaporation of the neutrons from fully accelerated fragments. These results, when compared with available experimental prompt neutron anisotropies, are found to be larger at higher E_k. This discrepancy can be attributed to the emission of an isotropic or less anisotropic component of prompt neutrons prior to the full acceleration of the fragments. Assuming that the discrepancy is due to the emission of isotropic component of prompt neutrons during the descent of the compound nucleus from saddle to scission, the fraction of these isotropic neutrons is deduced. Although this fraction increases with E_k, the absolute number of these neutrons $\bar{\nu}_{p.s.}$ is constant (~ 0.3) with E_k. This suggest that the average prescission excitation energy of the fissioning nucleus is constant with E_k. Also, for an average $\bar{\nu}_{p.s.}$ of 0.3, the time between saddle to scission should be of the order of 10^{-19} sec. Such a long time implies that the motion of the compound nucleus between saddle and scission is quite slow and viscous.

+Published in J. Phys. G: Nucl. Phys. 7 (1981) 59-63.

I.5 INVESTIGATION ON FISSION FRAGMENT ANGULAR MOMENTUM IN LOW ENERGY ACTINIDE FISSION

T. Datta, S.P. Dange, A.G.C. Nair, Satya Prakash and M.V. Ramaniah

Radiochemistry Division,
Bhabha Atomic Research Centre, Trombay, Bombay-400 085, India

Studies on fission fragment angular momentum yield useful information about the scission configuration. The existence of high angular momentum of fragments has been interpreted in terms of strong coulombic interaction between the fragment for non-linear scission configuration or bending mode oscillation. Accordingly, the fragment angular momentum might depend on its deformation, mode of charge split and bending mode amplitude.

With the aim to investigate the above correlation, angular momenta of fragments corresponding to ^{95}Nb and ^{132}I in ^{233}U (n, f) and of ^{117}Cd and ^{134}I in ^{252}Cf (sf) have been estimated from the radiochemically determined independent isomeric yield ratios of these fission products using the statistical model formalism of Vandenbosch and Huizenga. Table-1 shows the data on the yield ratio and angular momenta values.

In ^{233}U (n, f), it was shown that for given neutron number around mass 130-132, the angular momentum value decreases with increasing proton number away from magic number 50 which could be due to deformed shell effect. In ^{252}Cf (sf), comparison of the data with the literature data on other fission products shows that there is no correlation between fragment angular momenta and prompt neutron number since angular momentum depends on scission point deformation while prompt neutron number depends on difference between fragment formation at scission point and at ground state. However for given fragment mass when ground state deformation is invariant, prompt neutron number correlates with angular momentum. The plot of angular momenta as a function of fragment proton number was seen to be inversely related to isotopic yield distribution since higher angular momentum indicate larger rotation in direction perpendicular to fission axis reducing the available energy and hence lowering the yield. Part of this work has been accepted for publication in Physical Review C.

Fissioning system	Fission product	Ym'/(Ym' + Yg')	Angular Momenta ($\hbar$)
^{233}U (n, f)	^{95}Nb	0.248 ± 0.029	$6.35 \begin{smallmatrix} +1.25 \\ -0.95 \end{smallmatrix}$
	^{132}I	0.268 ± 0.084	5.7 ± 1.2
^{252}Cf (sf)	^{117}Cd	0.710 ± 0.036	5.2 ± 1.0
	^{134}I	0.548 ± 0.020	11.5 ± 1.1

I.6 CHARGE DISTRIBUTION IN THE SPONTANEOUS FISSION OF ^{252}Cf:

Determination of fractional cumulative yields of ^{138}Xe and ^{139}Cs.

A. Ramaswami, B.K. Srivastava, S.B. Manohar, Satya Prakash and M.V. Ramaniah

Radiochemistry Division,
Bhabha Atomic Research Centre, Trombay, Bombay-400 085, India

The fractional cumulative yields (F.C.Y.) of ^{138}Xe and ^{139}Cs in the spontaneous fission of ^{252}Cf have been determined using radiochemical separation and direct gamma-ray counting of the irradiated catcher foil on 60 c.c. Ge(Li) coupled to a 4K analyser. The fractional cumulative yields were calculated from the growth and decay of the daughter products ^{138}Cs and ^{139}Ba respectively. The values of fractional cumulative yields are 0.85 ± 0.03 and 0.977 ± 0.006 for ^{138}Xe and ^{139}Cs respectively. These values correspond to a width (σ) of 0.60. This is similar to trend observed in the thermal neutron induced fission of ^{235}U, σ value being lowest for mass chain 136 and increases as the mass approaches to 140. This variation in σ is attributed to shell effects which lowers the width of the charge distribution around mass 136.

I.7 CHARGE DISTRIBUTION IN ^{245}Cm (n, f) SYSTEM

T. Datta, S.P. Dange, A.G.C. Nair, S.B. Manohar, Satya Prakash and M.V. Ramaniah

Radiochemistry Division,
Bhabha Atomic Research Centre, Trombay, Bombay-400 085, India

In view of the observation of 82 - neutron shell effect on width (σ) of charge distribution in a given isobaric mass chain around mass region 132-136 in ^{235}U (n_{th}, f) elsewhere and ^{252}Cf (s, f) in this laboratory, fractional cumulative yields of ^{135}I and ^{140}Ba in ^{245}Cm (n, f) system have been determined. The yield values were determined from direct counting of the daughter product activities pertaining to ^{135}I and ^{140}Ba on a 60 c.c. Ge(Li) detector coupled to a 4K analyser as a function of time. The parameter σ was determined for mass chain 135 & 140. From the observed yield values and using the most probable charge (Zp) calculated according to the equation

$$Zp = A' \frac{Z_F}{A_F} \pm 0.45$$

where A' is fragment mass, Z_F and A_F are fission nuclides charge and mass respectively. It was observed that σ value for 135 mass chain was low (~ 0.45) while that of 140 mass chain (~ 0.75) are high compared to normally expected value 0.56 ± 0.06 analogous to observation in other fissioning systems. This confirmed the existence of the influence of shell effect on mass chain 135 and of nucleon-pairing and/or absence of shell effect on mass chain 140. It was further shown that there could be a correlation between the fractional cumulative yield and neutron to proton ratio of the fissioning system. This work has been published in Physical Review C 21, 1411, (1980).

I.8 MASS DISTRIBUTION IN THE THERMAL NEUTRON INDUCED FISSION OF ^{229}Th

R.J. Singh, S.S. Rattan, A.V.R. Reddy, C.R. Venkatasubramani,
A. Ramaswami, Satya Prakash and M.V. Ramaniah

Radiochemistry Division,
Bhabha Atomic Research Centre, Trombay, Bombay-400 085, India

Mass yields distribution in thermal neutron induced fission of ^{229}Th have been studied using direct gamma spectrometric and radiochemical techniques. The mass yields have been determined by comparison method relative to those of ^{235}U (n_{th}, f). The yield values determined in this work differ significantly from the earlier reported values for most of the masses. The mass distribution in ^{229}Th (n_{th}, f) is predominantly asymmetric though there exists a small but significant peak corresponding to the symmetric mass division (Fig. 1). The average mass for the light and heavy fission products are 88.5 and 139.5 respectively and asymmetric peak to symmetric peaks ratio is 250. The existence of the symmetric peak has been qualitatively explained on the basis of the difference in the symmetric and asymmetric outer fission barrier heights and on the width of the mass distribution.

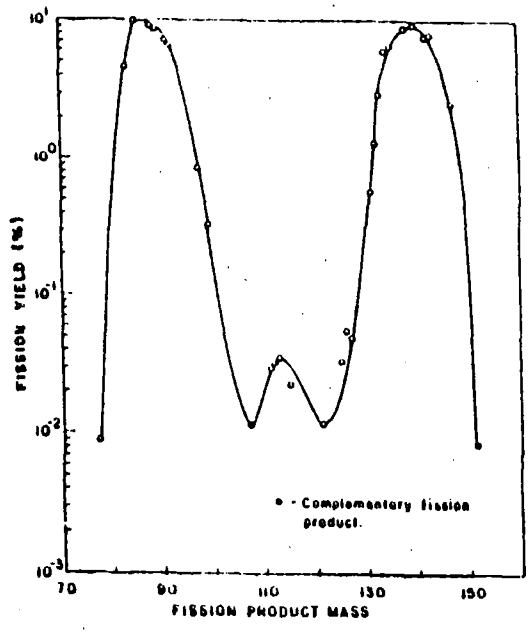

FIG.-1. THE MASS DISTRIBUTION IN THE THERMAL NEUTRON INDUCED FISSION OF ^{229}Th

I.9 ABSOLUTE FISSION YIELDS IN THE NEUTRON INDUCED FISSION OF ACTINIDES USING TRACK-ETCH CUM GAMMA RAY SPECTROMETRY

R.H. IYER, A. RAMASWAMI, V. NATARAJAN, R. SAMPATKUMAR
B.K. SRIVASTAVA and N.K. CHAUDHURI
Radiochemistry Division
Bhabha Atomic Research Centre
Trombay, Bombay 400 085.

As part of a long range program of work on nuclear data measurements in the neutron fission of actinide isotopes, we have evolved a new approach to absolute fission yield measurements, particularly suitable for short-lived fission products, which are very important from the point of view of decay heat calculations and which are not easily amenable to measurements by other currently available techniques. The absolute yields of a number of long lived ($t_{\frac{1}{2}} > 1$ hr) and short-lived ($t_{\frac{1}{2}}$ a few min) products including some gaseous fission products are reported for the neutron induced fission of ^{232}Th, ^{233}U, ^{235}U, ^{239}Pu and ^{245}Cm (1-4).

The merit and novelty of the present technique lie in the fact that it eliminates the need for the measurement of neutron flux, ϕ, fission cross section, σ, and the exact number of target atoms, n, thereby eliminating the errors associated with these measurements and gives very accurate values of the number of fissions. The total number of fissions, F(total), occuring in the target is determined directly with a high degree of accuracy ($\pm 2\%$) by recording in a mica track detector the number of fissions occuring in a small but representative sample of a solution of the target containing a mica strip and irradiated simultaneously under the same irradiation environment. F(total) is given by the expression

$$F(\text{total}) = (n\sigma\phi t) = \frac{Td}{K_{wet} \times C}$$

where Td is the fission track density (#/cm^2), K_{wet} is a constant (dimension cm) which may be identified as track registration efficiency in solution, 'C' is the concentration of the solution (g/cm^3) and, t, is the irradiation time. The accuracy of F (total) will depend mainly on the accuracy of the K_{wet} value, which has been determined rigorously by two independent techniques in this laboratory : (i) direct comparison with the number of fissions in a thin target-detector assembly, (ii) by accurate measurement of thermal neutron flux. The present method requires the scanning of a small representative area of the detector thereby ensuring better accuracy and ease of evaluation.

The fission product atoms formed in the target are determined by direct gamma ray spectrometry using a 60 C.C. Ge(Li) coupled to a 4K analyser. The system has been calibrated using standard calibrated gamma sources and the calibration accuracy has been checked to be within ±2%. For short irradiations, (30 secs) the pneumatic carrier facility in CIRUS reactor was used. The fission product gamma spectra of the irradiated sample were recorded on magnetic tape for two minutes intervals and were analysed later.

This technique will enable us to determine an exhaustive set of absolute yield values for the fission of actinides. Some recent data on the thermal neutron fission of ^{245}Cm are given in Table 1.

References

1. R.H. IYER, R. SAMPATHKUMAR and N.K. CHAUDHURI, Nucl. Instr. Methods, 115, 23 (1974)
2. A. RAMASWAMI, V. NATARAJAN, B.K. SRIVASTAVA, R. SAMPATHKUMAR, N.K. CHAUDHURI and R.H. IYER, J. Inorg. Nucl. Chem. 41, 1531 (1979).
3. A. RAMASWAMI, V. NATARAJAN and R.H. IYER, J. Inorg. Nucl. Chem. 42, 1213 (1980)
4. A. RAMASWAMI, V. NATARAJAN, B.K. SRIVASTAVA and R.H. IYER, J. Inorg. Nucl. Chem. (In press).

Table - 1

Absolute Yields of fission products from Thermal neutron induced fission of ^{245}Cm

S. No.	Nuclide	$T_{\frac{1}{2}}$	Gamma-ray energy (Kev)	Gamma-ray intensity (%)	Determined Yield (%)
1.	^{91}Sr	9.48 H	1024.3	33.5	0.98 ± 0.03*
2.	^{92}Sr	2.71 H	1383.9	90	1.28 ± 0.10
3.	^{97}Zr	17.0 H	743.4	97.96	2.40 ± 0.05
4.	^{99}Mo	66.6 H	140.5	90.7	4.05 ± 0.02
5.	^{105}Ru	4.4 H	724.3	48.0	6.39 ± 0.06
6.	^{105}Rh	35.4 H	318.9	19.2	5.89 ± 0.06
7.	^{131}I	8.05 D	364.5	82.5	2.78 ± 0.04
8.	^{132}Te	3.28 D	228.3	88.2	3.79 ± 0.03
9.	^{133}I	20.8 H	530.0	87.3	5.28 ± 0.04
10.	^{135}Xe	9.15 H	249.8	90	6.45 ± 0.06
11.	^{138}Cs	32.2 M	1435.9	76.3	5.90 ± 0.10
12.	^{140}Ba	12.8 D	537.6	24.4	5.41 ± 0.06
13.	^{142}La	93.3 M	641.3	52.5	4.59 ± 0.15
14.	^{143}Ce	32.7 H	293.3	43.4	4.28 ± 0.04

M - minutes H - hours D - days

* Statistical error

I.10 FISSION YIELDS OF LONG LIVED AND STABLE FISSION PRODUCTS IN THERMAL NEUTRON FISSION OF ^{241}Pu

S.A. Chitambar, S.N. Acharya, H.C. Jain and C.K. Mathews

Radiochemistry Division,
Bhabha Atomic Research Centre, Trombay, Bombay-400 085, India

Fission yields for 24 mass numbers have been determined using mass spectrometry and the data is compared with literature data (Refer Table 1).

References:

1. Proc. of the Nuclear Chemistry and Radiochemistry Symposium, Andhra University, Waltair, P 142-147 (1980).

TABLE-1

Fission Yields in Thermal Neutron Fission of ^{241}Pu

Nuclide	Present work (1980)	Farrar et al 1970 Ref.5	Lisman et al 1970 Ref.5	Compilation by R.A.C. Crouch	Compilation by Rider and Meek 1978 Ref.14
^{88}Sr	0.954*	-	0.950	0.954	1.021
^{90}Sr	1.48±0.024	-	1.53	1.49	1.574
^{91}Zr	1.820±0.024	-	1.82	1.79	1.89
^{92}Zr	2.250±0.023	-	2.23	2.23	2.392
^{93}Zr	2.90*	-	2.90	2.90	3.086
^{94}Zr	3.280±0.046	-	3.33	3.30	3.543
^{95}Mo	4.01*	-	3.92	4.01	4.072
^{96}Zr	4.28±0.060	-	4.33	4.33	4.619
^{97}Mo	5.11±0.10	-	4.76	4.81	4.85
^{98}Mo	5.24±0.10	-	-	-	5.14
^{100}Mo	7.13±0.10	-	-	-	6.12
^{101}Ru	5.94*	-	5.94	5.94	6.004
^{102}Ru	6.53±0.10	-	6.32	6.32	6.389
^{104}Ru	7.15±0.10	-	6.80	6.80	6.87
^{133}Cs	6.46*	6.56	6.71	6.46	6.768
^{137}Cs	6.38±0.04	6.62	6.60	6.49	6.863
^{140}Ce	5.77±0.05	5.78	5.86	5.82	6.167
^{142}Ce	4.74±0.04	4.70	4.80	4.78	5.03
^{143}Nd	4.43±0.04	4.44	4.48	4.42	4.703
$^{144}Ce+Nd$	4.22±0.04	4.07	4.13	4.09	4.33
^{145}Nd	3.18±0.03	3.16	3.19	3.14	3.342
^{146}Nd	2.67±0.02	2.68	2.68	2.66	2.861
^{148}Nd	1.88*	1.91	1.89	1.88	1.987
^{150}Nd	1.17±0.02	1.24	1.16	1.16	1.248

* Reference nuclide

I.11 Study of LRA Emission in keV Neutron Fission of ^{235}U.

S.C.L. Sharma and G.K. Mehta
I.I.T., Kanpur-208016.

Previous measurements have indicated an increase in the yield of long-range alphas-particles (LRA) emitted from ^{235}U fission at neutron energies around E_n = 200 keV. These measurements were carried out at few neutron energies (two to three energy points) in the range from 120 keV to 500 keV having large energy spreads in them. To see the variation of LRA yield with neutron energy more explicitly, the LRA accompanied fission of ^{235}U induced by keV neutrons has been studied in detail using a cellulose nitrate track detector. The measurements have been carried out at neutron energies; thermal, 125$\pm$12, 155$\pm$11, 185$\pm$10, 210$\pm$9, 240$\pm$9, 365$\pm$50 and 480$\pm$45 keV. Results show an increase of about 50% in the LRA yield at neutron energies 150 keV $\leqslant E_n \leqslant$ 220 keV as compared to that of thermal neutrons. At higher neutron energies ($E_n >$ 220 keV) the yield decreases and tends towards the thermal value. The LRA energy distribution parameters (average energy and width) do not show significant variation with the incident neutron energy.

I.12 Characteristics of Fragment Mass Distributions in Binary and Ternary Fission of ^{235}U Induced by Thermal Neutrons.

D.M. Nadkarni, R.K. Choudhury, S.S.Kapoor
and P.N. Rama Rao
Bhabha Atomic Research Centre, Trombay, Bombay-400085.

Measurements of various parameters such as fragment mass, energy, LRA energy and angle have been made for the case of thermal neutron induced ternary fission of ^{235}U employing a back-to-back gridded ionization chamber and semiconductor detectors. The details of the experimental method and analysis have been described elsewhere[1]. In the present work ternary fission fragment mass distribution has been determined explicitly incorporating the recoil correction due to the alpha particle emission. When this distribution is compared with binary fragment mass distribution, a shift mainly of the light fragment peak was observed. Prominent fine structures in the mass distribution have been observed in ternary fission corresponding to events with very large single fragment kinetic energy and these are compared with that in binary case. A comparison of the dependence of the most probable fragment kinetic energy $\langle E_k \rangle$ and the standard deviation σE_k on the fragment mass in binary and ternary fission shows that significantly higher σE_k are observed in ternary fission for fragment masses near $M_H \sim 130$ amu. These observations are discussed in terms of LRA emission probabily P_α and its dependence on fragment mass.

1. R.K. Choudhury, S.S. Kapoor, D.M. Nadkarni and P.N. Rama Rao, Nucl. Instr. & Meth. 164, 323 (1979).

I.13 A Simple Statistical Model for Prompt Mass Distribution in Fission

Hareshit Majumdar
Saha Institute of Nuclear Physics
Calcutta 700009

and

Aparesh Chatterjee
Physics Department, Calcutta University
Calcutta 700 009.

A structure-sensitive statistical saddle-scission point model (SSP) has been developed and utilised to study the prompt mass distributions. This model specifically takes into account the effects of structure fluctuations and deformations and the influence of excitation on these factors. A phase-space analysis for the fission decay process is carried out assuming the principle of detailed balance. Utilising a recently studied deformation dependent interaction potential[1] acting between two complex nuclei for barrier penetrability calculation, we have represented the fragment yield by a product of three quantities: the product level density of the conjugate fragments, the barrier penetrability and the fragment charge yield probability. Fragment excitations and the total kinetic energies have been evaluated from SSP model. The statistical level density parameters, with excitation dependence, are taken from our recent study. Predictions for $^{235}U\ (n_{th},f)$, $^{239}Pu(n_{th},f)$ and $^{252}Cf(s.f)$ agree well with the experimental data.

1. H. Majumdar and A. Chatterjee, Lett.Al Nuovo Cim. 26, 519 (1979).

I.14 Mass and Charge Distribution in Quasi-Fission Reactions.

M. Rajasekaran and V. Devanathan
Department of Nuclear Physics
University of Madras, Madras 600 025.

The mass and charge distribution in quasi-fission reactions have been obtained using nuclear level density calculations which have already been successfully employed to obtain the mass distribution in the fissioning of heavy nuclei. The theoretical yield curves compare well with experimental ones. The phenomena of sequential fission and ternary fission have also been dealt with. Some of the systems for which the mass yield have been calculated are $^{84}Kr + ^{238}U$, $^{40}Ar + ^{238}U$, $^{84}Kr + ^{209}Bi$ and $^{129}Xe + ^{197}Au$.

I.15 Mass-and Charge-Yield Distributions of $^{258}104$

R. Aroumougame and Raj K. Gupta
Physics Department, Panjab University
Chandigarh 160014.

Element 104 has been of large experimental interest recently. It is found that whereas $^{50}Ti + ^{208}Pb$ give measurable fusion cross-sections, $^{84}Kr + ^{174}Er$ give rise to a completely new phenomenon of projectile - like fragments. In this paper, we present our calculations for both ~~the~~ mass - and charge-yield distributions of $^{258}104$ using the fragmentation theory. Our preliminary calculations show that the yield of $^{50}Ti + ^{208}Pb$ products is much larger compared to that for $^{84}Kr + ^{174}Er$ products.

I.16 Polar Emission in the Neutron Induced Fission of 235U.

A.K. Sinha, M.M. Sharma, S.C.L.Sharma,
G.K. Mehta, I.I.T. Kanpur and
D.M. Nadkarni, B.A.R.C.
Bombay.

Experimental data on Polar-Emission in light-charged-particle (LCP) accompanied fission is very limited and entirely confined to thermal neutron fission. A new geometry has been used consisting of two ionization chambers with collimators in between to measure simultaneously the equatorial and the polar particles emitted in the fission process. A semiconductor ΔE-E detector telescope is used for particle identification. The polar and equatorial particle emission is studied for ^{235}U fission at 500 keV neutron energy and thermal energy. The ratio of polar to equatorial yield shows a significant increase in the fast neutron fission as compared to that in the thermal neutron fission.

II. NEUTRON CROSS-SECTIONS

II.1 Calculation of σ (n,xn), x = 2,3,4 taking into account Pre-equilibrium emission for medium and heavy nuclei upto 28 MeV:

R.P. Anand, M.L. Jhingan*, S.K. Gupta and M.K. Mehta,
Nuclear Physics Division, Bhabha Atomic Research Centre,
Bombay 400085.
* Member of T.I.F.R., Colaba, Bombay 400005.

INTRODUCTION: In our previous[1] calculations of (n,2n) and (n,3n) cross-sections all non-equilibrium effects were presumed to be accounted by an empirical factor. The calculations for ^{232}Th and ^{238}U agreed well upto 15 MeV while at higher energies it deviated significantly and systematically from the experimental data due to the inadequacy of the empirical factor. In the present work we have overcome this shortcoming by considering the pre-equilibrium effects in the emission of first particle. Subsequent particle emissions are calculated according to the statistical model only. Emission of protons is also considered but only in the pre-equilibrium part.

METHOD: The general expression for (n,xn) cross-section may be written as

$$\sigma(n,xn) = \sigma_M \int_0^{L_1} P_1(\epsilon_1) \int_0^{L_2} P_2(\epsilon_1,\epsilon_2) \cdots \int_0^{L_{x-1}} P_{x-1}(\epsilon_1,\epsilon_2 \cdots \epsilon_{x-1}) \int_0^{L_x} (1-P_x)\, d\epsilon_1 d\epsilon_2 \cdots d\epsilon_x \qquad (1)$$

For nonfissile nuclei $\sigma_M = \sigma_R(E_n)$ and for fissile nuclei $\sigma_M = \{\sigma_R(E_n) - \sigma_f(E_n)\}$. $P_1(\epsilon_1)$ is the probability that the first particle is emitted with energy between ϵ_1 and $(\epsilon_1 + d\epsilon_1)$ and is given by

$$P_1(\epsilon_1) = \left\{ \frac{df_{P.E.}(\epsilon_1)}{d\epsilon_1} + (1-\delta) \frac{\epsilon_1 . \sigma_{inv}(\epsilon_1) . \rho_1(E_n-\epsilon_1)}{\int_0^{E_n} \epsilon_1 . \sigma_{inv}(\epsilon_1)\, \rho_1(E_n-\epsilon_1)\, d\epsilon_1} \right\} \qquad (2)$$

here the first term is due to pre-equilibrium and is given by

$$\frac{df_{P.E.}(\epsilon_1)}{d\epsilon_1} = \frac{(2s+1).m.\epsilon_1.\sigma_{inv}(\epsilon_1)}{2\pi\, \hbar^2 . |M|^2 . g^4 . E^3} \times \sum_{n=3}^{\bar{n}} \left(\frac{U}{E}\right)^{n-2} . (n+1)^2 . (n-1) . Q_b \qquad (3)$$

where the symbols have the usual meaning. $g = A/13$ MeV^{-1}. $\sigma_{inv}(\epsilon_i)$ are taken from reaction cross-sections based on Wilmore-Hodgson optical potential. The squared Matrix element $|M|^2$ is adopted from Kalbach[2)] where it is given as a function of excitation energy per exciton, (E/n).

The second term in eq.(2) represents the equilibrium part. $\mathcal{E}$ represents the total pre-equilibrium component. After the emission of first neutron, the second one is emitted with an energy between ϵ_2 and $(\epsilon_2 + d\epsilon_2)$ with a probability $P_2(\epsilon_1, \epsilon_2)\, d\epsilon_2$ and similarly for subsequent neutrons.

The level density at energy E is given as $\rho(E) \sim \exp(2\sqrt{aE})$ where 'a' is the Pearlstein level density parameter[3)] and it is lower by a factor of 2.7 for each nucleus from that of Gilbert and Cameron[4)]. The effect of neglecting gamma emission, particularly near the threshold, is compensated by using the apparent level density parameter given by Pearlstein. A computer code has been developed for (n,xn), $x = 2,3,4$ cross-sections. Calculations have been performed using this code from threshold to 28 MeV for 13 nuclei viz. ^{89}Y, ^{90}Zr, ^{93}Nb, ^{103}Rh, ^{107}Ag, ^{151}Eu, ^{169}Tm, ^{175}Lu, ^{181}Ta, ^{191}Ir, ^{197}Au, ^{203}Tl and ^{209}Bi. For two fissionable nuclei ^{232}Th and ^{238}U the cross-sections are calculated upto 20 MeV. The values of $|M|^2$ given in ref.2) were increased twofold to obtain a satisfactory agreement with the measured data. The calculations agree well with the recent measurements within 10-15%.

Conclusion : The effect of pre-equilibrium emission plays an important role to calculate (n,xn) cross-sections above 15 MeV. A further application of this work will be in predicting reliably (n,xn) cross-sections for unstable nuclei where measurements are not possible.

References:

1) M.L. Jhingan, R.P. Anand, S.K. Gupta and M.K. Mehta, Int. Conf. on Neut. Phys. and Neut. Data, Harwell, 1049 (1978).
2) Kalbach, Z. Physik A 287, 319 (1978).
3) S. Pearlstein, Nucl. Sci. Engg. 23, 238 (1965).
4) A. Gilbert and A.G.W. Cameron, Can. J. Phys. 34, 804 (1965).

II.2 Displacement Cross Section

C.P. Reddy and S.M. Lee
Reactor Research Centre, Kalpakkam 603 102
Tamil Nadu.

Radiation damage is one of the major considerations in the design of any component which resides in the radiation field. In order to assess the radiation damage, we require displacement cross sections. There are various models to calculate displacement cross sections. We have chosen Torrens-Robinson-Norgett[1] (TRN) model to calculate damage energy crosssection given by

$$\sigma_{i,\,damage} = \int_{T_d}^{T_{max}} \frac{d\sigma_i}{dT}(E,T)\, T_{damage}\, dT \qquad (1)$$

where

$\sigma_{i,\,damage}(E)$ = The damage energy cross section as a function of neutron energy E for the ith reaction type.

$\frac{d\sigma_i(E,T)}{dT}$ = The heavy-ion primary recoil spectrum for the reaction type as a function of recoil energy T of the neutrons of energy E.

T_{damage} = That fraction of the energy T which will produce further nuclear displacements and

T_d = The effective threshold energy.

We have taken only the elastic scattering cross section into account as this is the major contributor. We also assumed that elastic 25 group cross sections are isotropic. The 25 group cross sections are taken from SETR-version 2 cross section set. The values generated by us agree quite well with the other published values. The details are given in Ref.2.

REFERENCES

1. M.J.Norgett, M.T. Robinson and I.M.Torrens, AERE Harwell Reactor TP494, Oak Ridge National Laboratory Report 55D 72-70 and Centre d' Etudes Nucleaire desaclay Report CEA - R4380.
2. C.P. Reddy, and S.M. Lee, Contribution to the Workshop on Nuclear Data Evaluation, Processing and Testing, August 4-5, 1981 RRC, Kalpakkam.

II.3 A STATISTICAL-PREEQUILIBRIUM MODEL BASED ANALYSIS OF (n, 2n) AND (n, 3n) CROSS-SECTIONS OF ^{232}Th AND ^{238}U*

by

Amar Sinha & S.B. Garg
Bhabha Atomic Research Centre
Trombay, Bombay - 400 085

An analysis has been carried out of (n, 2n) and (n, 3n) cross-sections of ^{232}Th and ^{238}U in the energy range 9.0 MeV to 20.0 MeV using the framework of preequilibrium and statistical models. Charged particle emission in these nuclides has been ignored since it will be minimal due to coulomb potential barrier. The interaction matrix constant and the energy shift factors have been evaluated to reproduce closely the measured [1] and calculated (n, 2n) cross-sections. In these analyses the inverse cross-sections have been calculated through a rigorous search of optical model parameters; the nonelastic cross-section has been obtained by taking into account the direct collective inelastic scattering and shape elastic cross-sections via deformed optical model; the effect of spin forbiddenness and competition between γ-ray and neutron emission processes near the reaction thresholds has been approximately accounted by including the energy shift factors; and the recommended level density parameters and pairing energy corrections of target and residual nuclei have been used. The mathematical model [2,3,4] and the extracted parameters can be adopted for the prediction of these cross-sections in the actinide region.

* Paper Communicated for publication to the Journal of Atomkernenergie.

References

1. H. Karius et. al. ; J. Phys. G : Nucl. Phys. 5, 715 (1979).
2. I. Kumabe et. al. ; J. Nucl. Sci. Technol. 14, 319 (1977).
3. J.J. Griffin ; Phys. Rev. Lett. 17, 478 (1966).
4. M. Blann ; Phys. Rev. Lett. 21, 3157 (1968).

II.4 OPTICAL MODEL POTENTIAL FOR ^{232}Th FOR NEUTRON INTERACTION*

by

Amar Sinha and S.B. Garg
Bhabha Atomic Research Centre
Trombay, Bombay - 400 085

Energy dependence of the local optical model potential has been determined for ^{232}Th by correctly reproducing the measured neutron total, elastic and differential elastic scattering cross-sections. Level width fluctuation corrections have been applied in the low energy region. The evaluated potential parameters have been used to yield the discrete and continuum level excitation, elastic and inelastic cross-sections upto 20 MeV.

* Paper presented at Nucl. Phys. & Solid St. Phys. Symp, IIT, Delhi (1980)

II.5 COUPLED CHANNEL CALCULATIONS OF NEUTRON REACTION CROSS-SECTIONS FOR ^{238}U*

by

S.B. Garg and Amar Sinha
Bhabha Atomic Research Centre
Trombay, Bombay - 400 085

Coupled channel calculations have been performed for the elastic, inelastic, level excitation and total cross-sections for ^{238}U using the non-adiabatic and adiabatic models of deformed target nucleus in the low energy range extending upto 2.5 MeV. Angular distributions of the scattered neutrons have also been evaluated by coupling the excited levels of the ground state rotational band. This work has been completed to meet the requirements of an International Nuclear Model Code Comparison Project sponsored by the NEA Data Committee vide its specification report NEANDC-128U.

* Paper communicated to NEA Data Bank, France.

II.6 (n,p) and (n, α) Cross Sections in Some Zinc and Selenium Isotopes at 14 MeV.

C.V. Srinivasa Rao, N.Lakshmana Das,
B.V. Thirumala Rao and J. Rama Rao,
Laboratories for Nuclear Research,
Andhra University, Waltair,
Visakhapatnam - 530 003.

A survey of the literature indicated some lacunae in the reported (n,p) and (n, α) cross sections at 14 MeV in some Zinc and Selenium isotopes. These have been measured using mixed powder technique and high resolution Ge(Li) detection. The cross sections measured are: Zn-66(n,p) Cu-66, Zn-68 (n,p) Cu-68, Se-78 (n, α) Ge-75 and Se-80 (n, α) Se-77m. The neutron irradiations were carried out at the 600 keV Cockcroft-Walton accelerator of Andhra University. The experimental cross sections are compared with the theoretical estimates.

II.7 Study of (n, α) Reactions in keV Region.

C.V. Srinivasa Rao, H.M. Agrawal and S.C.L. Sharma,
Department of Physics, Indian Institute of
Technology, Kanpur-208016.

The direct charged particle counting technique is being used for the study of (n, α)reaction cross sections in the neutron energy region from thermal to 1 MeV for few high Z elements.

The ^{6}Li (n, α)^{3}H reaction is studied simultaneously with the reaction of interest to provide relative cross-sections. The Li sample is placed at a distance of about 5.5cm from the centre of the neutron target and at about 2 mm from a silicon surface barrier detector facing the sample. The sample makes an angle of 30° with the proton beam direction. The samples of interest are also placed in an exactly identical geometry. The charged particle spectra are recorded simulteneously in both the channels. The spectrum from ^{6}Li is found to be consistent with that reported in the literature. Measurement on (n, α) reaction cross sections for ^{197}Au is in progress and that on 90, 91, 92, 94$_{Zr}$ isotopes will be attempted later.

II.8 (N,α) Reactions in the Preequilibrium Model.

S. Ray
Kalyani University
Kalyani, West Bengal

and

G. Keeni, A. De and S.K. Ghosh
Saha Institute of Nuclear Physics
Calcutta.

In the analysis of (N,α) reactions in the framework of preequilibrium model, two different approaches are followed. In the first the α-particle is assumed to be preformed in the target nucleus and in the second it is assumed that two neutrons and two protons coalesce to form an α-particle in the excited target+projectile composite nucleus. Both the preformation and coalescence probabilities are introduced as multiplicative factors in the preequilibrium cross-section expression and their values are obtained phenomenologically by fitting with emitted spectra and angular distributions. We abandon this phenomenological approach and calculate the α-preformation probability in the target nucleus as the overlap of the wave functions of the parent and α + daughter nucleus assuming that two neutrons and two protons in the outermost shell of the target nucleus combine to form an α-particle. In the reaction process the momentum of the incident nucleon is shared between the α-particle and the daughter nucleus (parent - α) leading to the observed excitation of the residual nucleus and the angular distribution of the emitted α-particle.

II.9 Optical Model Analysis of Neutron Scattering at 7 MeV.

U. Satyanarayana and S. Ramamurthy
Laboratories for Nuclear Research, Andhra University, Waltair-530 003.

The available experimental data on 7 MeV neutron elastic scattering from chromium, iron, zirconium, tin, tantalum, bismuth, thorium and uranium are analysed using optical model formalism. The χ^2 per point is 12.8. The parameters are given fully as also the comparison of the experiment and theory. Isospin dependence is put into both real and imaginary parts and a spin-orbit potential is also included in the analysis. The potential is

$$V = V_0\left[1+\exp\left(\frac{r-R_0}{a_0}\right)\right]^{-1} - \alpha V_1\left[1+\exp\left(\frac{r-R_1}{a_1}\right)\right]^{-1}$$
$$+ 4a_{0I}\, i W_0 \frac{d}{dr}\left[1+\exp\left(\frac{r-R_{0I}}{a_{0I}}\right)\right]^{-1} - 4a_{1I}\, i W_1 \alpha \frac{d}{dr}\left[1+\exp\left(\frac{r-R_{1I}}{a_{1I}}\right)\right]^{-1}$$
$$+ V_{SO}\, \vec{\sigma}\cdot\vec{l}\left(\frac{\hbar}{m_\pi c}\right)\frac{d}{r\,dr}\left[1+\exp\left(\frac{r-R_0}{a_0}\right)\right]^{-1}$$

The parameters are:-

V_0 = 52.49 MeV	R_0' = 1.205 fm	a_0 = 0.608 fm
V_1 = 21.96 MeV	R_1' = 1.115 fm	a_1 = 0.769 fm
W_0 = 8.59 MeV	R_{0I}' = 1.15 fm	a_{0I} = 0.712 fm
W_1 = 12.12 MeV	R_{1I}' = 1.31 fm	a_{1I} = 0.56 fm

with R_0', R_1', R_{0I}', R_{1I}' nuclear unit radii in the corresponding potentials.

II.10 A Global Optical Potential for 14 MeV Neutrons.

S.K. Gupta and K.H.N. Murthy*
Nuclear Physics Division
Bhabha Atomic Research Centre, Bombay 400085.

Experimental values of total, angle-integrated elastic and reaction cross-sections for 14 MeV neutrons over the periodic chart are compared systematically with the predictions of the available global optical potentials in literature. All the potentials are found rather unsatisfactory. We propose a new potential which describes the data well. This potential has been obtained by modifying the Wilmore-Hodgson potential.

*CSIR Junior Research Fellow, Mysore University.

III. HALF LIFE MEASUREMENTS

III.1 HALF-LIFE OF ^{243}Am

S.K. Aggarwal, A.R. Parab and H.C. Jain

Radiochemistry Division,
Bhabha Atomic Research Centre, Trombay, Bombay-400 085, India

The half-life of ^{243}Am was determined by the relative activity method. Synthetic mixtures were prepared by using solutions of ^{241}Am and ^{243}Am isotopes. The alpha activity ratios and the atom ratios in these mixtures was kept close to unity by employing the double dilution technique so that these could be measured with high precision and accuracy.

Reference:

III.2 HALF-LIFE OF ^{233}U

S.K. Aggarwal, S.N. Acharya and H.C. Jain,

Radiochemistry Division,
Bhabha Atomic Research Centre, Trombay, Bombay-400 085, India

The half-life of ^{233}U was determined by specific activity method. The number of ^{233}U atoms was determined by isotope dilution mass spectrometry while the alpha disintegration rate was obtained by liquid scintillation counting as well as by alpha proportional counting. The radiochemical purity of ^{233}U was checked by alpha spectrometry. A value of $(1.5885 \pm 0.0075) \times 10^5$ y was obtained for the half-life of ^{233}U. The uncertainty given is a combination of one standard deviation on the average value and the error evaluated from estimates on various error components.

III.3 HALF-LIFE OF ^{238}Pu

S.K. Aggarwal, A.V. Jadhav, S.A. Chitambar, K. Raghuraman, S.N. Acharya, A.R. Parab, C.K. Sivaramakrishnan and H.C. Jain

Radiochemistry Division,
Bhabha Atomic Research Centre, Trombay, Bombay-400 085, India

The half-life of ^{238}Pu has been determined by the relative activity method taking ^{238}Pu as a reference isotope. Five synthetic mixtures were prepared by using solutions of ^{238}Pu and ^{239}Pu isotopes. The alpha activity ratios and the atom ratios in these mixtures were kept close to unity so that these could be measured with high precision and accuracy.

Reference:

1. Radiochem. Radioanal. Letters (In press).

III.4 HALF-LIFE OF ^{241}Pu

S.K. Aggarwal, S.N. Acharya, A.R. Parab and H.C. Jain

Radiochemistry Division,
Bhabha Atomic Research Centre, Trombay, Bombay-400 085, India

The expertise developed in the fields of mass spectrometry and alpha spectrometry have been utilised in the determination of half-life of ^{241}Pu by different methods.

(i) Studying the ingrowth of ^{241}Am by alpha spectrometry on a synthetic mixture prepared by mixing different isotopes of plutonium.(1)

(ii) Studying the ingrowth of ^{241}Am in two independent sets of experiments: (a) by alpha spectrometry taking ^{242}Pu as well as ^{239}Pu and ^{240}Pu as reference isotopes, and (b) by alpha proportional counting. Synthetic mixtures of different plutonium isotopes were prepared.[2]

(iii) Studying the ingrowth of ^{241}Am using isotope dilution alpha spectrometry and employing ^{243}Am as a spike. The isotope dilution alpha spectrometry technique was developed in this laboratory for various other important applications.[3]

A summary of all the methods and the present status of the half-life of ^{241}Pu was presented at the DAE Nuclear Chemistry and Radiochemistry Symposium, Waltair, February, 1980 and Nuclear Physics and Solid State Physics Symposium, Delhi, December, 1980 respectively.

References:

1. Phys. Rev., C21, 2033 (1980).

2. Phys. Rev., C23, 1748 (1981).

3. Radiochemica Acta. (In Press).

IV. GENERATION OF MULTIGROUP NEUTRON CROSS-SECTIONS

IV.1 Generation of Protoactinium-233 Multigroup Neutron Cross-sections

P. Mohanakrishnan
Theoretical Reactor Physics Section
Bhabha Atomic Research Centre
Bombay - 400 085.

Protoactinium-233(^{233}Pa) is an important isotope in thorium fuel cycle studies as it connects ^{232}Th neutron capture to ^{233}U production. Any neutron absorption in ^{233}Pa, which otherwise decays to ^{233}U with a half life of 27.4 days, will result in loss of fissile material production. For example, it has been found that in the Light Water Breeder Reactor fuelled with thorium containing ^{233}U operating at Shipping Port Atomic Power Station, the reactivity worth of equilibrium ^{233}Pa at full power is as much as 2.5 %[1].

Following data for ^{233}Pa neutron cross-sections was obtained from ENDF/B-V files at IAEA[2] by request:- (i) Resolved resonance parameters valid in the energy range $1X10^{-3}$eV to 38.5 eV, (ii) Unresolved resonance parameters valid in the energy range 38.5eV to $1X10^{4}$eV, (iii) Point data for neutron cross-sections above $1X10^{4}$eV.

Existing programs SIGRESS[3] and UNREST[4] were modified for generating multigroup cross-sections using this data. Programs SIGRESS and UNREST were combined to form one program RESSIG which can generate multigroup cross-sections from both resolved and unresolved resonance parameters. It is possible to consider negative energy resonances in the resolved energy region in RESSIG. Further, in the unresolved resonance region, it is possible to consider higher 'l' value resonances with different level spacings and respective J values. It is assumed that resonance partial widths are distributed according to Porter-Thomas distribution having degree of freedom unity.

Fission, absorption, ν -fission, total and scattering cross-sections were generated in 69 neutron energy groups covering the energy range 0 to 10MeV using RESSIG and the above data. They have also been condensed to a smaller 27 group structure using a fuel spectrum suitable for heavy water moderated reactors.

<u>References</u> :

1. Freeman L.B. and Hecker H.C. - Reactivity worth of ^{233}Pa inferred from measurements Trans. of Am. Nucl. Soc, <u>34</u>, 763 (1980).

2. Letter of DayDay No., Nuclear Data Section, IAEA, Vienna, July (1980).

3. Menon S.V.G., Private Communication TRPS, BARC (1981).

4. Huria H.C., Private Communication TRPS, BARC (1981).

IV.2 RAMBHA - Processing Code for Generation of Multigroup Cross Section Set for Fast Reactor Calculations Using RRC Data File (RRCDF).

S. Ganesan, V. Gopalakrishnan, M.L. Sharma, P.B. Rao, R. Vaidyanathan, M.M. Ramanadhan and R. Shankar Singh, Reactor Research Centre, Kalpakkam 603 102, Tamil Nadu.

The nuclear data processing code RAMBHA has been completed and the major modules doing the various functions of cross-section processing (see fig.1.3.1 of Ref.1) have been successfully commissioned individually. Integrated one shot generation of the complete set of multigroup cross sections has been completed for typical fissile, fertile and structural isotopes. There was scope for further improvements which were identified during trial runs for ^{232}Th, Ni, Fe, ^{230}Th and ^{231}Pa. Some of these are mentioned below. These have been implemented(2).

1. The module XSAVG which calculates the group cross sections from point data has been extended to use different specified interpolation schemes.
2. The addition of background cross sections (floor corrections) to both infinite dilution as well as self shielded group cross sections (for subsequent evaluation of self shielding factors has been introduced).
3. Proper calculation of transport cross sections in all the energy regions has been incorporated.
4. Provisions were made to write out the output data in the format required by the LCAT module, which prepares the cross sections in SETR format.
5. Modifications to take into account isotopewise resonance data given in ENDF/B file for some materials have been made.

The format for RRC DF has also been evolved in this process. Calculations to perform our integral testing and validation of the generated multigroup cross section set by calculation of fast reactor benchmarks will be reported in Ref.3.

REFERENCES

1. R. Shankar Singh et al. Page 5, Activity Report of Reactor Physics Section for 1979, RRC (1980).

2. S. Ganesan et al. Page 16, Activity Report of Reactor Physics Section for 1980 (1981).

3. S. Ganesan et al, in Workshop on Nuclear Data Evaluation, Processing and Testing August 4.5, 1981, RRC, Kalpakkam.

IV.3 27 GROUP CROSS-SECTIONS OF Mo AND Pb

by

S.B. Garg
Bhabha Atomic Research Centre
Trombay, Bombay - 400 085

In our series of generating 27-group cross-sections and scattering matrices for the reactor elements [1,2,3,4], we have included Mo and Pb using their basic cross-section data from ENDF/B library. Molybdenum is invariably present in the structural material and lead is used in shields and currently also finds usage in the fusion blankets as a neutron multiplying agent due to its (n, 2n) reaction.

References

1. S.B. Garg ; A 27-Group Cross-Section Set Derived from ENDF/B Library, INDC(IND)-21/G + SP.(1977) and BARC-892.

2. S.B. Garg ; ENDF/B Based 27-Group Cross-Sections for some Rare Earth and Concrete Elements, INDC(IND)-25/GV (1979) and BARC-1000.

3. S.B. Garg & V.K. Shukla ; Multigroup P_8 - Elastic Scattering Matrices of Main Reactor Elements, BARC-1001 (1979).

4. S.B. Garg ; Multigroup Resonance Self-Shielding Factors and Cross-Sections of Main Reactor Elements, BARC-1002 (1979).

IV.4 (n, 2n) GROUP SCATTERING MATRICES FOR ^{9}Be

by

S.B. Garg
Bhabha Atomic Research Centre
Trombay, Bombay - 400 085

Beryllium has a low energy threshold for (n, 2n) reaction and is suitable as a neutron multiplier in fusion blankets. Recently a pseudo-energy level structure consisting of 33 levels of its (n, 2n) cross-section data has been given by Young and Stewart [1]. In order to study the effect of the modified cross-section data on the neutronics of fusion blankets we have re-generated 27-group cross-sections and scattering matrices for ^{9}Be.

1. P.G. Young and L. Stewart ; Evaluated Data For n + ^{9}Be Reactions; LA-7932-MS (ENDF-283) (1979).

V. EVALUATIONS OF CROSS-SECTIONS

V.1 EVALUATION OF ^{231}Pa NEUTRON CROSS-SECTIONS

by

V.K. Shukla & S.B. Garg
Bhabha Atomic Research Centre
Trombay, Bombay - 400 085

Using the optical model parameters extracted for ^{233}Pa total, elastic, inelastic and level excitation cross-sections have been calculated for ^{231}Pa in the energy range 1.0 MeV to 20.0 MeV. The recently measured [1] fission cross-sections and the evaluated (n,2n) and (n, 3n) cross-sections have been taken into account in the calculation of compound elastic and level excitation cross-sections. This work has been done under an IAEA Co-ordinated Research Programme on the Intercomparison of Actinide Neutron Nuclear Data.

Reference

1. S. Plattard et.al. ; High Resolution Fission Cross-Section of ^{231}Pa, Intern. Conf. Nucl. Cross. Techn. Knoxville, U.S.A., Oct. 1979.

V.2 EVALUATION OF ^{232}U NEUTRON CROSS-SECTIONS

by

S.B. Garg & Amar Sinha
Bhabha Atomic Research Centre
Trombay, Bombay - 400 085

Coupled channel and spherical optical model based studies have been carried out for ^{232}U to obtain the total, elastic, inelastic and level excitation neutron cross-sections in the energy range 1.0 MeV to 20.0 MeV. The (n, 2n) and (n, 3n) cross-sections have been computed using the statistical-preequilibrium exciton models. This work has been done under an IAEA Co-ordinated Research Programme on the Intercomparison of Actinide Neutron Nuclear Data.

V.3 EVALUATION OF ^{233}Pa NEUTRON CROSS-SECTIONS

by

Amar Sinha & S.B. Garg
Bhabha Atomic Research Centre
Trombay, Bombay - 400 085

The spherical optical model parameters have been extracted for ^{233}Pa by fitting its total cross-section in the energy range 1.0 MeV to 15.0 MeV. Using these parameters elastic, inelastic and level excitation cross-sections have been evaluated in the energy range 1.0 MeV to 20.0 MeV. Cross-sections of (n, 2n) and (n, 3n) reactions have been obtained by using the combined statistical pre-equilibrium exciton models. This evaluation has been carried out under the IAEA Co-ordinated Research Programme on the Intercomparison of Actinide Neutron Nuclear Data.

V.4 NEUTRON INDUCED REACTION CROSS-SECTIONS OF ^{59}Co*

by

S.B. Garg, V.K. Shukla and Amar Sinha
Bhabha Atomic Research Centre
Trombay, Bombay - 400 085

Total, elastic, inelastic, (n,p), (n,α), (n, d), (n, ^3He), (n, 2n), (n, np), (n, nt), (n, pn), (n, 2p) and (n,γ) cross-sections have been evaluated for ^{59}Co in the energy range 0.5 MeV to 20.0 MeV using the multistep Hauser-Feshbach statistical theory by taking into account the level width fluctuations and continuum level excitations. Precompound neutron, proton and α -emissions have been evaluated with Griffin's exciton model and the giant dipole-radiation model of Brink and Axel has been employed to generate the (n,γ) cross-sections. This work has been completed to meet the requirements of an International Nuclear Model Code Comparison Project sponsored by the NEA Data Bank Committee vide its specification report NEANDC-130U.

* Paper communicated to NEA Data Bank, France.

V.5 Evaluation of Resonance Parameters in Resolved and Unresolved Resonance Region for ^{233}U.

S. Ganesan and M.L. Sharma
Reactor Research Centre, Kalpakkam 603 102
Tamil Nadu.

The single level Breit Wigner resonance parameters are evaluated for ^{233}U in the resolved resonance region starting from the area analysis data reported by Nizamuddin and Blons(1). Consistent values of the neutron width Γ_n and the statistical spin factor g were deduced for 136 well resolved levels. For the case of 33 'artificial' broad levels which were added in the vicinity of some of the highly asymmetric resonances(1), an iteration procedure based on well known conservation relations was employed to deduce acceptable values of Γ_n and fission width Γ_f . The complete set Γ_n, Γ_γ, Γ_f, E_0 and g are given in ref.2 for 142 levels which occur in the energy region 0 - 100 eV.

In the unresolved resonance region, the unresolved parameters are, to some extent nonunique, the nonuniqueness arising from the choice among the mean resonance data sets; all such sets leading to the same average cross sections within their quoted uncertainties(3,4).

The statistical mean resonance parameters for ^{233}U in the unresolved resonance region are evaluated by simultaneous and consistent adjustment of mean fission width and p and s wave strength functions. Our evaluated mean resonance parameters reproduce the total cross sections within 3 to 5% on the average.

It was found that the nuclear radius given in ENDF/B-IV file was so small that the p and s wave strength functions were required to be adjusted much beyond their spread reported in the literature. The scattering cross sections also could not be satisfactorily fitted using this value of the nuclear radius. We found after some parametric studies using ADDJA Code[5] that a value of R = 0.9 fm is acceptable. Ref.2 gives the selected set of unresolved parameters. The symbols have their usual meanings[5]. The calculated mean cross sections from ENDF/B-IV files and those using our parameters agree well (see ref.2).

It was pointed out in Ref.4 that in the ENDF/B-V evaluation, the unresolved resonance parameters for ^{232}Th are extracted by a fit to the capture cross sections. This procedure followed in ENDF/B-V evaluation of the unresolved resonance parameters for ^{232}Th (Ref.6 and Ref.7) does not guarantee the correct reproduction of total cross sections.

REFERENCES

1. A. Nizamuddin and J. Blons, Nucl. Sci. Eng., 54, 116 (1974).
2. S. Ganesan and M.L. Sharma, Evaluation of Resonance Parameters in Resolved and Unresolved Resonance Region for ^{233}U, RRC-43 (1980).
3. S. Ganesan, Nucl. Sci. Eng. 74, 49 (1980).
4. S. Ganesan, Evaluation of Statistical Resonance Parameters for ^{232}Th in 4 to 41 keV Energy Region, INDC (INDC)-26/GJ (1980) IAEA, Vienna and RRC-42 (1980).
5. S. Ganesan, Atomkernenergie, 29, 14 (1977).
6. M.R. Bhat, Summary Documentation for ^{232}Th, in R. Kinsey (Ed) ENDF-201 (1979).
7. G. Desaussure and R.L. Macklin, Evaluation of the ^{232}Th Neutron Capture Cross Section above 3 keV, ORNL TM-6161, (ENDF-255) (1977).

V.6 Generation and Evaluation of the Pseudo Fission Product Cross Section Set.

M.L. Sharma
Reactor Research Centre,
Kalpakkam 603 102
Tamil Nadu.

Zero dimensional burnup calculations have been performed[1] to obtain the time dependent concentrations of individual fission product nuclides in a reactor having average properties similar to those of SNR-300. With these concentrations as weights pseudo fission product cross sections for the two fissile (^{235}U, ^{239}Pu) and a fertile (^{238}U) nuclide are generated by processing the evaluated fission product cross section data of the Australian library. The effect of fission yields on the concentrations of individual fission product nuclides is studied in some detail. Constants derived are compared with the corresponding results based on some other recent and old evaluations. The reliability of the multigroup fission product cross sections generated by us is assessed by correlating computed values against the integral measurements performed at the STEK facility by RCN, Petten, the Netherlands. The integral parameter chosen is the capture reactivity worth of three mixed fission product samples in four different neutron spectra.

REFERENCES

1. M.L. Sharma, Generation and Evaluation of the Pseudo Fission Product Cross Section Set, RRC-FRG/RP-206 (1980).
2. J.L. Cook Fission Product Cross Sections, AAEC-TM-549 (1969).

V.7 Evaluation of 14MeV Neutron Cross Sections for Fe^{56}, Ca^{40}, K^{39}, Cl^{35}, S^{32} & P^{31}.

K.K. Manocha*, R.S. Khanchi** and
R.K. Mohindra
Physics Department, Univ., Kurukshetra-132119.

All possible interaction cross sections of Fe^{56}, Ca^{40}, K^{39}, Cl^{35}, S^{32} and P^{31} with 14 MeV neutrons have been computed using the compound nucleus formalism with optical potential parameters. The reactions of the type (n,n'), (n,2n), (n,np), (n,na); (n,p), (n,pn), (n,pp), (n,pa); (n,a), (n,an), (n,ap) have been considered and their cross sections evaluated. For Fe^{56}, computations are at 14.8 MeV and for other isotopes at 14.1MeV neutron energy for comparison with experimental cross-sections. The level density parameter of Lang and Le Couteur which has been found better earlier[1,2], has only been used here. The agreement with experimental cross sections is reasonable for most of the above cross-sections but few cross sections disagree by an order of magnitude. No theoretical framework has been so far found able to predict all such cross-sections consistantly correct.

1. Wadhwa and Mohindra, J.Nucl.Science & Engg.56 (1975) 96
2. Wadhwa, Manocha and Mohindra, In.J.Pure & App.Phys.12 (1974) 645

*Medical College, Rohtak. **Dyal Singh College, Karnal.

V.8 Prediction of fission yield data and its evaluation

D.N. Sharma, P.P. Chakraborty, M.R. Iyer and A.K. Ganguly

Health Physics Division
Bhabha Atomic Research Centre
Trombay, Bombay - 400 085

The order-disorder model (ODM) developed earlier, forms basis to predict mass and total elemental yields of fragments in spontaneous fission of various nuclides as well as for predicting independent yields in higher energy fission. In case of spontaneous fission the only input required is the stable neutron number as a function of charge number. For prediction of independent yields in higher energy fission, experimental data on fission product mass yields are also needed. The mass and total elemental yields for spantaneous fission obtained exhibit all the qualitative characteristics viz, peak to valley ratio, bunching of higher mass/charge peaks etc. The absolute values have some discrepancy with experimental values though an improvement in the right direction has been noticed by using later data on nuclear stability. The predicted values on independent yields and cumulative yields for higher energy fission of U-235 are in reasonable agreement with the few experimental values available.

The experimental data on fission product mass yields and charge distribution parameters compiled by Meek and Rider have been evaluated by checking the equality of yields for complementary charges which is a necessary condition in the fission process. The evaluation criterion is valid even for data on products because charge of the fragment remains unchanged in prompt neutron evaporation. The evaluation shows that the data on fast and 14.0 MeV neutron induced fission are not as consistent as for thermal fission.

REFERENCES:

(i) Change distribution, Neutron evaporation and Energy distribution in high energy fission
D.N. Sharma, M.R. Iyer and A.K. Ganguly
Phys. Rev. C 14, 181 (1976)

(ii) Asymmetry of Mass and Charge division in spontaneous Fission
P.P. Chakraborthy, D.N. Sharma, M.R. Iyer and A.K. Ganguly
Pramana, Vol. 13, No. 5, Nov. 1979.

VI. OTHER NUCLEAR DATA ACTIVITIES

VI.1 Analysis of Fast Critical Assemblies in Support of Criticality Predictions for FBR 500.

S. Ganesan and R. Venkatesan
Reactor Research Centre, Kalpakkam 603 102
Tamil Nadu.

Calculation of multiplication factors was made for six fast systems as a followup of a previous study[1]. The assemblies[2-5] studied were having characteristics ranging from small to very large sizes, VERA-11A, VERA-1B, BAKER MODEL, SNEAK-9C2/POZ, ZPPR-5A and the 1200 MWe IAEA/NEACRP benchmark. The details are given in Ref.6. Following conclusions have been drawn:

1. The earlier diffusion calculation by Sharma et al[1] and the present calculation have established that with the Cadarache set available with us the predictional capability of K_{eff} of assemblies with normal Pu or U fuel is satisfactory and the uncertainty is around 0.5 to 1% for sizes in the range 100 to 4000 litres.
2. For cores fuelled with high ^{240}Pu such as case 4 there is an under prediction. This tendency leads to a recommendation that the higher Pu isotopes need updating in the Cadarache set available at RRC, though the discrepancy is not too alarming.
3. In the case of NEACRP benchmark, the differences between one set and the adjusted UK and the recent French sets (CARNAVAL-III) are thought to be mainly due to discrepency in the cross sections of structural elements. In Baker model, such a difference is not present as structural

materials are much less in that case.

4. Our prediction for ZPPR-5A is very good. This corresponds to the size of a 500 MWe, Oxide fuelled LMFBR core.

Additional assemblies with carbide cores have been identified for which analysis will be taken up in future when inhouse computer becomes available. A detailed comparison study of all aspects of case 6 will also be taken up at that time. Detailed analysis of some already identified ZPPR assemblies involving a higher Pu content in Pu-U fuelled system as well as those involving ^{232}Th - ^{233}U fuel will also be made. The full details of the present study are documented in Ref.6.

REFERENCES

1. M.L. Sharma, V. Gopalakrishnan and R. Shankar Singh, Analysis of Selected Fast Critical Assemblies, RRC-23 (1977)

2. R.W. Hardie et al., Nucl. Sci. Eng., 57, 222 (1975)

3. A.I. Voropaev et al., Comparison calculations of standard fast reactors INDC (CCP)-125/LV, IAEA Nuclear Data Section, Vienna (1978)

4. L.G. LeSage et al., Proceedings of the NEACRP/IAEA Specialists Meeting on the International comparison calculation of a Large Sodium-cooled Fast Breeder Reactor at ANL on Feb.7-9,1978: ANL-80-78 (1980)

5. W. Scholtyssek et al., Physics Investigations of Sodium-Cooled Fast Reactors; SNEAK - Assembly 9C, KfK-2361 (1977)

6. S. Ganesan and R. Venkatesan, Analysis of Fast Critical Assemblies in Support of Criticality Predictions for FBR-500, RRC-FRG/RP-209 (1980)

VI.2 **Evaluation of Thermal Reactor Cross-sections through Integral Measurements**

H.C. Huria, P.D. Krishnani, H.K. Bhatia, P. Mohanakrishnan and B.P. Rastogi
Theoretical Reactor Physics Section
Bhabha Atomic Research Centre
Bombay - 400 085.

Abstract

Integral measurements of various types provide valuable data to assess the adequacy of the cross-sections used in predicting the nuclear characteristics of reactors. In this context measurements of reactivity, relative reaction rates and neutron balance assume fundamental importance. The lattice physics calculational model of TRPS uses the 69-group WIMS library or its collapsed versions, for light water and heavy water moderated systems. The library has been generated using the fundamental nuclear data from UKNDL and weighting spectra typical of thermal reactors.

The accuracy of the physical formulation of the model which uses interface currents has been established by comparisons with results from more sophisticated approaches and also with Monte Carlo calculations. A broad spectrum of experimental data was selected to evaluate the adequacy of the cross-sections used in the code. The selected experiments include natural uranium, enriched uranium, 233U - enriched and plutonium oxide fuelled lattices in D_2O and H_2O moderator, and they cover a wide range of parameters. The analyses included not only reactivity prediction, but also compassion of measured

and calculated reaction rate ratios. Internationally recommended benchmarks for thermal reactors have also been extensively analysed. The observed discrepancies did lead to modifications in some areas of basic nuclear data for fissile and fertile materials. However, the work with regard to the suspected uncertainties in the data for moderating materials is in progress.

VI.3 Studies on Neutron Width Statistics for ^{232}Th below 500 eV.

S. Ganesan
Reactor Research Centre, Kalpakkam 603 102
Tamil Nadu.

Attempts were made to find the possible reasons for the 'ν discrepancy' for ^{232}Th below 500 eV. Rahn et al[1] have experimentally observed a clear departure from Porter-Thomas[2] distribution (PTD) with $\nu = 1$. Though the $\Gamma_n^{(c)}$ values follow a PTD when resonances beyond 500 eV are covered, a peak of $\nu = 2.7$ occurs below 500 eV. The number of degrees of freedom, ν in PTD is the number of channels open for the decay of compound nucleus by the process to be described by the particular partial level width under consideration. Since below 1keV only s waves contribute significantly, the total angular momentum of the neutron leaving the compound nucleus can only be $j = 1/2$ and thus there is only one channel leading to $\nu = 1$.

We found that the calculated value of ν is quite sensitive to the method of estimation employed. This appears to make the discrepancy less strong. The moments method gives a value of $\nu = 2.7$ when resonance in the range 0.0 to 380.0 eV are taken into account. For the same energy region the method of maximum likelihood without accounting for finite sample size gives $\nu = 1.71$.

When the finiteness of the sample size is accounted for a higher value $\nu = 2.24$ is obtained. The calculated variance as a function of energy fluctuates between 0.3 and 0.03.

The various reasons that can, in a combined manner account for the discrepancy in ν for ^{232}Th below 500 eV are: 1. Missing of levels with small $\Gamma_n^{(o)}$ values. 2. Possible presence of a systematic error leading to overestimation of $\Gamma_n^{(o)}$ values and 3. Misassignment of ℓ values. It is easy to show that assigning a large p wave resonance as s wave or a small s wave as p wave can lead to effective errors 1 and 2 cited above thereby leading to a higher observed ν. The present investigations however indicate that none of these reasons can, taken alone explain the ν discrepancy. Finally though the validity of PTD is itself well established it will be important from nuclear structure point of view to theoretically investigate the possibility of some nuclei obeying a non PTD in some high energy regions. As a remark, a value of unity for ν for ^{232}Th is used in the unresolved resonance region calculations[5]. The results of the present calculations were discussed in Ref.4 in detail.

REFERENCES

1. F. Rahn et al, Phys. Rev. 60, 1854 (1972).
2. C.E. Porter and R.G. Thomas, Phy. Rev. 104, 483 (1956).
3. B.E. Clancy, J.L. Cook and E.K. Rose, The Effect of Missing levels on the observed channels open in Neutron Fission, Australia, AAEC/E444/(1978).
4. S. Ganesan, Paper presented at Nucl. Phys. & Solid State Phys. Symp. held at IIT, Delhi during Dec.11-15, 1980.
5. S. Ganesan, Evaluation of Statistical Resonance Parameters for ^{232}Th in 4 to 41 keV Energy Region, INDC (IND)-26/GJ, Vienna and RRC-42 (Kalpakkam) (1980).

VI.4 DETERMINATION OF GAMMA RAY ENERGIES AND ABUNDANCES OF ^{229}Th

S.S. Rattan, A.V.R. Reddy, V.S. Mallapurkar, R.J. Singh,
Satya Prakash and M.V. Ramaniah

Radiochemistry Division,
Bhabha Atomic Research Centre, Trombay, Bombay-400 085, India

Gamma energies in the alpha decay of ^{229}Th were precisely determined using a 2 c.c. Ge detector (Resolution 600 eV at 122 KeV) coupled to a 4096 channel analyser. Absolute abundances of these gamma rays were also determined. A modified energy level diagram for ^{225}Ra was proposed using these results. Twenty one new gamma rays were observed in the present investigations, whereas 16 gamma rays earlier reported(1) could not be observed. Present results along with literature data(1) for ^{229}Th are given in Table 1.

Reference:

1. K.S. Toth, Nucl. Data Sheets 24, 263 (1978).

TABLE 1. GAMMA RAY ABUNDANCES OF ^{229}Th.

Present: Energy in KeV	Present: % Abundance	Reported (Ref.1): Energy in KeV	Reported (Ref.1): % Abundance
12.33 ± 0.04*	5.960 ± 0.536	11.1 ± .1	-
14.81 ± 0.02*	9.381 ± 0.781		
15.25 ± 0.02*	42.480 ± 1.592		
17.82 ± 0.02*	17.033 ± 0.772	17.36 ± .03	0.16
18.31 ± 0.03*	4.068 ± 0.403		
		25.39 ± 0.02	0.035
28.50 ± 0.14	0.117 ± 0.024		
31.13 ± 0.03	0.896 ± 0.080	30.30 ± .10	-
31.53 ± 0.04	1.692 ± 0.085	31.30 ± .20	4.0
		37.80 ± .10	-
42.63 ± 0.02	0.188 ± 0.010	42.76 ± .03	0.16
43.96 ± 0.02	0.604 ± 0.020		
53.84 ± 0.09	0.017 ± 0.003	53.20 ± .10	-
56.50 ± 0.03	0.246 ± 0.006	56.60 ± 0.03	0.32
68.05 ± 0.08	0.052 ± 0.014	68.18 ± 0.07	0.10
68.80 ± 0.07	0.060 ± 0.013	68.90 ± 0.04	0.11
75.10 ± 0.05	0.420 ± 0.043	75.20 ± 0.07	0.51
		75.30 ± 0.10	
85.43 ± 0.04*	9.820 ± 0.017		
86.35 ± 0.04	2.732 ± 0.074	86.30 ± 0.10	0.37
		86.44 ± 0.05	3.0
88.48 ± 0.04*	16.681 ± 0.251	88.48	
94.72 ± 0.02	0.232 ± 0.006		
99.47 ± 0.02*	2.245 ± 0.070		
100.18 ± 0.02*	3.927 ± 0.086		
102.99 ± 0.02*	1.443 ± 0.046		
103.71 ± 0.03	0.451 ± 0.035		
107.15 ± 0.02	0.656 ± 0.009	107.17 ± 0.05	0.82
109.21 ± 0.06	0.023 ± 0.004		
110.38 ± 0.03	0.107 ± 0.004		
118.21 ± 0.09	0.015 ± 0.005		
120.16 ± 0.08	0.017 ± 0.003		
123.19 ± 0.03	0.120 ± 0.004		
124.59 ± 0.02	1.040 ± 0.012	124.50 ± 0.10	1.2
		124.70 ± 0.10	0.6
126.76 ± 0.09	0.013 ± 0.004		
		131.97 ± 0.05	0.32
		132.60 ± 0.10	
134.33 ± 0.08	0.015 ± 0.003	134.80 ± 0.10	
		135.71 ± 0.07	
136.99 ± 0.03	0.904 ± 0.018	137.03 ± 0.06	1.6
		140.30 ± 0.20	

Present		Reported (Ref. 1)	
Energy in KeV	% Abundance	Energy in KeV	% Abundance
142.97 ± 0.03	0.314 ± 0.006	142.95 ± 0.10	0.42
147.66 ± 0.03	0.163 ± 0.014	147.80 ± 0.10	
148.17 ± 0.03	0.708 ± 0.017		
149.91 ± 0.04	0.042 ± 0.003	150.20 ± 0.30	
		151.60 ± 0.30	
154.37 ± 0.02	0.612 ± 0.012	154.40 ± 0.70	0.65
156.41 ± 0.02	0.972 ± 0.018	156.48 ± 0.04	1.1
158.42 ± 0.04	0.034 ± 0.003	158.50 ± 0.07	
160.48 ± 0.56	0.005 ± 0.003	161.60 ± 0.30	
		165.70 ± 0.30	
167.14 ± 0.04	0.113 ± 0.010		
171.59 ± 0.07	0.020 ± 0.005		
172.91 ± 0.04	0.093 ± 0.006	172.90 ± 0.10	0.22
179.75 ± 0.03	0.176 ± 0.005	179.80 ± 0.20	0.50
183.95 ± 0.03	0.118 ± 0.006	184.00 ± 0.10	0.23
		190.20 ± 0.20	
193.53 ± 0.02	3.769 ± 0.075	193.63 ± 0.06	4.5
200.81 ± 0.03	0.066 ± 0.005		
204.70 ± 0.02	0.495 ± 0.012	204.90 ± 0.30	
210.31 ± 0.05	0.210 ± 0.033		
210.90 ± 0.05	2.467 ± 0.063	210.97 ± 0.10	3.2
215.16 ± 0.08	0.146 ± 0.016		
218.15 ± 0.04	0.149 ± 0.037	218.10 ± 0.20	0.14
221.31 ± 0.09	0.022 ± 0.003		
225.25 ± 0.06	0.048 ± 0.004		
236.31 ± 0.06	0.158 ± 0.028	236.20 ± 0.20	0.035
242.61 ± 0.07	0.065 ± 0.007	242.60 ± 0.30	
		243.50 ± 0.30	
252.49 ± 0.05	0.089 ± 0.005		
259.15 ± 0.05	0.033 ± 0.011		
		261.00 ± 0.50	
		290.00 ± 0.50	

*X-rays of Radium.