KfK 3220
Dezember 1981

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Numerical Results of a (2E,2v)-Measurement for Fast Neutron Induced Fission of ^{235}U and ^{237}Np

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Kernforschungszentrum Karlsruhe GmbH
ISSN 0303-4003

ABSTRACT

Numerical results obtained from measurements of fragment properties in fast neutron induced fission of ^{235}U and ^{237}Np are given in tabular form together with figures and a short description of the experiment. A detailed presentation of experiment and data analysis and the discussion of the results is in preparation.

Numerische Ergebnisse einer (2E,2v)-Messung für die Spaltung von ^{235}U und ^{237}Np mit schnellen Neutronen

ZUSAMMENFASSUNG

Die Ergebnisse einer Messung der Fragmenteigenschaften bei der Spaltung von ^{235}U und ^{237}Np mit schnellen Neutronen werden zusammen mit einer Kurzbeschreibung des Experiments in Tabellen und Abbildungen dargestellt. Eine ausführliche Darstellung des Experiments und der Datenanalyse sowie eine Diskussion der Ergebnisse ist in Vorbereitung.

This report summarizes the results of measurements which were carried out in collaboration between KfK and the University of Tübingen with the aim to obtain information on the scission point configuration by investigating the characteristic properties of the fission fragments. To this end we have measured the kinetic energies and velocities of correlated fragments from fission induced by fast neutrons of well defined energy. Neutrons as projectiles have the advantage that not much angular momentum is transferred which keeps the situation simple and that a direct comparison can be made to existing measurements with thermal neutrons. The latter is important as it illustrates how the scission configuration is influenced by the excitation energy of the nucleus at the saddle point.

Our measurements were carried out on ^{235}U and ^{237}Np. The even-even fissioning system (^{235}U+n) is best investigated at thermal energies (1,2,3,4) and additional information at higher neutron energies, that means, at higher excitation energies were highly desirable. (^{237}Np+n) is of interest because it is the neighbouring odd-odd system. So, a comparative study may reveal the influence of pairing effects.

Neutron energies of 0.50 and 5.55 MeV where chosen for ^{235}U and for ^{237}Np we used 0.80 and 5.55 MeV. The higher energy was just below the threshold for second chance fission and represents the highest possible excitation for a well defined compound system. The lower energies were selected to differ sufficiently from thermal energies and also with respect to a maximum neutron yield. In case of ^{237}Np the lower energy was slightly higher than for ^{235}U because of the fission threshold at 0.7 MeV. If one considers the respective fission barrier, these neutron energies correspond to the following excitation energies at the saddle point: E_{exc} = 1.3 and 6.3 MeV for (^{235}U+n) and 0.1 and 4.8 MeV for (^{237}Np+n).

A schematic view of the experimental set-up is shown in Fig. 1. Neutrons are produced by the $^{7}Li(p,n)$ and the $^{2}H(d,n)$-reactions. The charged particle beam from the Karlsruhe 3 MV Van de Graaff accelerator was pulsed to about 500 ps and therefore the beam pick-up signals could be used directly for the velocity determination of the fragments instead of a time zero detector. The samples were 100 $\mu g/cm^2$ thick layers of UO_2 and NpO_2 evaporated on 30 $\mu g/cm^2$ thick carbon backings. Sample masses and isotopic compositions are given in Table I. Large area surface barrier detectors (which were calibrated by ^{252}Cf sources once a day) were used for fragment detection. Various shutters in the flight tubes shielded the detectors from fragments scattered from the walls. Typical fission rates were about 100 s^{-1}. For investigation of systematic uncertainties and for the determination of the time zero point t_o in the time-of-flight spectra, measurements were performed at four different fragment flight paths. Fission events were recorded in list mode on magnetic tape and simultaneously control spectra were accumulated in an on-line computer.

The calibration scheme of Schmitt et al. (5) was used to convert the detector pulse height signals to kinetic energies. However, a correction to the calibration constants given in Ref. (5) was necessary because the original ones lead to severe discrepancies of 2 MeV compared to the corresponding energies determined from fragment velocities. In the analysis also corrections for neutron momentum, fragment energy losses in the sample, resolution effects, geometric effects and flight path dependent distortions were considered.

The mean values of fragment properties and the related variances are important parameters which allow for a systematic comparison between data taken at different excitation energies and with different techniques. The mean values derived for ($^{235}U+n$) and ($^{237}Np+n$) are given in Tables II and III, respectively.

The quoted uncertainties are only due to statistics. In addition, the following systematic uncertainties have to be included in the determination of the overall uncertainties. The primary fragment masses and the total kinetic energy are derived from the fragment velocities. In evaluating the fragment velocities a systematic uncertainty of $\sim$20 ps in the time-of-flight is caused to about equal amounts by uncertainties in the calibration of the time scale and in the definition of t_o. Flight path uncertainties of 0.15 mm are negligible for the longer flight paths but contribute significantly to the velocity uncertainty at 70 mm. Hence, typical systematic uncertainties for the long flight path are 0.07 % and 0.05 % for the velocities of the light and heavy fragments. Propagation of these uncertainties leads to uncertainties of 0.09 % in TKE*, 0.06 % in A^*_L and 0.04 % in A^*_H. The uncertainties of the secondary kinetic energies $E_{1,2}$ can be estimated from the calibration scheme of Schmitt et al. (5), assuming a negligible effect of the corrections to the calibration procedure. This might be justified because of their normalization to experimental values of $\bar{\nu}$ and $d\nu/dA$. Then uncertainties of 0.25 and 0.35 channels in the peak positions P_1 and P_2 of the ^{252}Cf calibration spectrum lead to uncertainties of 0.2 MeV in E_1 and E_2. As all these systematic uncertainties are identical for all measurements, they can be neglected if our results for different neutron energies or for ^{235}U and ^{237}Np are compared mutually.

The following tables IV to IX summarize the distributions of fragment mass P(A*), fragment total kinetic energy TKE(A*) and the average number of fission neutrons emitted per fragment ν(A*). All distributions are given with respect to primary fragment masses A* before neutron evaporation. The mass intervals in all tables are 0.5 amu for which the analysis was carried out. One must be aware, however, that the mass resolution in the experiment was limited to 2.1 amu. Therefore, the figures show the distributions in mass intervals of 1 amu. The uncertainties quoted in tables IV to IX are statistical uncertainties only. For the total kinetic energy and for ν(A*) also the variances are included. However, $\sigma_{\nu(A*)}$ is dominated by the mass resolution and is therefore only of limited value.

ACKNOWLEDGEMENTS

We would like to thank Dr. H.J. Maier from the University of Munich for the excellent sample preparation and Dr. F. Dickmann for helpful and stimulating discussions. We are grateful to Prof. G. Schatz and to Prof. F. Gönnenwein for their interest and support.

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Table I Sample masses and isotopic compositions

Mass (µg)	Isotopic Composition (at.%)					
	^{234}U	^{235}U	^{236}U	^{238}U		
150	0.168	99.505	0.027	0.300		
	^{237}Np	^{238}Pu	^{239}Pu	^{240}Pu	U	Th
150	99.52	<0.081	<0.015	<0.002	<0.1	<0.02

Table II Mean values of fragment properties for fission of ^{235}U at 0.50 and 5.55 MeV neutron energy. The quoted uncertainties are of statistical nature, total uncertainties are included in brackets.

neutron energy (MeV)		0.50 ± 0.08	5.55 ± 0.25
excitation energy at the saddle point (MeV)		1.3	6.3
primary fragment mass (amu)	A^*_L	96.44 ± 0.03 (± 0.07)	97.11 ± 0.09
variance (amu)	σ_{A^*}	5.49 ± 0.02 (± 0.05)	6.37 ± 0.06
secondary fragment masses (amu)	A_L	95.00 ± 0.05 a)	95.63 ± 0.10
	σ_{A_L}	5.33 ± 0.025	6.14 ± 0.07
	A_H	138.54 ± 0.05 a)	137.18 ± 0.11
	σ_{A_H}	5.12 ± 0.025	5.96 ± 0.07
fragment velocities (cm/ns)	v_L	1.4201 ± 0.0007	1.4089 ± 0.0011
	v_H	0.9813 ± 0.0007	0.9856 ± 0.0014
	σ_{v_L}	0.0518 ± 0.0004 (± 0.0005)	0.0676 ± 0.0009
variances (cm/ns)	σ_{v_H}	0.0698 ± 0.0003 (± 0.0005)	0.0740 ± 0.0006
	$r_{v_L v_H}$	-0.561 ± 0.006 (± 0.008)	-0.622 ± 0.009
total kinetic energy (MeV)	TKE*(2E)	170.35 ± 0.05 b)	169.42 ± 0.07 b)
	TKE*(2v)	170.40 ± 0.15 (± 0.25)	169.55 ± 0.22
variance (MeV)	σ_{TKE^*}	10.05 ± 0.03 (± 0.05)	9.98 ± 0.03
	$\langle\sigma_{TKE^*};A^*\rangle$	7.60 ± 0.03 (± 0.06)	8.57 ± 0.04
	$\langle\frac{dTKE^*}{dA^*}\rangle\ (\frac{MeV}{amu})$	1.20 ± 0.01 (± 0.03)	0.80 ± 0.02

Table II (continued)

number of neutrons emitted per fragment	ν_L	1.44 ± 0.08[a]	1.48 ± 0.05
	ν_H	1.02 ± 0.08[a]	1.71 ± 0.07
	$\frac{d\nu_L}{dA^*}$ (amu^{-1})	0.039 ± 0.006[a]	0.046 ± 0.006
	$\frac{d\nu_H}{dA^*}$ (amu^{-1})	0.079 ± 0.006[a]	0.074 ± 0.006
	$\langle\frac{d\nu_T}{\delta TKE}\rangle$ (A*) (MeV^{-1})	-0.131 ± 0.01 (± 0.015)	-0.135 ± 0.010
peak-to-valley ratio in P(A*)	P/V	450 ± 70	30 ± 2
gradients with excitation energy	$\frac{\Delta TKE^*}{\Delta E_n}$	-0.180 ± 0.006	
	$\frac{\Delta\nu_L}{\Delta E_n}$ (MeV^{-1})	0.010 ± 0.02	
	$\frac{\Delta\nu_H}{\Delta E_n}$ (MeV^{-1})	0.14 ± 0.02	

a) results of this work combined with radiochemical data. The respective uncertainties include the normalization

b) adjusted to TKE* (2v) via energy calibration scheme.

Table III Mean values of fragment properties for fission of ^{237}Np at 0.8 and 5.55 MeV neutron energy. The quoted uncertainties are of statistical nature.

neutron energy (MeV)		0.80 ± 0.05	5.55 ± 0.25
excitation energy at the saddle point (MeV)		0.1	4.8
primary fragment mass (amu)	A_L^*	98.66 ± 0.06	99.12 ± 0.05
variance (amu)	σ_{A^*}	5.80 ± 0.05	6.59 ± 0.05
secondary fragment masses (amu)	A_L	97.07 ± 0.06[a)]	97.53 ± 0.06
	σ_{A_L}	5.60 ± 0.07	6.33 ± 0.07
	A_H	138.21 ± 0.06[a)]	137.01 ± 0.06
	σ_{A_H}	5.59 ± 0.07	6.36 ± 0.09
fragment velocities (cm/ns)	v_L	1.3997 ± 0.0013	1.3893 ± 0.0013
	v_H	0.9874 ± 0.0010	0.9877 ± 0.0009
variances	σ_{v_L}	0.0591 ± 0.0009	0.0738 ± 0.0008
	σ_{v_H}	0.0742 ± 0.0007	0.0782 ± 0.0006
total kinetic energy (MeV)	TKE*(2E)	175.050 ± 0.12[b)]	172.422 ± 0.12[b)]
	TKE*(2v)	174.803 ± 0.37	173.532 ± 0.35
	σ_{TKE^*}	10.385 ± 0.09	10.432 ± 0.08
number of neutrons emitted per fragment	ν_L	1.59[a)]	1.59 ± 0.08
	ν_H	1.14[a)]	1.87 ± 0.08
	$\frac{d\nu_L}{dA^*}$ (amu^{-1})	0.046 ± 0.005	0.048 ± 0.005
	$\frac{d\nu_H}{dA^*}$ (amu^{-1})	0.046 ± 0.007	0.043 ± 0.008
peak-to-valley-ratio in P(A*)	P/V	670 ± 125	31 ± 3
gradients with excitation energy	$\frac{\Delta TKE^*}{\Delta E_n}$	-0.559 ± 0.	
	$\frac{\Delta\nu_L}{E_n}$ (MeV^{-1})	0.0 ± 0.08	
	$\frac{\Delta\nu_H}{\Delta E_n}$ (MeV^{-1})	0.155 ± 0.08	

a) results of this work combined with radiochemical data. The respective uncertainties include the normalization.

b) adjusted to TKE*(2v) via energy calibration scheme.

Table IV The primary fragment mass yield P(A*) in fast neutron induced fission of ^{235}U

	EN=0.5 MEV	EN=5.5 MEV
MASS	MASS YIELD(%)	MASS YIELD(%)
118.0	0.017	0.251
118.5	0.019	0.156
119.0	0.007	0.297
119.5	0.015	0.167
120.0	0.023	0.125
120.5	0.023	0.201
121.0	0.008	0.280
121.5	0.005	0.309
122.0	0.024	0.151
122.5	0.048	0.289
123.0	0.008	0.205
123.5	0.037	0.281
124.0	0.036	0.428
124.5	0.052	0.292
125.0	0.011	0.192
125.5	0.063	0.322
126.0	0.054	0.345
126.5	0.0	0.473
127.0	0.213	0.842
127.5	0.269	1.047
128.0	0.541	1.672
128.5	0.752	1.382
129.0	1.251	2.092
129.5	1.673	1.958
130.0	2.083	2.952
130.5	2.471	2.976
131.0	2.896	3.223
131.5	3.368	3.898
132.0	4.107	4.290
132.5	4.721	5.480
133.0	5.881	5.189
133.5	5.741	5.668
134.0	6.119	4.898
134.5	6.177	5.631
135.0	5.773	5.786
135.5	5.793	6.064
136.0	5.912	5.835
136.5	5.694	6.239
137.0	5.984	5.860
137.5	6.232	5.041
138.0	6.469	6.205
138.5	6.579	5.612
139.0	6.327	5.950
139.5	6.720	6.177
140.0	6.431	5.763
140.5	5.882	6.306
141.0	5.596	5.498
141.5	5.482	5.261
142.0	5.687	4.429
142.5	5.344	5.190

Table IV, continued

143.0	5.590	4.830
143.5	5.103	4.074
144.0	5.656	4.040
144.5	5.137	3.018
145.0	5.143	3.397
145.5	4.712	4.311
146.0	3.741	4.116
146.5	2.810	2.911
147.0	2.462	2.214
147.5	2.442	2.024
148.0	2.151	1.942
148.5	1.629	2.122
149.0	1.468	2.090
149.5	1.410	1.276
150.0	1.330	1.380
150.5	1.052	0.903
151.0	0.886	1.097
151.5	0.644	0.630
152.0	0.401	0.845
152.5	0.315	0.593
153.0	0.219	0.798
153.5	0.266	0.401
154.0	0.200	0.269
154.5	0.153	0.276
155.0	0.132	0.337
155.5	0.109	0.255
156.0	0.088	0.329
156.5	0.043	0.162
157.0	0.023	0.064
157.5	0.011	0.047
158.0	0.005	0.045
158.5	0.013	0.0
159.0	0.009	0.0
159.5	0.014	0.0
160.0	0.014	0.023
160.5	0.0	0.0
161.0	0.0	0.0
161.5	0.0	0.0
162.0	0.0	0.0
162.5	0.0	0.0
	TOTAL EVENTS 59779.	TOTAL EVENTS 12652.

Table V Primary fragment mass yield P(A*) in fast neutron induced fission of ^{237}Np

MASS	EN=0.8 MEV MASS YIELD(%)	EN=5.5 MEV MASS YIELD(%)
119.0	0.0	0.293
119.5	0.015	0.220
120.0	0.015	0.168
120.5	0.0	0.199
121.0	0.015	0.188
121.5	0.0	0.157
122.0	0.015	0.241
122.5	0.030	0.262
123.0	0.045	0.220
123.5	0.030	0.335
124.0	0.061	0.345
124.5	0.076	0.429
125.0	0.076	0.544
125.5	0.167	0.618
126.0	0.197	0.775
126.5	0.455	1.026
127.0	0.409	1.183
127.5	0.742	1.591
128.0	1.197	1.581
128.5	1.379	1.916
129.0	1.652	2.481
129.5	2.182	2.921
130.0	2.561	3.109
130.5	3.167	3.319
131.0	3.788	4.094
131.5	4.470	4.491
132.0	4.712	4.439
132.5	5.500	4.889
133.0	5.682	5.350
133.5	6.273	5.245
134.0	6.136	5.737
134.5	6.652	6.188
135.0	6.394	5.968
135.5	5.955	5.873
136.0	6.364	5.832
136.5	6.485	5.748
137.0	6.348	6.051
137.5	5.818	6.428
138.0	6.182	5.978
138.5	6.121	5.800
139.0	5.318	5.434
139.5	5.530	5.497
140.0	6.197	5.360
140.5	5.682	4.973
141.0	5.576	4.795
141.5	5.727	5.088
142.0	5.348	4.732
142.5	5.091	4.460
143.0	5.121	3.884
143.5	4.197	3.947

Table V, continued

144.0	3.742	3.727
144.5	4.197	3.424
145.0	3.439	3.267
145.5	3.182	3.172
146.0	3.470	2.670
146.5	2.894	2.523
147.0	2.621	2.429
147.5	2.197	2.471
148.0	1.894	1.989
148.5	1.576	1.591
149.0	1.227	1.707
149.5	1.121	1.298
150.0	1.121	1.026
150.5	0.848	1.194
151.0	0.909	1.036
151.5	0.939	0.995
152.0	0.606	0.701
152.5	0.652	0.743
153.0	0.439	0.607
153.5	0.409	0.544
154.0	0.273	0.387
154.5	0.182	0.377
155.0	0.152	0.272
155.5	0.242	0.220
156.0	0.121	0.241
156.5	0.076	0.251
157.0	0.136	0.178
157.5	0.106	0.063
158.0	0.045	0.115
158.5	0.0	0.126
159.0	0.015	0.063
159.5	0.0	0.063
160.0	0.0	0.042
160.5	0.0	0.021
161.0	0.0	0.052
161.5	0.015	0.0
162.0	0.0	0.0
162.5	0.0	0.0
	TOTAL EVENTS 13200.	TOTAL EVENTS 19103.

Table VI The total kinetic energy TKE(A*) in fast neutron induced fission of ^{235}U. The statistical uncertainty and the variance σ_{TKE} are also included(all values in MeV).

MASS	EN=0.5 MEV			EN=5.5 MEV		
	TKE(A)	ERROR	SIG.TKE	TKE(A)	ERROR	SIG.TKE
118.0	146.30	2.62	8.10	160.30	1.66	9.46
118.5	156.20	3.19	11.29	159.80	1.96	8.41
119.0	174.60	4.76	10.41	156.70	1.45	8.71
119.5	171.20	3.11	8.66	160.80	1.75	8.48
120.0	161.80	2.15	7.98	158.00	2.49	9.82
120.5	168.80	1.95	7.84	159.80	1.99	10.25
121.0	167.30	3.48	7.12	161.80	1.67	10.11
121.5	158.20	5.37	9.28	162.90	1.32	8.04
122.0	169.50	3.16	12.22	156.50	1.51	6.59
122.5	166.70	2.17	12.12	161.20	1.35	8.39
123.0	171.50	6.09	10.53	171.00	2.18	11.23
123.5	169.40	1.99	9.21	160.40	1.96	12.60
124.0	176.30	1.84	8.90	165.90	1.55	11.99
124.5	169.90	2.34	10.72	163.20	1.99	11.72
125.0	168.30	0.19	8.80	169.60	2.21	11.00
125.5	172.70	1.83	10.13	167.70	1.87	11.49
126.0	173.00	1.80	9.94	170.30	1.56	10.53
126.5	171.40	0.11	10.81	173.10	1.40	10.36
127.0	176.00	1.03	11.23	171.00	1.09	10.36
127.5	178.10	0.76	9.89	175.60	0.88	10.19
128.0	180.10	0.60	10.78	175.90	0.76	10.79
128.5	180.70	0.42	9.10	174.50	0.82	10.68
129.0	182.50	0.32	8.69	177.50	0.63	10.05
129.5	182.10	0.30	9.61	178.30	0.63	10.17
130.0	182.90	0.26	9.13	179.10	0.51	10.02
130.5	181.70	0.23	8.85	180.40	0.53	10.39
131.0	181.30	0.20	8.25	178.70	0.49	10.07
131.5	180.90	0.19	8.44	177.40	0.44	9.94
132.0	180.60	0.17	8.16	178.30	0.35	8.16
132.5	179.60	0.17	9.00	177.00	0.34	8.91
133.0	179.20	0.16	9.33	177.00	0.34	8.86
133.5	178.60	0.14	8.43	176.60	0.33	8.74
134.0	178.30	0.14	8.51	176.80	0.36	8.88
134.5	177.60	0.13	7.92	177.00	0.29	7.81
135.0	176.90	0.14	8.15	175.60	0.29	7.84
135.5	175.40	0.14	8.04	173.70	0.27	7.33
136.0	174.10	0.13	7.98	172.10	0.34	9.00
136.5	173.80	0.13	7.37	173.70	0.29	7.96
137.0	172.70	0.13	7.52	172.60	0.32	8.50
137.5	172.50	0.12	7.39	171.30	0.33	8.08
138.0	171.70	0.12	7.28	170.30	0.27	7.65
138.5	171.20	0.11	7.19	170.20	0.28	7.70
139.0	170.90	0.12	7.32	170.80	0.23	6.51
139.5	169.90	0.12	7.40	169.80	0.24	6.98
140.0	169.20	0.12	7.23	169.50	0.26	7.01
140.5	168.70	0.12	6.88	169.30	0.26	7.31
141.0	168.20	0.11	6.32	167.60	0.28	7.48
141.5	167.50	0.11	6.45	166.80	0.29	7.36
142.0	166.70	0.11	6.43	165.40	0.30	6.83
142.5	165.70	0.12	6.82	165.90	0.25	6.53

Table VI, continued

143.0	165.80	0.11	6.41	164.70	0.28	6.79
143.5	165.00	0.12	6.58	164.40	0.30	6.48
144.0	164.90	0.11	6.44	164.70	0.30	6.90
144.5	164.70	0.12	6.68	165.20	0.32	6.35
145.0	164.40	0.11	6.29	164.80	0.28	5.59
145.5	164.30	0.13	6.78	162.20	0.22	5.39
146.0	162.80	0.14	6.64	162.20	0.29	6.85
146.5	161.50	0.16	6.49	161.40	0.43	7.74
147.0	160.90	0.18	6.54	162.10	0.46	7.84
147.5	160.70	0.15	5.74	161.40	0.50	8.23
148.0	160.30	0.16	5.87	161.00	0.37	5.45
148.5	159.10	0.22	6.59	160.90	0.44	7.28
149.0	158.80	0.24	6.83	160.40	0.39	6.32
149.5	158.80	0.23	6.80	158.90	0.61	7.20
150.0	159.00	0.22	6.10	159.20	0.53	6.86
150.5	158.60	0.24	6.03	156.80	0.65	7.43
151.0	157.60	0.25	5.74	156.20	0.60	7.08
151.5	156.60	0.31	6.03	155.70	0.76	7.02
152.0	155.50	0.33	5.23	158.00	0.70	6.90
152.5	155.80	0.47	6.50	158.90	0.71	6.62
153.0	156.40	0.69	7.39	157.10	0.73	7.56
153.5	154.60	0.56	7.04	155.60	0.82	5.48
154.0	155.10	0.57	6.16	156.00	1.20	6.90
154.5	155.20	0.51	4.57	156.70	1.21	7.06
155.0	155.80	0.75	6.39	154.20	1.43	9.28
155.5	152.40	0.92	7.69	155.10	1.04	6.40
156.0	151.40	1.10	8.27	153.20	1.16	8.00
156.5	151.80	0.98	4.91	165.10	0.0	0.0
157.0	152.90	1.25	4.82	154.40	2.48	6.89
157.5	147.80	0.82	2.45	151.70	2.13	4.96
158.0	143.70	4.33	7.48	153.10	4.73	12.93
158.5	148.00	1.90	5.30	0.0	0.33	0.0
159.0	146.30	1.64	3.11	0.0	0.32	0.0
159.5	146.80	0.0	0.0	0.0	0.33	0.0
160.0	140.40	0.67	1.87	167.50	0.0	0.0
160.5	0.0	0.41	0.0	0.0	0.53	0.0
161.0	0.0	0.50	0.0	0.0	0.52	0.0
161.5	0.0	0.58	0.0	149.50	0.64	0.0
162.0	0.0	0.63	0.0	0.0	0.46	0.0
162.5	142.50	1.16	0.0	0.0	1.39	0.0

Table VII The total kinetic energy TKE(A*) in fast neutron induced fission of ^{237}Np as a function of primary fragment mass A*

	EN=0.8 MEV			EN=5.5 MEV		
MASS	TKE(A)	ERROR	SIG.TKE	TKE(A)	ERROR	SIG.TKE
119.0	0.0	0.0	0.0	164.07	1.34	10.05
119.5	163.16	0.0	0.0	162.80	1.36	8.78
120.0	146.53	0.0	0.0	165.76	1.40	7.93
120.5	0.0	0.0	0.0	168.16	1.49	9.18
121.0	165.53	0.0	0.0	169.65	1.47	8.81
121.5	0.0	0.0	0.0	164.55	2.37	12.97
122.0	177.35	0.0	0.0	167.08	1.85	12.55
122.5	181.51	3.30	6.61	174.33	1.45	10.25
123.0	172.48	3.96	9.69	165.89	1.32	8.54
123.5	187.31	3.19	6.38	167.47	1.25	9.98
124.0	171.42	5.21	14.73	171.09	1.56	12.65
124.5	177.55	3.87	12.23	175.24	0.87	7.86
125.0	180.13	2.52	7.96	173.49	0.94	9.63
125.5	177.59	1.95	9.15	174.65	0.97	10.49
126.0	183.39	1.32	6.74	174.70	0.98	11.89
126.5	179.86	1.18	9.17	176.15	0.73	10.19
127.0	180.57	1.31	9.61	176.81	0.69	10.45
127.5	183.97	0.98	9.74	177.30	0.61	10.63
128.0	184.37	0.65	8.17	179.20	0.56	9.81
128.5	182.72	0.67	8.97	178.40	0.56	10.68
129.0	182.42	0.58	8.51	179.75	0.48	10.48
129.5	184.02	0.56	9.48	179.31	0.44	10.50
130.0	184.46	0.46	8.54	180.09	0.41	10.01
130.5	183.74	0.41	8.39	179.70	0.38	9.69
131.0	184.01	0.41	9.12	179.41	0.40	11.22
131.5	182.96	0.39	9.42	179.43	0.33	9.66
132.0	183.15	0.36	9.04	178.51	0.32	9.21
132.5	182.84	0.32	8.57	178.73	0.31	9.46
133.0	182.71	0.33	9.11	177.75	0.30	9.55
133.5	181.75	0.29	8.41	177.66	0.30	9.52
134.0	181.28	0.31	8.88	178.24	0.27	8.95
134.5	180.91	0.28	8.42	177.33	0.26	8.99
135.0	179.47	0.30	8.63	176.44	0.28	9.51
135.5	179.41	0.30	8.38	176.07	0.27	9.09
136.0	178.76	0.29	8.33	176.17	0.28	9.27
136.5	177.92	0.30	8.82	175.69	0.26	8.64
137.0	177.91	0.29	8.42	174.99	0.24	8.32
137.5	176.76	0.29	8.05	173.67	0.25	8.90
138.0	175.40	0.29	8.25	173.36	0.24	8.27
138.5	174.75	0.28	8.03	172.17	0.24	8.15
139.0	174.74	0.30	7.94	171.75	0.26	8.45
139.5	173.26	0.30	8.12	171.08	0.25	8.13
140.0	172.74	0.26	7.37	170.94	0.26	8.17
140.5	172.89	0.27	7.37	170.23	0.25	7.74
141.0	172.28	0.27	7.43	170.46	0.27	8.19
141.5	170.97	0.28	7.73	169.32	0.24	7.47
142.0	170.68	0.27	7.13	168.95	0.25	7.53
142.5	170.37	0.29	7.62	168.68	0.28	8.20
143.0	169.49	0.29	7.51	168.02	0.29	7.78
143.5	169.41	0.29	6.93	166.37	0.30	8.32

Table VII,continued

144.0	168.46	0.32	7.08	166.79	0.28	7.42
144.5	167.34	0.33	7.68	166.67	0.30	7.72
145.0	167.72	0.34	7.22	166.55	0.31	7.87
145.5	166.65	0.36	7.29	166.21	0.32	7.78
146.0	166.37	0.34	7.30	164.91	0.32	7.33
146.5	166.05	0.39	7.67	164.58	0.36	7.89
147.0	166.04	0.42	7.82	164.16	0.36	7.79
147.5	164.93	0.45	7.64	164.23	0.38	8.21
148.0	165.11	0.47	7.42	162.68	0.37	7.23
148.5	164.31	0.50	7.16	163.05	0.44	7.70
149.0	162.82	0.56	7.07	163.51	0.43	7.71
149.5	162.68	0.62	7.55	162.71	0.51	8.09
150.0	161.91	0.52	6.27	161.99	0.57	7.91
150.5	161.33	0.67	7.09	162.28	0.56	8.46
151.0	162.93	0.78	8.51	160.73	0.54	7.66
151.5	161.82	0.61	6.78	161.57	0.56	7.70
152.0	161.45	0.78	7.01	163.23	0.66	7.67
152.5	160.04	0.79	7.36	158.51	0.62	7.43
153.0	160.31	0.82	6.21	160.45	0.82	8.80
153.5	160.92	0.72	5.30	158.60	0.92	9.37
154.0	158.79	1.29	7.75	154.75	0.92	7.93
154.5	158.37	1.19	5.85	156.29	0.92	7.83
155.0	160.51	0.96	4.31	158.42	0.89	6.44
155.5	157.38	0.81	4.55	156.12	1.18	7.63
156.0	155.42	2.29	9.15	155.02	1.13	7.67
156.5	159.87	2.19	6.92	156.95	1.14	7.92
157.0	157.20	1.72	7.31	158.45	1.09	6.36
157.5	154.59	0.90	3.36	156.15	1.81	6.26
158.0	156.92	1.46	3.58	163.74	1.55	7.25
158.5	0.0	0.0	0.0	155.51	1.25	6.10
159.0	139.23	0.0	0.0	157.88	1.38	4.78
159.5	0.0	0.0	0.0	148.97	1.54	5.32
160.0	0.0	0.0	0.0	152.83	3.12	8.84
160.5	0.0	0.0	0.0	155.80	2.98	5.96
161.0	0.0	0.0	0.0	143.76	3.73	11.80
161.5	0.0	0.0	0.0	0.0	0.0	0.0
162.0	0.0	0.0	0.0	0.0	0.0	0.0
162.5	0.0	0.0	0.0	0.0	0.0	0.0

Table VIII The average number of neutrons emitted per fragment ν(A*) in fast neutron induced fission of ^{235}U. The statistical uncertainty Δν and the variance σ_ν are also included.

MASS	EN=0.5 MEV			EN=5.5 MEV		
	NU(A)	ERROR	SIG.NU	NU(A)	ERROR	SIG.NU
73	0.0	0.0	0.0	2.38	0.0	0.0
74	-0.99	0.0	0.0	0.0	0.0	0.0
75	0.08	0.79	2.23	-6.59	0.0	0.0
76	-1.19	0.89	2.52	0.0	0.0	0.0
77	-0.32	0.91	3.03	-0.17	0.83	2.50
78	0.92	0.41	2.13	0.95	0.81	3.13
79	-0.94	0.38	2.97	-0.70	0.39	2.29
80	0.02	0.28	2.69	0.99	0.41	2.65
81	0.33	0.26	3.17	0.95	0.33	2.27
82	0.58	0.19	2.70	0.42	0.25	2.34
83	0.56	0.14	2.57	1.09	0.24	2.42
84	0.72	0.12	2.95	1.21	0.23	2.67
85	0.73	0.11	3.03	0.46	0.22	2.84
86	0.91	0.09	2.94	0.77	0.16	2.61
87	0.93	0.08	2.90	1.69	0.19	3.06
88	1.08	0.07	3.07	0.83	0.18	3.22
89	1.23	0.06	2.93	1.52	0.12	2.66
90	1.24	0.06	2.99	1.40	0.14	2.82
91	1.26	0.06	3.20	0.96	0.13	3.02
92	1.40	0.06	3.17	1.23	0.13	3.19
93	1.30	0.06	3.28	1.68	0.11	2.78
94	1.43	0.06	3.24	1.24	0.11	3.00
95	1.42	0.05	3.31	1.37	0.11	3.01
96	1.54	0.05	3.33	1.58	0.12	3.11
97	1.29	0.06	3.42	1.45	0.12	3.29
98	1.37	0.06	3.33	1.42	0.11	3.14
99	1.35	0.06	3.37	1.67	0.12	3.11
100	1.57	0.06	3.40	1.21	0.12	3.29
101	1.73	0.06	3.35	1.64	0.12	3.10
102	1.57	0.06	3.56	1.66	0.13	3.26
103	1.60	0.08	3.57	1.75	0.15	3.45
104	1.89	0.09	3.53	1.52	0.17	3.39
105	1.93	0.11	3.65	1.72	0.18	3.21
106	2.01	0.16	3.96	2.56	0.21	3.14
107	1.80	0.24	4.17	2.49	0.25	3.23
108	2.39	0.36	3.66	1.99	0.32	3.08
109	3.12	0.60	4.62	1.78	0.47	3.47
110	3.20	0.70	3.07	2.22	0.47	2.79
111	2.07	0.61	3.07	2.20	0.47	3.13
112	1.32	1.24	4.96	2.34	0.49	2.76
113	1.07	1.16	3.67	2.97	0.47	2.51
114	-1.03	0.72	2.29	3.62	0.33	1.82
115	1.76	0.69	2.30	1.85	0.74	3.30
116	0.96	1.05	2.98	3.11	0.68	3.65
117	1.97	0.78	2.48	2.48	0.70	3.86

Table VIII, continued

118	2.25	1.04	2.93	1.78	0.72	3.90
119	0.23	0.87	2.89	0.77	0.87	3.91
120	-2.52	1.46	4.63	3.08	0.60	3.35
121	2.66	0.98	3.11	3.61	0.47	2.55
122	1.16	0.92	3.70	1.97	0.62	3.49
123	1.27	0.65	3.25	0.95	0.51	3.39
124	-0.05	1.16	5.05	1.12	0.65	3.82
125	1.55	0.47	3.66	1.25	0.52	3.80
126	-0.03	0.32	3.25	1.18	0.36	3.45
127	-0.27	0.24	4.10	1.33	0.27	3.56
128	-0.18	0.16	3.99	1.77	0.23	3.42
129	0.16	0.11	3.74	1.00	0.22	3.92
130	0.12	0.09	3.83	0.26	0.19	3.90
131	0.0	0.09	4.07	0.91	0.18	4.02
132	0.31	0.07	3.95	0.82	0.15	3.77
133	0.67	0.07	3.82	1.08	0.15	3.80
134	0.78	0.07	3.90	1.07	0.14	3.75
135	0.73	0.07	3.96	1.91	0.13	3.50
136	0.84	0.07	3.92	1.53	0.14	3.81
137	0.81	0.06	3.95	1.53	0.15	4.02
138	1.15	0.07	4.02	1.75	0.15	4.15
139	1.13	0.07	4.14	1.81	0.14	3.84
140	1.23	0.07	4.07	2.04	0.15	3.95
141	1.06	0.07	4.15	2.28	0.15	3.73
142	1.37	0.07	4.02	1.54	0.16	3.99
143	1.30	0.07	4.09	1.70	0.17	3.98
144	1.27	0.08	4.07	1.98	0.19	3.93
145	1.48	0.08	4.03	2.44	0.17	3.73
146	1.54	0.10	4.15	1.85	0.25	4.47
147	1.26	0.11	4.09	3.39	0.24	3.90
148	1.73	0.13	4.17	2.23	0.22	3.56
149	1.78	0.15	4.27	1.45	0.33	4.31
150	1.62	0.18	4.42	3.44	0.32	3.69
151	2.10	0.20	3.76	3.47	0.33	3.31
152	2.32	0.28	3.93	2.90	0.47	4.29
153	1.76	0.41	5.04	3.65	0.53	3.58
154	1.73	0.50	4.73	4.76	0.52	3.40
155	1.48	0.58	4.51	3.55	0.64	3.79
156	2.60	0.63	3.27	3.26	0.46	1.78
157	-0.43	1.16	3.85	7.32	1.39	4.17
158	3.09	2.07	5.86	0.0	0.0	0.0
159	6.79	1.46	4.14	-0.59	0.0	0.0
160	-2.16	0.0	0.0	0.0	0.0	0.0
161	0.0	0.0	0.0	4.27	0.0	0.0
162	7.35	0.0	0.0	0.0	0.0	0.0
163	0.0	0.0	0.0	7.74	0.0	0.0

Table IX The average number of neutrons emitted per fragment $\nu(A^*)$ in fast neutron induced fission of ^{237}Np. The statistical uncertainty $\Delta\nu$ and the variance σ_ν are also included.

MASS	EN=0.8 MEV NU(A)	ERROR	SIG.NU	EN=5.5 MEV NU(A)	ERROR	SIG.NU
73	0.0	0.0	0.0	0.0	0.0	0.0
74	0.0	0.0	0.0	0.0	0.0	0.0
75	0.0	0.0	0.0	0.0	0.0	0.0
76	0.0	0.0	0.0	0.0	0.0	0.0
77	-0.82	0.0	0.0	-0.06	1.49	3.34
78	1.21	1.36	1.36	-0.16	1.13	2.77
79	-0.94	1.02	1.78	-0.56	1.13	3.73
80	-1.86	1.03	4.10	0.06	1.08	2.41
81	-0.25	1.02	2.68	0.08	0.50	3.55
82	1.12	0.74	2.11	0.24	0.74	3.84
83	0.44	0.41	2.55	0.40	0.56	3.22
84	0.97	0.46	3.15	0.39	0.47	3.41
85	0.99	0.42	2.44	1.13	0.40	3.27
86	1.31	0.27	2.87	1.43	0.31	3.04
87	1.28	0.26	2.73	1.37	0.26	2.92
88	1.25	0.24	2.62	1.20	0.21	3.02
89	1.17	0.21	2.70	1.35	0.21	3.47
90	1.36	0.18	2.67	1.46	0.20	3.21
91	1.37	0.15	2.77	1.58	0.17	2.94
92	1.51	0.14	2.77	1.62	0.14	3.29
93	1.58	0.13	2.81	1.35	0.15	3.38
94	1.46	0.13	2.88	1.36	0.14	3.39
95	1.46	0.12	2.69	1.33	0.13	3.37
96	1.45	0.10	2.87	1.48	0.12	3.45
97	1.55	0.11	2.95	1.74	0.12	3.45
98	1.74	0.11	2.97	1.56	0.11	3.59
99	1.70	0.11	2.89	1.69	0.11	3.61
100	1.66	0.10	3.03	1.55	0.11	3.57
101	1.75	0.11	3.01	1.73	0.11	3.67
102	1.65	0.10	2.96	1.50	0.11	3.69
103	1.95	0.10	3.03	1.86	0.11	3.65
104	1.92	0.10	3.26	2.01	0.10	3.46
105	1.94	0.12	3.10	2.07	0.11	3.74
106	2.36	0.12	2.88	2.08	0.12	3.83
107	2.31	0.14	2.93	2.35	0.12	3.69
108	2.12	0.15	3.24	2.10	0.13	3.74
109	1.85	0.20	2.96	2.34	0.15	3.86
110	2.00	0.23	3.69	1.90	0.17	3.64
111	1.25	0.42	3.44	2.07	0.20	3.21
112	1.86	0.52	2.98	2.24	0.20	3.16
113	4.02	0.74	2.51	2.06	0.24	3.72
114	4.53	0.83	3.04	2.56	0.35	3.80
115	-0.02	1.37	0.0	3.27	0.44	3.33
116	-0.01	0.0	0.0	3.30	0.46	3.64
117	0.0	0.0	0.0	3.00	0.53	3.68

Table IX, continued

118	0.01	0.0	0.0	1.19	0.64	2.91
119	0.01	0.0	0.0	2.37	0.49	3.49
120	0.01	0.0	0.0	2.28	0.50	3.57
121	0.10	0.0	0.0	2.30	0.60	3.37
122	-1.33	0.0	8.25	2.31	0.59	4.26
123	1.95	3.69	2.09	1.83	0.61	4.09
124	0.95	0.70	3.64	1.99	0.56	3.61
125	0.48	0.91	4.01	2.25	0.42	3.56
126	0.72	0.61	3.39	1.90	0.34	3.85
127	-0.25	0.39	2.75	1.51	0.29	4.11
128	0.81	0.21	3.58	1.15	0.25	4.29
129	0.60	0.23	3.56	1.22	0.23	4.15
130	0.46	0.18	3.38	1.11	0.18	4.39
131	0.67	0.15	3.54	1.34	0.18	4.29
132	0.52	0.14	3.49	1.46	0.15	4.26
133	0.66	0.12	3.41	1.50	0.14	4.34
134	0.88	0.12	3.51	1.19	0.14	4.42
135	1.01	0.12	3.67	1.68	0.13	4.37
136	1.11	0.13	3.66	1.84	0.13	4.42
137	1.50	0.13	3.62	2.18	0.13	4.39
138	1.18	0.13	3.77	1.90	0.13	4.37
139	1.30	0.14	3.79	2.22	0.13	4.41
140	1.15	0.14	3.74	1.88	0.14	4.49
141	1.11	0.14	3.63	1.83	0.14	4.34
142	1.15	0.14	4.04	1.81	0.14	4.50
143	1.41	0.16	3.89	2.32	0.15	4.53
144	1.13	0.17	3.59	2.29	0.17	4.60
145	1.58	0.17	3.82	2.27	0.18	4.12
146	1.30	0.19	3.77	2.20	0.17	4.43
147	1.17	0.21	3.88	2.00	0.20	4.43
148	0.63	0.26	4.05	1.89	0.20	4.19
149	1.81	0.33	3.89	1.78	0.23	4.61
150	1.66	0.34	4.80	2.43	0.27	4.60
151	1.96	0.43	3.99	2.83	0.32	4.64
152	1.84	0.44	3.93	1.98	0.33	4.21
153	1.92	0.48	3.73	1.98	0.36	5.16
154	2.29	0.68	3.53	3.59	0.49	4.07
155	1.54	0.69	3.88	2.46	0.48	4.44
156	1.88	1.08	3.51	0.0	0.0	0.0
157	3.92	0.88	4.88	0.0	0.0	0.0
158	8.30	2.82	5.95	0.0	0.0	0.0
159	0.0	0.0	0.0	0.0	0.0	0.0
160	0.0	0.0	0.0	0.0	0.0	0.0
161	0.0	0.0	0.0	0.0	0.0	0.0
162	0.0	0.0	0.0	0.0	0.0	0.0
163	0.0	0.0	0.0	0.0	0.0	0.0

FIGURE CAPTIONS

Fig. 1 Schematic view of the experimental set-up.

Fig. 2 Primary fragment mass yields P(A*) in fast neutron induced fission of ^{235}U.

Fig. 3 Primary fragment mass yields P(A*) in fast neutron induced fission of ^{237}Np.

Fig. 4 Distributions of the total kinetic energy TKE(A*) in fast neutron induced fission of ^{235}U.

Fig. 5 Distributions of the total kinetic energy TKE(A*) in fast neutron induced fission of ^{237}Np.

Fig. 6 The variance of the total kinetic energies in fast neutron induced fission of ^{235}U.

Fig. 7 The variance of the total kinetic energies in fast neutron induced fission of ^{237}Np.

Fig. 8 The average number of neutrons emitted per fragment $\nu(A^*)$ in fast neutron induced fission of ^{235}U.

Fig. 9 The average number of neutrons emitted per fragment $\nu(A^*)$ in fast neutron induced fission of ^{237}Np.

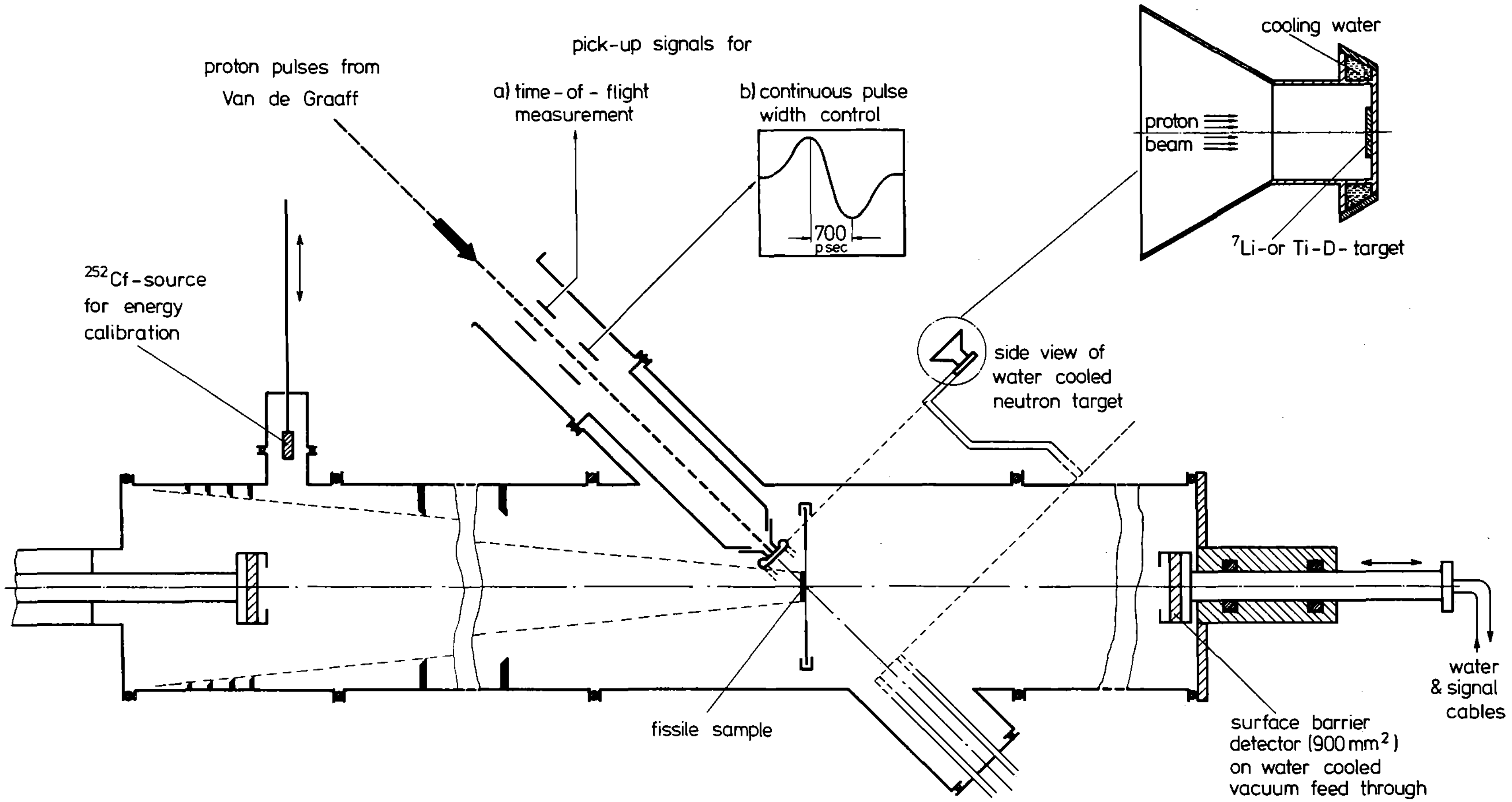

pick-up signals for
proton pulses from
Van de Graaff
a) time-of-flight
measurement
b) continuous pulse
width control
700
psec
cooling water
proton
beam
⁷Li-or Ti-D-target
²⁵²Cf-source
for energy
calibration
side view of
water cooled
neutron target
fissile sample
water
& signal
cables
surface barrier
detector (900 mm²)
on water cooled
vacuum feed through

Fig. ,1

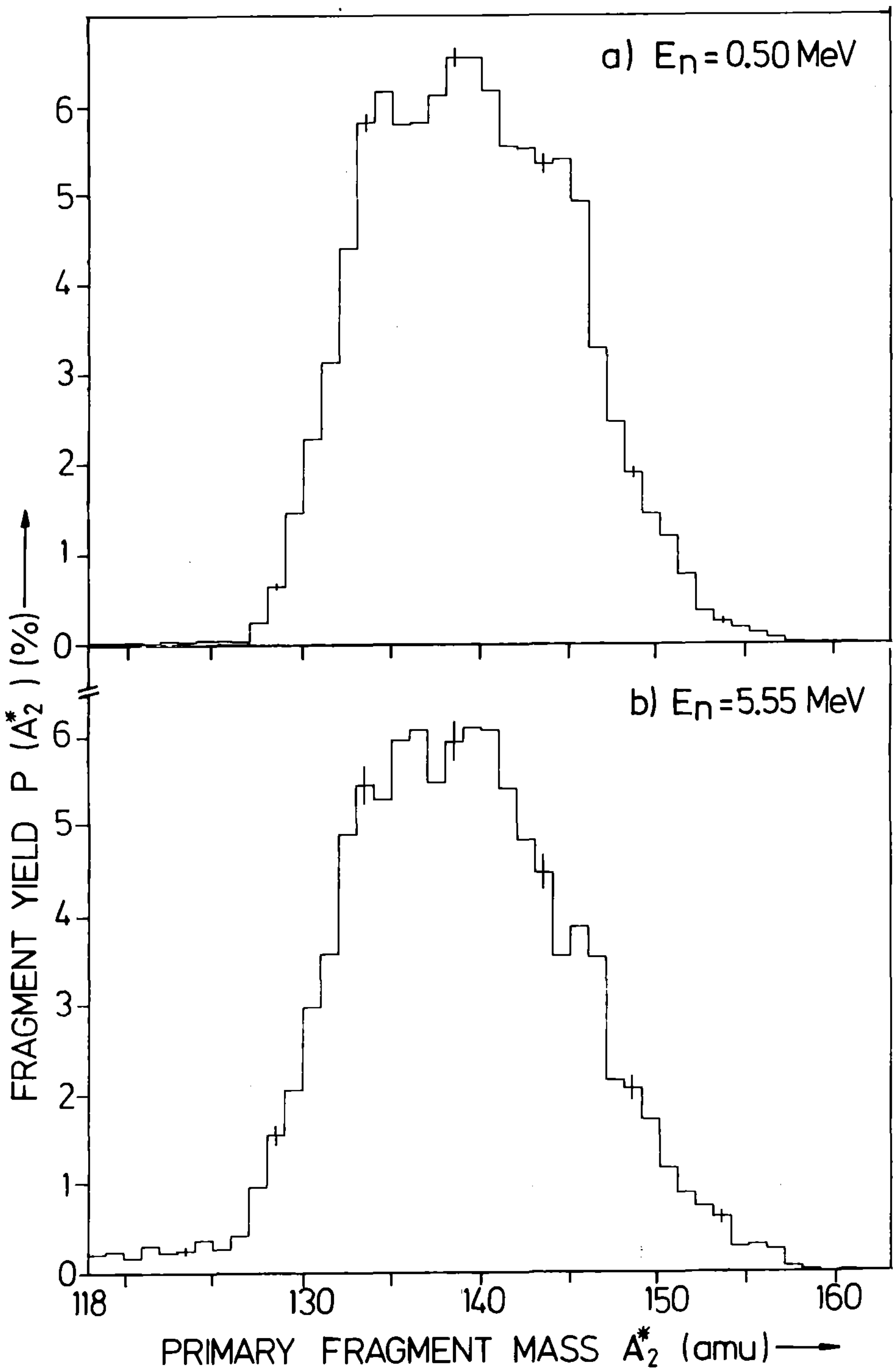

a) En = 0.50 MeV
b) En = 5.55 MeV
FRAGMENT YIELD P (A*2) (%)
0
1
2
3
4
5
6
118
130
140
150
160
PRIMARY FRAGMENT MASS A*2 (amu)

Fig. 2

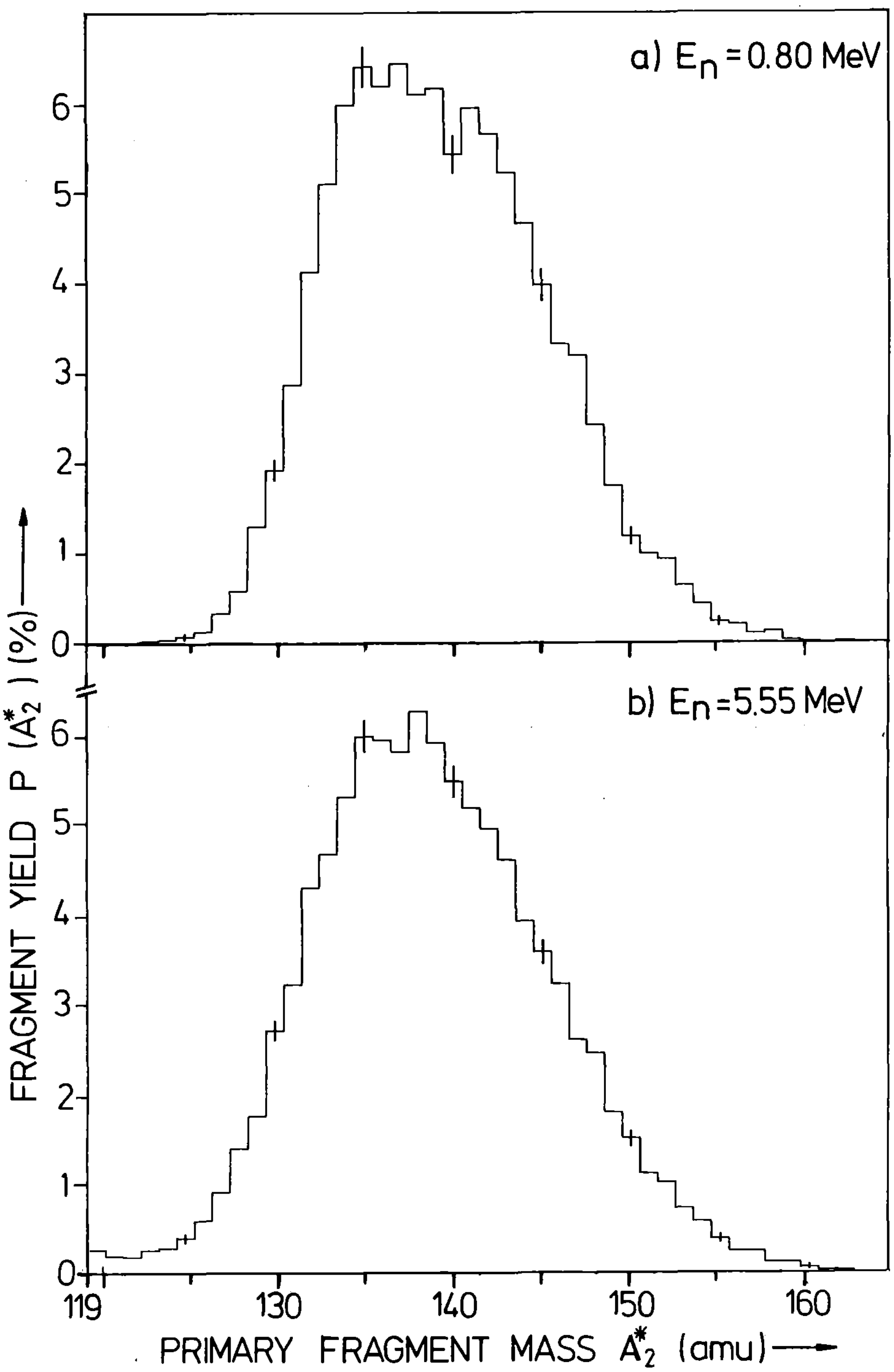

a) E_n = 0.80 MeV
b) E_n = 5.55 MeV
FRAGMENT YIELD P (A_2^*) (%)
PRIMARY FRAGMENT MASS A_2^* (amu)
0
1
2
3
4
5
6
119
130
140
150
160

Fig. 3

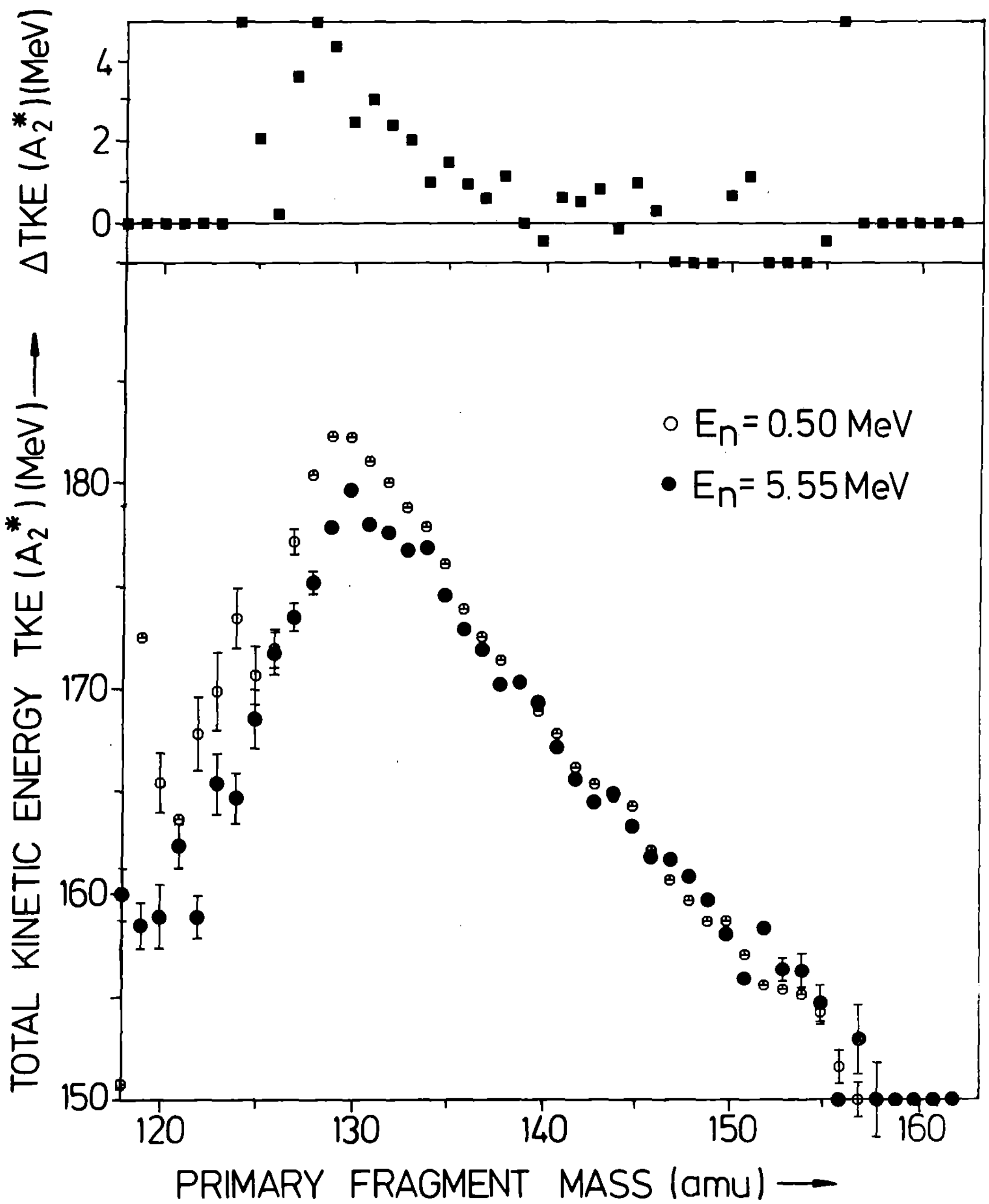

ΔTKE (A₂*) (MeV)
4
2
0
TOTAL KINETIC ENERGY TKE (A₂*) (MeV)
180
170
160
150
○ En = 0.50 MeV
● En = 5.55 MeV
120
130
140
150
160
PRIMARY FRAGMENT MASS (amu)

Fig. 4

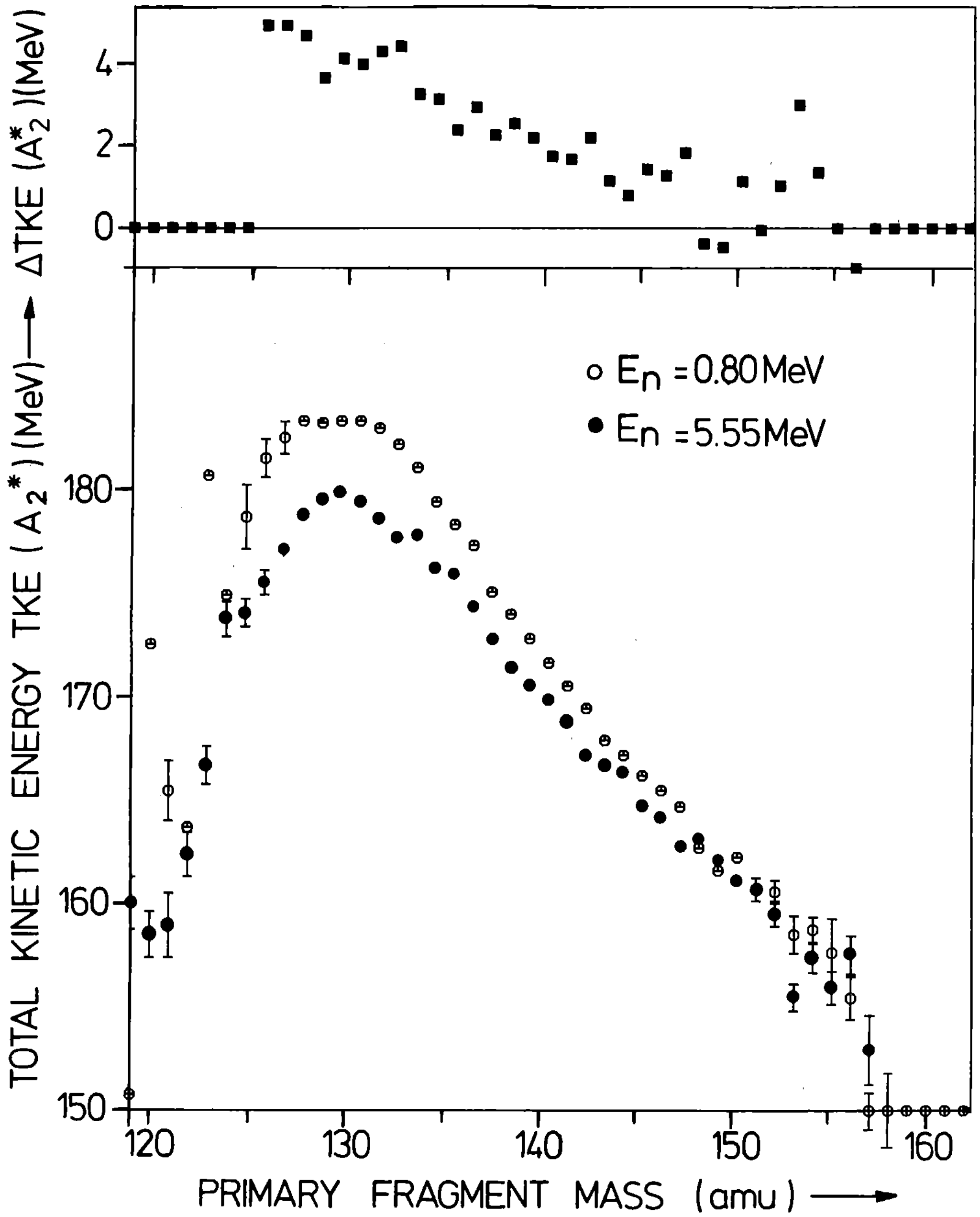
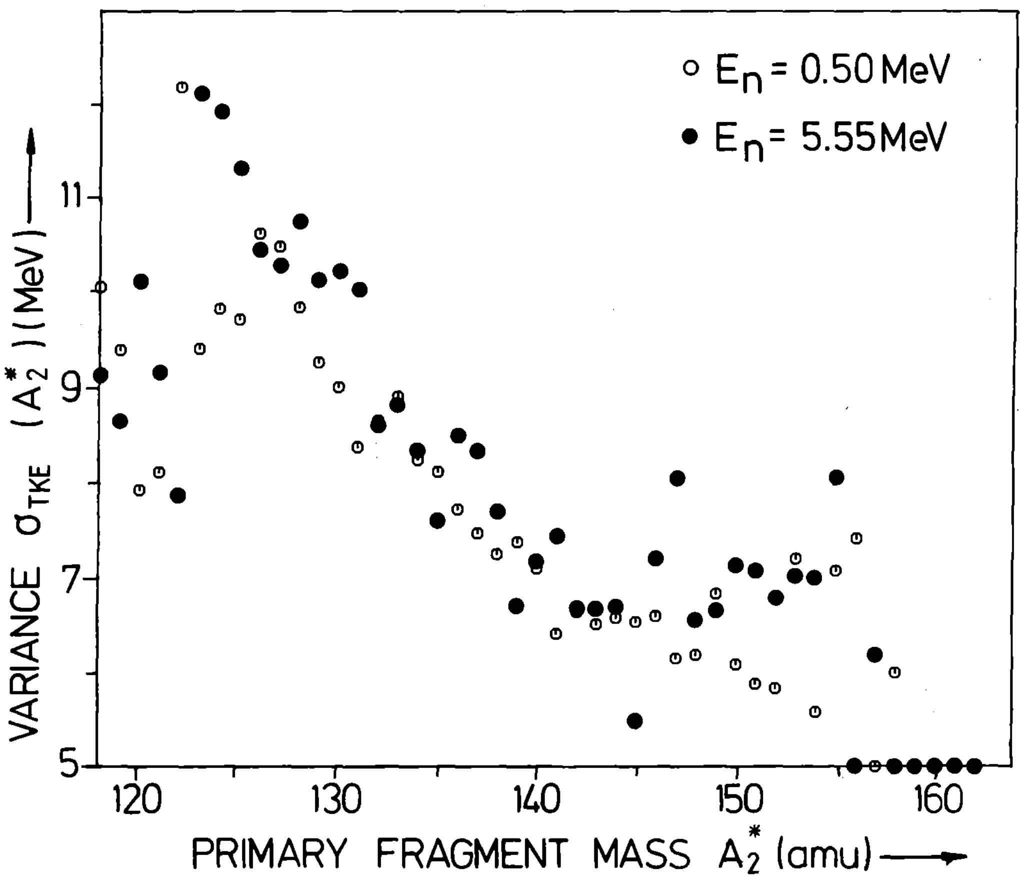
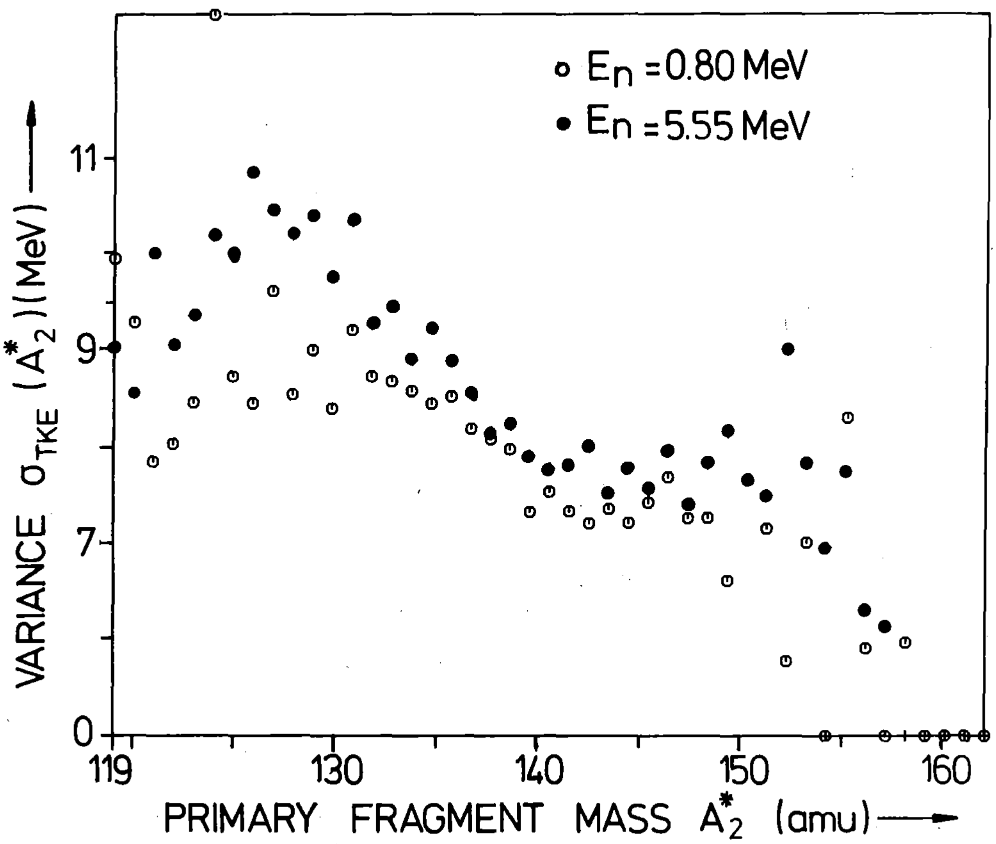

ΔTKE (A$_2^*$)(MeV)
4
2
0
TOTAL KINETIC ENERGY TKE (A$_2^*$) (MeV)
180
170
160
150
○ En =0.80MeV
● En =5.55MeV
120
130
140
150
160
PRIMARY FRAGMENT MASS (amu)

Fig. 5



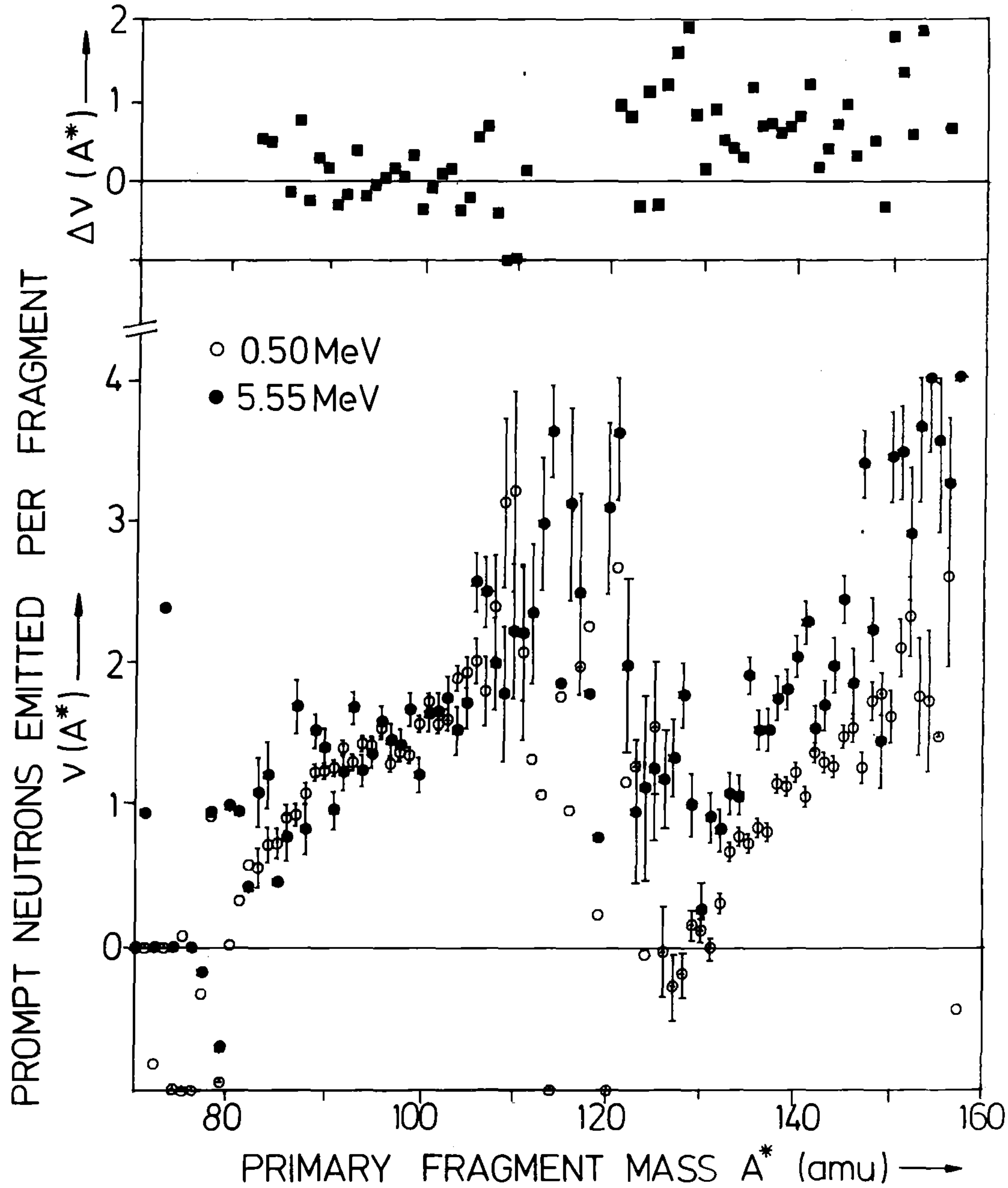
○ En = 0.50 MeV
● En = 5.55 MeV
VARIANCE σTKE (A2*) (MeV)
11
9
7
5
120
130
140
150
160
PRIMARY FRAGMENT MASS A2* (amu)

Fig. 6



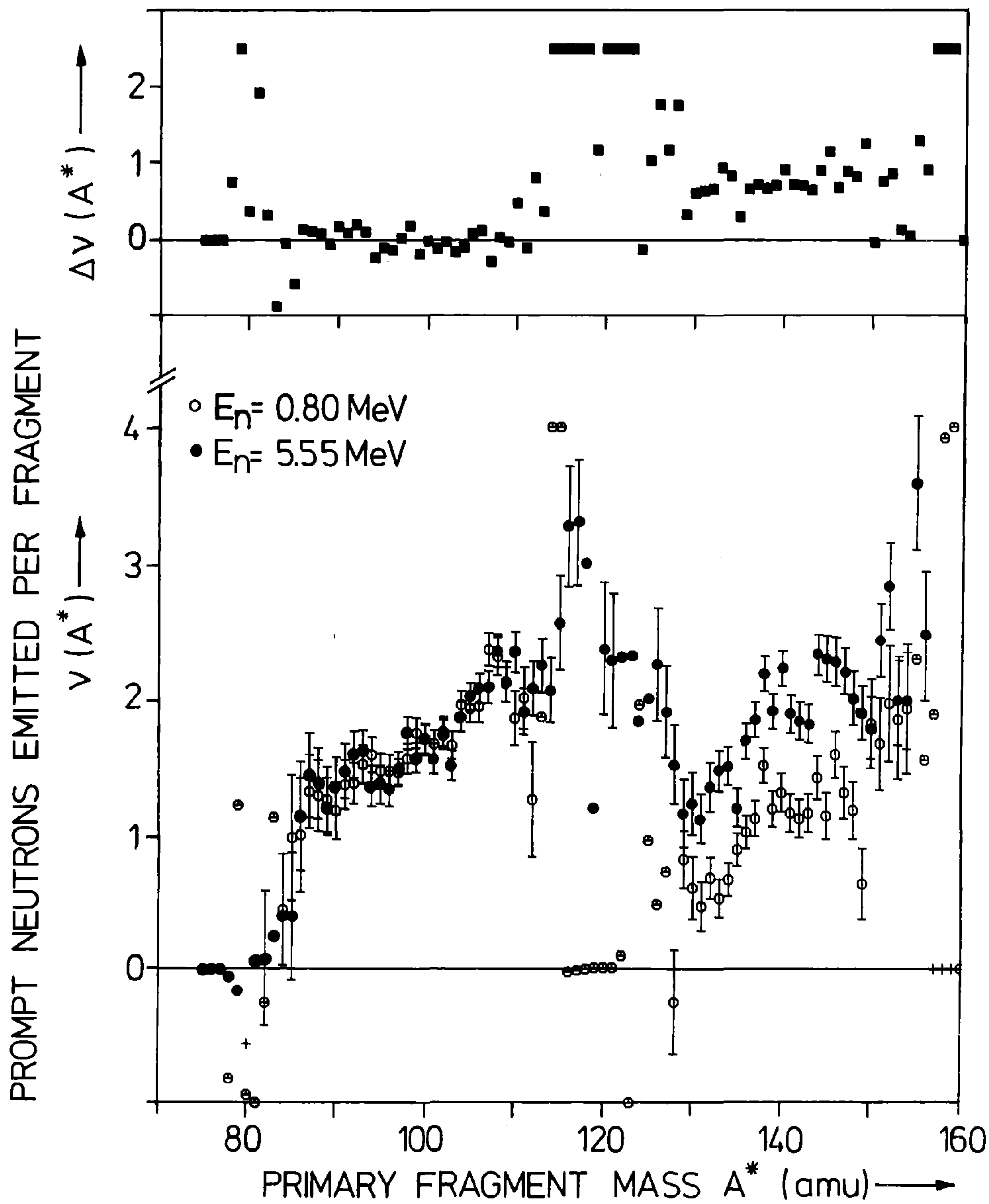
o En =0.80 MeV
• En =5.55 MeV
11
9
7
0
VARIANCE σTKE (A*2)(MeV)
119
130
140
150
160
PRIMARY FRAGMENT MASS A*2 (amu)

Fig. 7



2
1
0
Δν (A*) ⟶
4
3
2
1
0
PROMPT NEUTRONS EMITTED PER FRAGMENT
ν (A*) ⟶
○ 0.50 MeV
● 5.55 MeV
80
100
120
140
160
PRIMARY FRAGMENT MASS A* (amu) ⟶

Fig. 8



Δν (A*)
2
1
0
PROMPT NEUTRONS EMITTED PER FRAGMENT
ν (A*)
4
3
2
1
0
○ En= 0.80 MeV
● En= 5.55 MeV
80
100
120
140
160
PRIMARY FRAGMENT MASS A* (amu)

Fig. 9