Progress Report on Neutron Physics Research in Yugoslavia

Compiled by
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Contents

Preface

Due to some misunderstanding regarding my appointment in I.N.D.C. we have only very recently start compiling the data from Yugoslav laboratories. Thus, in many ways this report will be insufficient. I hope that the report that Dr.N. Cindro will verbally deliver at the Bombay meeting will supplement the present material.

Laboratories in SFR Yugoslavia
working in the field of neutron
physics research

Institute "Ruđer Bošković", Zagreb:
Department of Nuclear and Atomic Physics
chairman Prof.dr. P. Tomaš
Department of Theoretical Physics
chairman Prof.dr. G. Alaga
Laboratory for Nuclear Chemistry
Head Prof.dr. P. Strohal
(this is in the Department for the Oceanographic research)

Institute "Boris Kidrič", Vinča
Department of Physics
chairman Prof.dr. B. Lalović

Institute "Jožef Stefan", Ljubljana
Department of Physics
chairman Prof.dr. D. Jamnik

Neutron Physics Research

1. S. Lulić, P. Strohal and I. Šlaus:
The Study of (n,2p) Reactions at 14 MeV
Nuclear Physics A154 (197o) 273-282

Entered in X4: 30106
24/4/72
CA

The study of (n, 2p) reactions can yield important information about reaction mechanisms and nuclear spectroscopy which cannot be obtained by charged particle induced reactions[1].

Attempts aimed so far to determine the cross section for the (n, 2p) reaction leading to radioactive nuclei with suitable properties have not been successful. Only upper limits have been quoted[6,7], the values ranging from 3 μb to 840 μb (refs.[6,7]). Husain et al. have measured the $^{1o3}Rh(n, 2p)^{1o2m}Tc$ reaction and found 7±4 μb (ref.[8]). However, an upper limit of 3 μb is quoted for this reaction in ref.[7]. The advent of high resolution Ge(Li) detectors and on-line computers, with refined chemical separation techniques, is making the study of (n, 2p) reactions much more promising.

The present investigation relies on the activation method employing Ge(Li) detectors in conjunction with a PDP-8 computer used as a 1024-channel analyser, and the chemical separation of Z-2 elements from predominantly Z and Z-1 materials.

The cross section was determined by using the internal monitor, i.e. comparing the intensity of photopeaks belonging to the investigated (n, 2p) reactions with those from the product of (n, alpha) reactions. The error due to the efficiency of the chemical separation procedure was

therefore eliminated, since the products of (n, 2p) and (n, alpha) reactions belong to the same chemical element. The uncertainty in the absolute cross section of the (n,2p) reactions depends upon the accuracy of the (n, alpha) cross section. Only for TiO_2, V_2O_5 and $Y(NO_3)_3$ the monitor was the (n,p) reaction. The targets used in this study, the monitor reaction, the value of its cross section and the half-life are given in table 1.

Table 1

Targets and monitors

Target	Chemical separation performed	Monitor				
		reaction	product half-life	value used (mb)	other values	ref.
KNO_3	yes	$^{41}K(n,\alpha)^{38}Cl$	37.3min	30±6[a]	31.4± 5	14)
Sc_2O_3	yes	$^{45}Sc(n,\alpha)^{42}K$	12.4h	63±12[a]	56±4	15)
					63±12	16)
TiO_2	no	$^{50}Ti(n,p)^{50}Sc$	1.7min	28± 6[a]	17± 2	17)
					9± 2	18)
					27± 3	19)
V_2O_5	no	$^{51}V(n,p)^{51}Ti$	5.8min	55±12[a]	37± 3	2o)
					53±15	21)
					30± 6	22)
					25± 4	23)
MnO_2	no	$^{55}Mn(n,\alpha)^{52}V$	3.7min	33[b]	32.5±1.5	24)
					31 ±5	25)
As_2O_3	yes	$^{75}As(n,\alpha)^{72}Ga$	14.1h	9.3±3.1[a]	10 ±0.8	15)
					12 ±1.1	14)
$RbNO_3$	yes	$^{87}Rb(n,\alpha)^{84}Br$	31.8min	59±12[c]	39 ±16	14)
$Y(NO_3)_3$	yes	$^{27}Al(n,p)^{27}Mg$	9.5min	82±10[d]	87.2± 7	26)
					93 ±10	27)
					52.4±9.4	14)
					77 ±8	16)
					53 ±5	19)
Nb_2O_5	yes	$^{93}Nb(n,\alpha)^{90}Y$	3.1h	5.9±2[e]	5 ±2	28)
$CsNO_3$	yes	$^{133}Cs(n,\alpha)^{130}I$	12.3h	1.0±0.9[a]	1.9 ±0.2	12)
$La(NO_3)_3$	yes	$^{139}La(n,\alpha)^{136}Cs$	13.7d	1.87±0.19[f]	1.3	29)

[a]) Ref.[6]), [b]) Ref.[8]), [c]) Ref.[9]), [d]) Ref.[10]), [e]) Ref.[11]), [f]) Ref.[12]).

Gamma-ray spectra were measured using a $20cm^3$ Ge(Li) detector coupled to the PDP-8 used as a 1024-channel analyser. Only the activity produced by irradiation of the TiO_2 target was studied using a 7.6x7.6cm NaI(Tl) scintillation counter in connection with a 256-channel analyser.

Gamma-ray spectra were analysed and the decay curves of characteristic photopeaks in the spectra were measured for several half-lives. Activities due to a specific radionucleide were calculated from the area under the photopeak.

The cross sections were determined taking into account all necessary corrections, such as branching ratios and the efficiency of the spectrometer as a function of the γ-ray energy.

The quality of the experimental arrangement was tested investigating the activities of Z-2 products for nuclei where the Q-value for (n,2p) reactions is less than -14.5 MeV and thus cannot occur at our bombarding energy.

The targets Sc_2O_3, V_2O_5, As_2O_3, $Y(NO_3)_3$, Nb_2O_5, $CsNO_3$ and $La(NO_3)_3$ were irradiated and the chemical separation of Z-2 products was performed for all targets, except for V_2O_5.

Table 2 shows the experimental results for (n, 2p) reactions. Columns 1 and 2 list the target and the residual nucleus, respectively. The Q-values of the reactions are given in column 3, and half-lives in column 4. The reaction cross sections in μb obtained in this experiment are listed in column 5, and the experimental errors are given in column 6. The upper limits for the investigated reactions given by Bramlitt and Fink are quoted in the last column.

Table ~~3~~ 2

Cross sections for (n,2p) reactions

Target	Residual nucleus	Q-values (MeV)	Half-lives	σ (μb)	Exp.error ($\pm$ μb)	Upper limit (μb)
^{45}Sc	^{44}K	-12.21	22.0 min	25	10	210
^{51}V	^{50}Sc	-13.74	1.7 min	$\approx$ 60		30
^{75}As	^{74}Ga	-11.72	7.8 min	52	29	500
^{89}Y	^{88}Rb	-11.53	18.0 min	50	40	30
^{93}Nb	^{92}Y	- 8.87	3.7 h	50	20	500
^{133}Cs	^{132}I	- 8.95	2.3 h	25	20	5
^{139}La	^{138}Cs	-10.85	32 min	30	20	46

2. M. Đikšić, P. Štrohal and I. Šlaus:
(n,^{3}He) and (n,t) reaction cross sections at 14 MeV

extract in X4: 30152 & X4:30169 26/4/72

The experimental data on (n,^{3}He) and (n,t) reactions are very scarce and even when the data exist they are often contradictory, the results range e.g. for ^{103}Rh(n,^{3}He)^{101}Te from upper limit of 0.4 μb[8] to 1500--3500 μb[3]. The successful measurement of (n,^{3}He) and (n,t) reaction cross section requires sensitive experimental techniques which can enable to discriminate the low yield of (n,^{3}He) and (n,t) reaction in the presence of large yields of (n,2n), (n,α), (n,nα) and (n,p) reactions. The high resolution gamma spectroscopy coupled with the radiochemical separations are basic features of our experimental method. In case of (n,^{3}He) reactions radiochemical separations exclude all radioactive products from (n,p) and (n,2n) reactions.

The present investigations were performed using the activation method. In some cases radiochemical separation was also applied, mostly for the separation of (Z-2) elements from the target material.

Experimentally determined cross sections for (n,^{3}He) and (n,t) reactions are presented in Tables 1 and 2. All cross sections correspond to measured values calculated on the basis of characteristic photopeaks of their gamma ray spectra. Tables 1 and 2 show the experimental results for (n,^{3}He) and (n,t) reactions. Columns 1 and 2 list target and residual nucleus, respectively. Target materials are given in column 3, while Q-values are present in column 4, and half-lives in column 5. The reaction cross sections obtained in this work are expressed

as weighted mean values and listed in column 6. Cross section values and upper limits of investigated reactions are listed in column 7, while column 8 indicate the corresponding references.

TABLE 1

Cross sections for (n, ^{3}He) reactions

Target nucleus	Residual nucleus	Target material	Q-value	half life	cross section (mb)	values of other autors	Ref.
^{31}P	^{29}Al	red phosphorus	-13.0795	6.6 min	222±100	700 500	2 3
^{41}K	^{39}Cl	KNO_3	-12.599	55.5 min	848±320	2500	2
^{55}Mn	^{53}V	MnO_2	-12.7017	2 min	800±320	2000-6000 50 420	3 4 2
^{59}Co	^{57}Mn	Co-foil	-11.6126	1.7 min	62±30	25 1000-3000 100	4 3 2
^{63}Cu	^{61}Co	^{63}Cu (sep.isot.)	-9.5130	99 min	113±40	3200±1100 80	5
^{71}Ga	^{69}Cu	Ga_2O_3	-11.0446	3 min	66±20		
^{75}As	^{73}Ga	As_2O_5	-10.1481	294 min	578±200	3000-7000 510 500	3 2 4
^{96}Zr	^{94}Sr	ZrO_2	-13.4697	1.35 min	136±50		
^{93}Nb	^{91m}Y	Nb_2O_5	- 7.7154	50.3 min	17.9±9.0	60	9
^{103}Rh	^{101}Tc	Rh-foil	- 8.5503	14 min	16±7	1500-3500 1.2±1 2.0±0.6 90 0.4 19	3 6 7 2 8 4

Table 1

^{109}Ag	^{107}Rh	$AgNO_3$	- 8.7193	21.7 min	23±10
^{115}In	^{113}Ag	In-foil	- 9.3409	5.3 h	33±15
^{130}Te	^{128}Sn	^{130}Te (sep.isot.)	-10.7969	59.0 min	15±8
^{187}Re	^{185}Ta	Re_2O_7	- 6.5999	50 min	4+3

TABLE 2

Cross sections for (n,t) reactions

Target nucleus	Residual nucleus	Target material	Q-value (MeV)	Half-life	Cross section (microbarns)	value of other autors	Ref.
^{32}S	^{30}P	sulphur powder	-12.6942	2.5 min	154±70	4±1	15
						20±5	16
						7.5±9	17
						2200±11%	18
						17	19
						10	20
^{40}Ca	^{38g}K	$CaCO_3$	-12.9401	7.71 min	310±180	20000±20%	18
						100	16
						15	20
						20	15
^{54}Fe	^{52m}Mn	^{54}Fe (sep.isot.)	-12.422	21.1 min	351±150	600±100	21
^{64}Zn	^{62}Cu	$ZnSO_4$	-10.0658	9.76 min	33.7±10	100	15
^{89}Y	^{87}Sr	$Y(NO_3)_3$	- 9.6919	2.83 h	15.4±10		

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3. M. Furić, V. Valković, Đ. Miljanić, P. Tomaš and B. Antolković:
Neutron-Proton Bremsstrahlung at 14.4 MeV
Nuclear Physics A156 (197o) 1o5-112

A kinematically complete experiment on the neutron-proton bremsstrahlung at a neutron energy of 14.4 MeV was performed. Protons and neutrons were detected on opposite sides of the neutron beam. Protons were identified and their energy measured. The associated particle method and the neutron-proton time-of-flight difference were used to reduce the background. An upper limit of 400 $\mu b \cdot sr^{-2}$ was found for the neutron-proton bremsstrahlung differential cross section at the detector setting $\theta_p = \theta_n = 30^o$.

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4. Đ. Miljanić, M. Furić and V. Valković:
2 x 4: 30102 A Study of (n,d) and (n,t) Reactions on ^7Li
Nuclear Physics A148 (1970) 312-324 → in CINDA already

Charged-particle spectra from neutron irradiation of ^7Li were measured at several angles. The angular distribution of deuterons from the $^7Li(n,d)^6He(g.s.)$ transition was compared with the DWBA prediction. The absolute value of the cross section was in satisfactory agreement, but the shape of the measured angular distribution was not well reproduced by the calculations.

The angular distribution of tritons in the peak of the spectra was compared with the DWBA prediction for the pickup of two nucleons. The shape of the angular distribution was reproduced reasonably well. A discrepancy in the absolute value was interpreted as a consequence of quasifree n-t scattering.

5. V. Valković, M. Furić, Đ. Miljanić and P. Tomaš:
Neutron-Proton Coincidence Measurement from the Neutron-Induced Breakup of the Deuteron
Physical Review C, No.4 (1970) 1221-1225

A method for measuring neutron-charged-particle coincidences from the 14.4 MeV neutron-induced reaction has been developed. The $n+d \longrightarrow p+n+n$ reaction has been studied by the coincidence detection of the outgoing proton and neutron. The cross section has been measured as a function of five independent kinematic variables. A contribution of neutron-proton quasifree scattering has been observed. The cross section for $\theta_n=\theta_p=30^o$ is found to be $\sigma=37.5\pm5.8 mb/sr^2$. This result is in fair agreement with the data for proton-proton quasifree scattering from the $p+d \longrightarrow p+p+n$ reaction.

6. B. Antolković:
The study of $^{10}B(n,\alpha\alpha t)$, $^{7}Li(n, n\alpha t)$ and $^{12}C(n,n\alpha\alpha\alpha)$
(work in progress)

These reactions have been measured using the photographic plates. The measurement is a kinematically complete experiment.

The results of the measurement are shown in Figs 1.and 2.

The cross reactions are

$^{7}Li(n,t)^{5}He_{gs}$	50mb
$^{7}Li(n,n')^{7}Li^{*}_{4.63}$	182mb
$^{7}Li(n,n')^{7}Li^{*}_{6.54}$	68mb
$^{10}B(n,t)^{8}Be_{gs}$	9.3mb
$^{10}B(n,t)^{8}Be_{2.9}$	21.4mb
$^{10}B(n,\alpha)^{7}Li_{4.63}$	19.2mb
$^{10}B(n,\alpha)^{7}Li_{6.54}$	10.3mb

All errors are $\sim$ 10%.

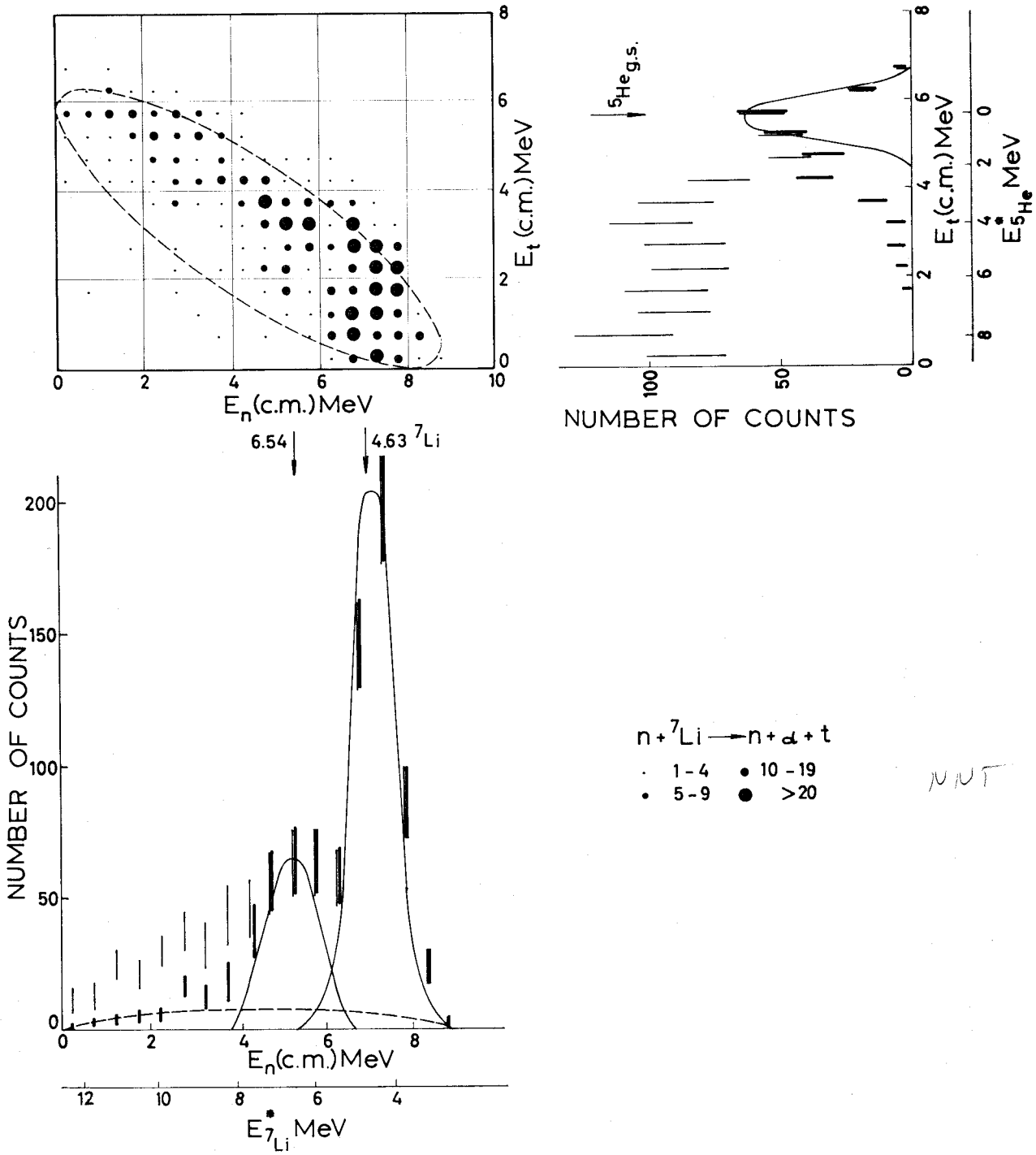
E_n(c.m.) MeV
E_t (c.m.) MeV
$^5He_{g.s.}$
NUMBER OF COUNTS
$E^*_{^5He}$ MeV
6.54
4.63 ^7Li
NUMBER OF COUNTS
$E^*_{^7Li}$ MeV
$n + {}^7Li \rightarrow n + \alpha + t$
1 - 4
5 - 9
10 - 19
>20

Fig.1.

7. I. Šlaus, J.W. Sunier, G. Thompson, J.C. Young, J.W. Verba, D.J. Margaziotis, P. Doherty and R.T. Cahill:
Neutron-Neutron Quasifree Scattering
Physical Review Letters Vol.26 (1971) 789-792

In collaboration with the group in The University of California, Los Angeles, the reaction D(n,2n)p was studied. The data are shown in Fig. 3.

The effective range, r_{nn}, has been extracted. The preliminary value is 2.4 ± 1.6fm. The upper limit for nd Bremsstrahlung was determined to be 2mb/sr^2.

8. Đ. Miljanić, V. Valković, D. Rendić and M. Furić:
Angular Distribution of tritons from the $^{11}B(n,t)^{9}Be$ Reaction at 14.4 MeV
Nuclear Physics A156 (197o) 193-198

The differential cross sections for the $^{11}B(n,t)^{9}Be$ reaction are shown in table 1.

Table 1

Differential cross section for the $^{11}B(n,t)^{9}Be$(g.s.)reaction

$\theta_{c.m.}$	$\frac{d\sigma}{d\omega}$(mb/sr)
0°	2.57 ± 0.08
$13^{o}18'$	2.15 ± 0.09
$26^{o}31'$	1.95 ± 0.08
$39^{o}33'$	1.55 ± 0.07
$52^{o}19'$	1.07 ± 0.09
$64^{o}43'$	0.81 ± 0.08

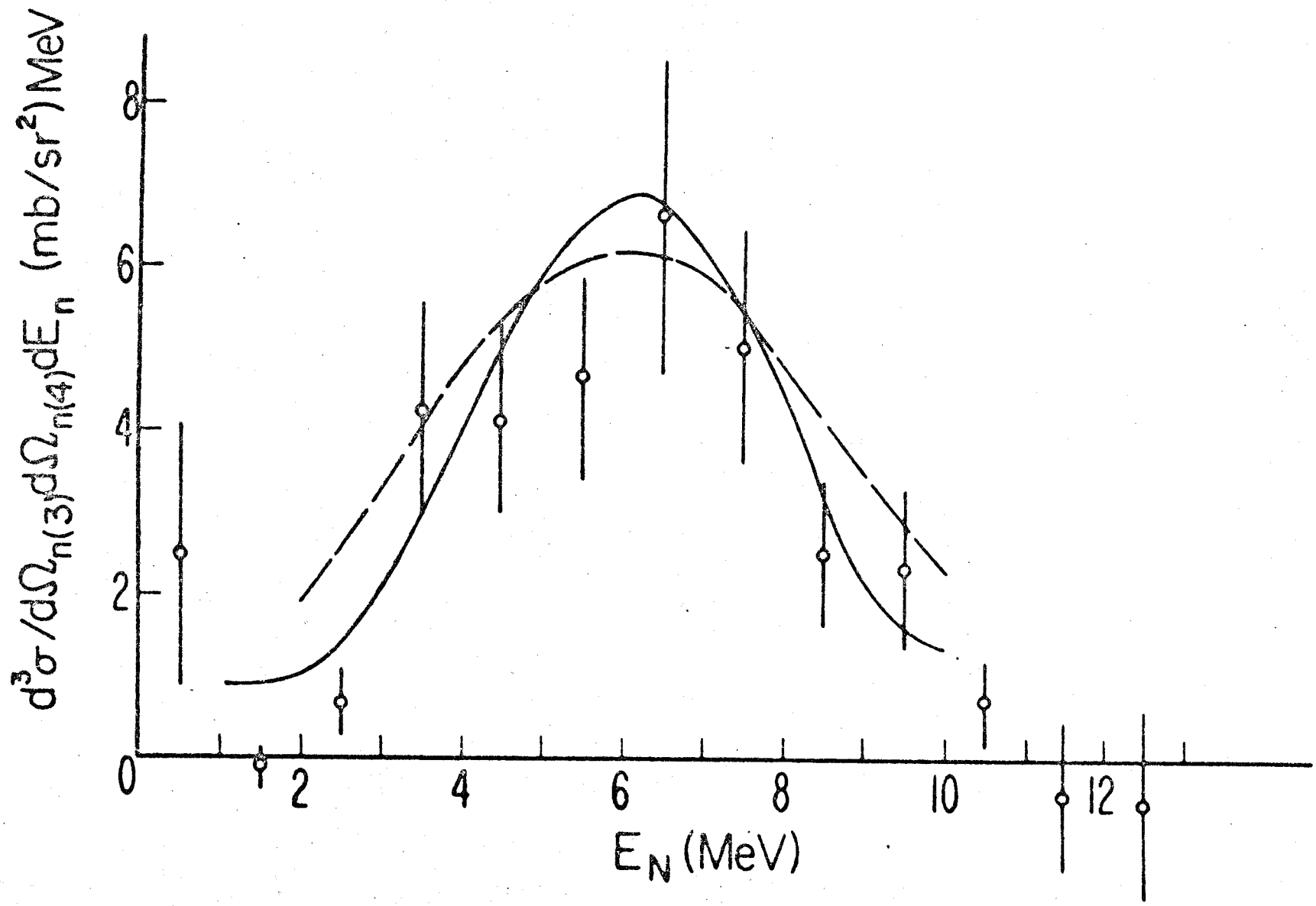
$d^3\sigma/d\Omega_{n(3)}d\Omega_{n(4)}dE_n$ (mb/sr^2) MeV
0
2
4
6
8
2
4
6
8
10
12
E_N (MeV)

Fig. 3

Experimental facilities

In the Institute Rudjer Bošković there are two Cockcroft-Walton accelerators and it is considered to use the internal beam of the 16 MeV cyclotron to produce neutrons.

The experimental techniques are improved:

1. V. Valković and P. Tomaš:
   A Position Sensitive Counter Telescope for the Study of Nuclear Reactions Induced by 14 MeV Neutrons
   Nuclear Instruments and Methods 92 (1971) 559-562

A counter telescope consisting of two multiwire proportional chambers and a residual-energy charged--particle detector is constructed. Instead of using a standard proportional counter, two batteries of a gas proportional counter were incorporated into the tandem arrangement of the detectors. The position sensitive part was made from stainless steel wires, 0.02mm in diameter with a wire spacing of 5mm. The distance between the mesh and the wires was 15mm. The lumped delay-line method was used to determine the identification pulse that is position sensitive. The spectra of the energy loss in the chamber were measured in the proportional region.

2. I. Šlaus, J.W. Sunier, G. Thompson, J.C. Young, J.W. Verba, D.J. Magaziotis, P. Doherty and R.T. Cahill
   Physical Review Letters Vol.26 (1971) 789-792

Neutron-neutron QFS was studied by bombarding a cylindrical 2-in.x2-in. C_6D_6 target with the 14.1-MeV neutron beam defined by associated alpha particles. Two

outgoing neutrons were detected at $\theta_{n(3)}=\theta_{n(4)}=30^{o}$, $\phi=180^{o}$. The overall angular resolution was $\pm 6^{o}$. The main experimental problem is the large background from γ's and from direct and elastically scattered neutrons. The background was reduced by requiring the four detectors (alpha, target, neutron-right, and neutron-left) to be in coincidence and by kinematically over-determining the process by measuring the time of flight and the scattering angles of the two neutrons and the energy of the recoil proton (E_T). A further reduction in background of 20-25% was achieved by requiring that the neutron energy derived from the scintillator light output be compatible with the energy derived from neutron time of flight. Real and accidental events were accumulated simultaneously.

Information on the research in Institutes "Boris Kidrič", Vinča, and "Jožef Stefan", Ljubljana are not complete due to the reason stated in the Preface.

Institute "Jožef Stefan":

Dr. N. Cindro has received some data from Ljubljana and he should be able to inform the I.N.D.C. The results of some (n, γ) studies are given in: Nucl. Phys. 130, 401; ibid 138, 412 and 158, 251, as well as in Fizika 2, 41.

Institute "Boris Kidrič":

1) Capture of thermal neutrons on caesium and lanthanum (work in progress).
   J. Simić, B. Lalović, V. Ajdačić, I. Slavić and B. Koički
   The new decay schemes have been determined.

2) The activation analyses and the study of reactor material (work in progress).
   T. Tasovac, V. Bulović, R. Drašković et al.

3) Neutron total cross section measurement on light nuclei
   F. Boreli,
   A part of this has been published in Fizika 2, 97 (1970).

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