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E. Arai, H. Miessner

GESELLSCHAFT FÜR KERNFORSCHUNG M. B. H.

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E. Arai[+] and H. Miessner

Gesellschaft für Kernforschung m.b.H., Karlsruhe

[+] On leave from Tokyo Institute of Technology

Introduction.

Since the first observation of isobaric analogue states in the compound nucleus [1], the usual method to investigate these states with (p,n) reactions is the following. The proton energy is shifted in steps of the energy resolution and the excitation function of the compound nucleus is obtained by measuring the neutron yield as a function of the proton energy. The energy resolution is given by the beam energy spread and the target thickness; it lies in most experiments between 5 and 25 keV. A higher resolution ($\leq$ 1 keV) can be achieved only with an additional stabilizing device for the accelerator and a very thin target [2].

In the present (p,n) experiments a thick target (a few hundred keV for 2 MeV protons) was used and the neutron spectrum was measured by the time-of-flight method. This spectrum gives the corresponding neutron yield as a function of the proton energy (energy range = target thickness), if the neutron energy is converted to the proton energy by addition of the Q value of the (p,n) reaction (neglecting reduction of proton intensity in the target). Neutrons which leave the residual nucleus in excited states can be identified, if these levels are known and if the target thickness is smaller than the spacings between available levels, including the ground state. The energy resolution of this method is independent of the stability of the beam energy and the target thickness, and is given by the time-of-flight spectrometer only. In the additional (p,γ) measurements the conventional technique as described above was used.

Measurements and Results.

In the present work the neutron time-of-flight spectrometer consisted of a pulsed and bunched 3 MeV Van de Graaff generator (pulse length 1 ns, peak current $\sim$ 8 mA, energy spread 2 keV) and a proton recoil detector with a flight path of 10 m. In the proton recoil detector [3] tow photomultipliers (Valvo XP 1040) in coincidence were coupled to the plastic scintillator (NE 102 A) in order to discriminate against multiplier noise and to make measurements at low neutron energies ($\approx$30 keV) possible. The overall energy resolution of the spectrometer was 400 eV, 900 eV, 1600 eV and 3150 eV for 100 keV, 200 keV, 300 keV and 500 keV neutrons, respectively. This shows that the present spectrometer is most advantageous for the study of analogue states with excitation energies not too high above the available level of the residual nucleus. The $^{59}Co(p,n)^{59}Ni$ reaction produces neutrons of about 200 keV in observing analogue states of interest. The energy resolution was <1 keV. However, in the $^{51}V\ (p,n)^{51}Cr$ measurement, in which the corresponding neutron energy lies between 400 and 1000 keV, an energy resolution of a few keV was achieved only.

Isobaric analogue states of ^{52}V and ^{60}Co in the compound nuclei ^{52}Cr and ^{60}Ni were investigated with the (p,n) reaction. Since the lowest expected analogue states in both compound nuclei lie below the Q value [4], they cannot be observed with a (p,n) reaction. However these states can be measured with an additional (p,γ) experiment which, further, at higher energies, makes a comparison with the (p,n) measurements possible. The (p,γ) reaction was already used in [5] to investigate analogue states in ^{52}Cr. For the present (p,γ) measurements thin targets of natural Co and V (≈ 8 keV and ≈ 10 keV thick for 2 MeV protons respectively) were evaporated on thin tantalum backings. The γ-ray intensity was measured as a function of the proton energy with a NaI crystal (diameter: 5 cm, thickness: 5 cm) coupled to a photo-multiplier. The detector was shielded with lead blocks and was placed perpendicularly to the target. The beam energy was measured with a proton resonance device placed in the homogeneous field of the analyzing magnet and was calibrated at the threshold of the $^{7}Li(p,n)^{7}Be$ reaction [6] and at some well known resonance energies of the $Al(p,\gamma)$ reaction [7]. The absolute proton energy scale was accurate to ± 5 keV. The beam intensity was controlled by a current integrator.

Fig. 1 shows the γ-ray intensity measured as a function of the proton energy for the $^{59}Co(p,\gamma)^{60}Ni$ reaction. The corresponding curve of the $^{51}V(p,\gamma)^{52}Cr$ reaction is very similar to that given in [5]; however, Teranishi's curve is shifted by about 20 keV to lower energies. Since the energy resolution in [5] is slightly better than in our (p,γ) experiment, for the comparison with the following (p,n) measurement, Teranishi's curve is presented (Fig. 2). The γ-ray intensity shows maxima at proton energies which may be interpreted as analogue states of $^{60}Co(^{52}V)$ in ^{60}Ni (^{52}Cr) comparing the measured proton energies E_p^{exp} (c.m. system) with the expected energies E_p^{calc}, calculated from the binding energy differences ΔBE [4], the Coulomb displacement energy ΔE_c and the excitation energies E^{exc} of the low lying states of $^{60}Co(^{52}V)$:

$$E_p^{calc} = \Delta E_c - \Delta BE + E^{exc} \qquad (1)$$

ΔE_c is given by the semiempirical formula [8]

$$\Delta E_c = (1.444 \pm 0.005)\ \frac{\bar{Z}}{A^{1/3}} - (1.13 \pm 0.04)\ [\mathrm{MeV}]\ , \qquad (2)$$

where $\bar{Z}$ is the mean charge of the compund nucleus and its isobar. Eq. (2) gives the following values:

$$\Delta E_c = (9.013 \pm 0.070)\ \text{MeV for the analogue pair}\ {}^{60}\text{Ni}\ {}^{60}\text{Co}\ ,$$

$$\Delta E_c = (7.96 \pm 0.070)\ \text{MeV for the pair}\ {}^{52}\text{Cr}\ {}^{52}\text{V}\ .$$

The low lying states of ^{60}Co (^{52}V) are known from the (d,p) reaction [9] ([10]) and from recent (n,γ) experiments [11] ([12]). The expected energies E_p^{cal} are obtained using mean values of the (d,p) and (n,γ) data. They are listed together with the experimental values E_p^{exp} for ^{60}Co and ^{52}V in table 1 and 2 respectively. The difference $E_p^{exp} - E_p^{cal}$ varies more than ± 10 keV for those states only, which are difficult to identify or for which E^{exc} is inaccurate (discrepancies in the (d,p) and (n,γ) data).

The Coulomb displacement energies were obtained experimentally using the first analogue states (peak No 1) observed in the (p,γ) measurement ($E^{exc} = 0$ in Eq. (1)); the results:

$$\Delta E_c = (9.085 \pm 0.020)\ \text{MeV for the analogue pair}\ {}^{60}\text{Ni}\ {}^{60}\text{Co}\ ,$$

and

$$\Delta E_c = (8.075 \pm 0.020)\ \text{MeV for the pair}\ {}^{52}\text{Cr}\ {}^{52}\text{V}\ .$$

The error is given mainly by the uncertainty of the binding energy differences [4]. Both values lie slightly higher than the calculated energies (Eq. 2), given above. However, for ^{52}V, ΔE_c agrees with the value obtained by Teranishi [5] within the accuracy and for ^{60}Co, for which no experimental data exist at present, ΔE_c lies between the values of the neighbouring nuclei ^{56}Fe, ^{59}Co, ^{65}Ni (Fig. 3). In Fig. 3 all hitherto measured data of ΔE_c in the range $47 \leq A \leq 77$, obtained by ß decay measurements and by isobaric reactions are summarized [13] together with the present values for ^{60}Co and ^{52}V.

For the (p,n) measurements thick targets of natural Co and V were used. The Co target (≈200 keV thick for 2 MeV protons) was prepared by electroplating on a tantalum backing. The V target was a 10 µ thick V foil (commercially obtained by Heraeus Hanau) pressed on a tantalum backing. The neutron spectra were measured at different proton energies in steps of the target thickness with an overlap of about 10 % of a step. The absolute proton energy scale was accurate to ± 5 keV. The uncertainty consists principally of the uncertainty of the Q value. The (p,n) measurements have been corrected for the background and for the energy dependent efficiency of the detector. Fig. 4a shows a ^{59}Co(p,n)^{59}Ni cross section measurement in the range of 2.09 to 2.30 MeV proton energy, using neutrons which left the residual nucleus ^{59}Ni in the ground state. The mean energy resolution is 800 eV.

The cross section shows a fine structure superimposed on a gross structure. For a better identification of the latter, the measured curve was folded into a Gaussian with a width ΔE which must be large in comparison with the width of the fine structure and still small enough not to deform the gross structure. It has been found that the averaged curves are practically independent of ΔE within the range ΔE = 6 to 12 keV. Fig. 4b shows the ^{59}Co(p,n)^{59}Ni cross section versus proton energy as averaged with ΔE = 8 keV. It is expected that the positions and the shape of the resonances must be the same for the (p,n) and (p,γ) reaction, since an analogue resonance is dominated by the proton channel. The positions of the peaks 6,7 and 8 in Fig. 4b agree excellently with those observed as single peaks in the (p,γ) measurement (Fig. 1 and table 1) and the resonance shapes in both measurements are similar. With the neutron time-of-flight method the fine structure within the analogue resonance peaks has been resolved as seen in Fig. 4.
Fig. 5a shows a ^{51}V(p,n)^{51}Cr cross section measurement in the range of 1.9 to 2.36 MeV proton energy using neutrons which left the residual nucleus ^{51}Cr in the ground state. The energy resolution lies between 1.7 and 5 keV. The averaged curve (Fig. 5b) (ΔE = 5 keV) was practically independent of ΔE in the range ΔE = 3...15 keV. Due to the poor energy resolution at higher energies there is no difference between the measured and the averaged curve above 2.3 MeV.

The peaks No 8 to 12 in Fig. 5b correspond to maxima in the (p,γ) yield (Fig. 2). While the positions of the peaks in both curves agree satisfactorily, there is a slight difference of their amplitudes (i.e. peak 8 and 11).

Summary

The neutron time-of-flight method was used to investigate the cross section of the reactions ^{59}Co(p,n)^{59}Ni and ^{51}V(p,n)^{51}Cr. The cross section shows a fine structure superimposed on a gross structure; the peaks of the latter are interpreted as analogue states of ^{60}Co and ^{52}V in the compound nuclei ^{60}Ni and ^{52}Cr respectively. Additional (p,γ) cross section measurements on ^{59}Co and ^{51}V served as a check and were also used to determine the Coulomb displacement energy.

We wish to thank Prof. Dr. K.H. Beckurts for his suggestion and for his interest in the present measurements.

Table 1 Isobaric analogue states in ^{60}Ni obtained from the (p,γ) reaction

States in ^{60}Co				Analogue states measured in proton energies (c.m. system)			Peak No.
(d,p) [9]	(n,γ) [11]	J [11]	Configuration [11]	E_p^{calc} [MeV]	E_p^{exper} [MeV]	$E_p^{exp}-E_p^{calc}$ [keV]	
0	0	5^+	$(f\frac{7}{2})_p^{-1}(f\frac{5}{2})_n^2(p\frac{3}{2})_n^{-1}$	1.522	1.594±0.004	72	1
0.058	0.0575	2^+	$(f\frac{7}{2})_p^{-1}(f\frac{5}{2})_n^2(p\frac{3}{2})_n^{-1}$	1.589	1.650 1.665	69	2
0.282	0.2760* 0.2881	4^+ 3^+	$(p\frac{3}{2})_n^4(p\frac{1}{2})_n^1$	1.798 1.810	1.867 1.886	69 76	3
0.432	0.4343	5^+	$(p\frac{3}{2})_n^4(f\frac{5}{2})_n^1$	1.955	2.037	82	4
0.501	0.5051	3^+	$(f\frac{5}{2})_n^2(p\frac{3}{2})_n^{-1}$	2.025	2.092	67	5
0.541	0.5405	2^+	$(p\frac{3}{2})_n^4(f\frac{5}{2})_n^1$	2.063	2.149	86	6
0.612	0.6131	3^+	-	2.135	2.219	84	7
0.738	(0.738)	$(1^+,2^+)$	-	2.260	2.273	13	8

* This doublet was already suggested in ref. 9

Table 2 Isobaric analogue states in ^{52}Cr

States in ^{52}V			Analogue states measured in proton energies (c.m. system)				Peak No.
(d,p) [10]	(n,γ) [12]	J	E_p^{calc}	E_p^{exp}		$E_p^{exp}-E_p^{calc}$ [keV]	
0	0	2^+	0.652	0.766±0.01	(p,γ) measurement	114	1
0.020	0.021		0.673	0.780		107	2
0.146	0.146		0.793	0.897		104	3
0.434	0.431		1.084	1.179		95	4
(0.768)	-		(1.420)	-		---	5
0.789	0.787		1.440	1.532		92	6
0.837	0.841		1.491	1.595		104	7
0.873	0.873		1.525	-		---	-
(1.287)	1.280		1.936	-		---	-
1.414	1.406		2.062	2.170±0.02	(p,n) measurement	108	8
1.488	1.434		2.113	2.265±0.005		152	9
1.556	1.550		2.205	2.301		96	10
1.577	1.557		2.219	-		---	--
1.732	1.653		2.344	2.469		125	11
1.756	-		2.408	2.450		82	12

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Figure Captions

Fig. 1 Gamma-ray yield as a function of the proton energy from the $^{59}Co(p,\gamma)$ reaction

Fig. 2 Gamma-ray yield as a function of the proton energy from the $^{51}V(p,\gamma)$ reaction [5]

Fig. 3 $\frac{\Delta E_c \cdot A^{1/3}}{Z}$ as a function of $\frac{Z}{A^{1/3}}$ in the range $47 \leq A \leq 77$ for those nuclei, for which the Coulomb displacement energy is known with an accuracy of better than 50 keV. The nucleus specified is the member of the analogue pair having the higher neutron excess.

Fig. 4 Neutron yield as a function of the proton energy (energy resolution $\sim$ 800 eV) for the $^{59}Co(p,n)$ reaction

a) measured
b) averaged with $\Delta E = 8$ keV

Fig. 5 Neutron yield as a function of the proton energy (energy resolution 1.7 - 5 keV) for the $^{51}V(p,n)$ reaction

a) measured
b) averaged with $\Delta E = 5$ keV

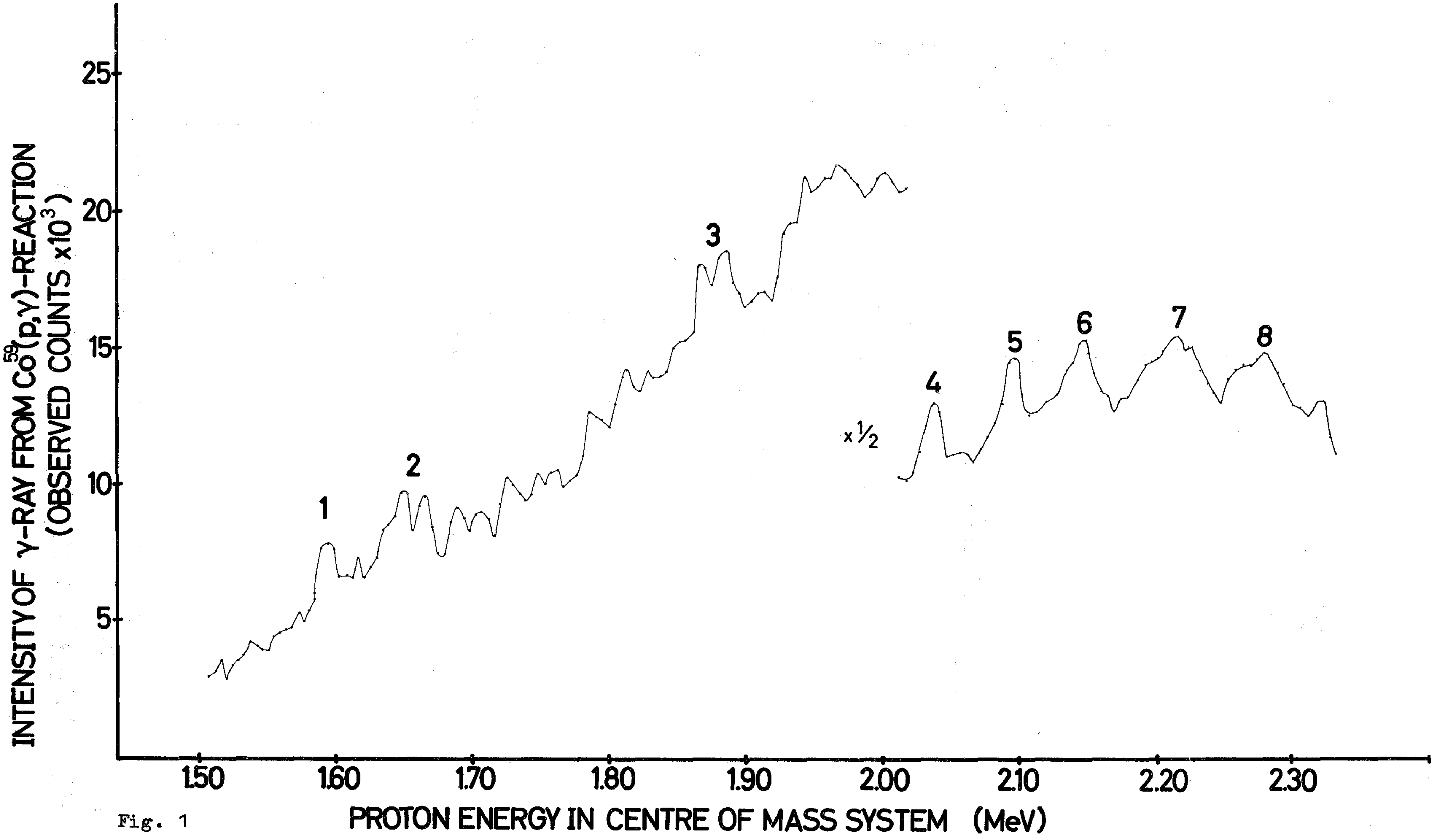
INTENSITY OF γ-RAY FROM Co59(p,γ)-REACTION
(OBSERVED COUNTS x10³)
25
20
15
10
5
1
2
3
4
5
6
7
8
x ½
1.50
1.60
1.70
1.80
1.90
2.00
2.10
2.20
2.30
PROTON ENERGY IN CENTRE OF MASS SYSTEM (MeV)

Fig. 1

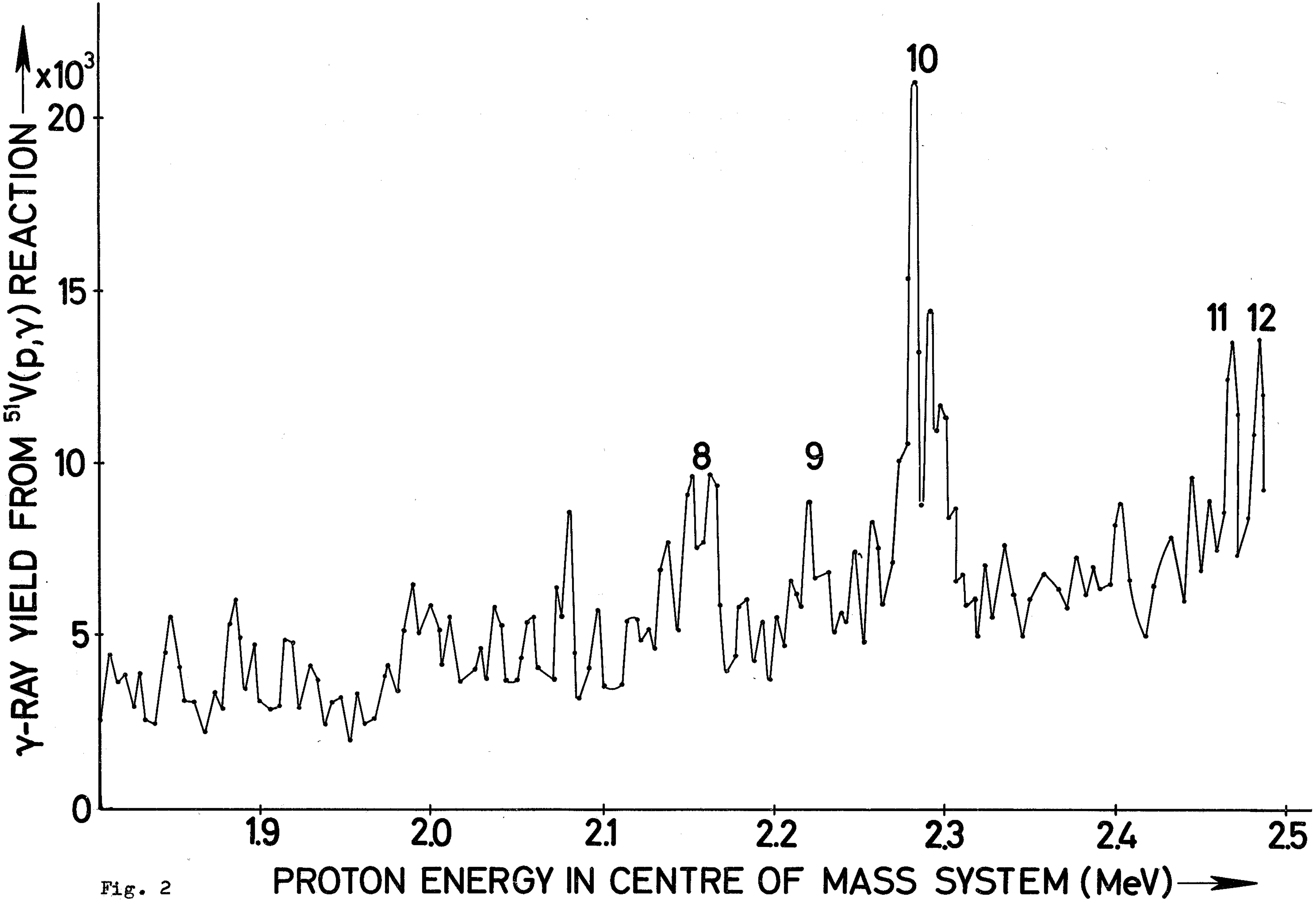
γ-RAY YIELD FROM ^{51}V(p,γ) REACTION
x10^3
20
15
10
5
0
10
8
9
11
12
1.9
2.0
2.1
2.2
2.3
2.4
2.5
PROTON ENERGY IN CENTRE OF MASS SYSTEM (MeV)

Fig. 2

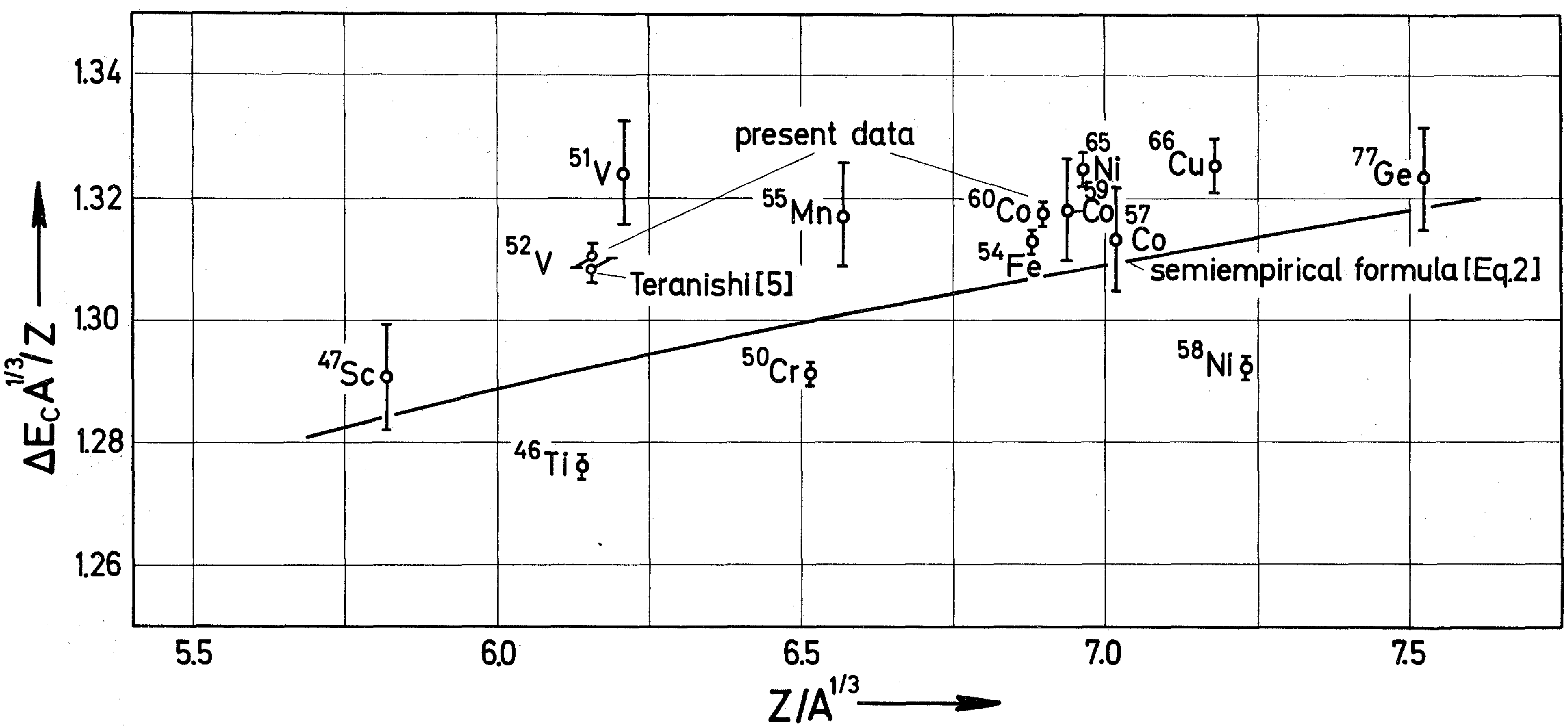
1.34
1.32
1.30
1.28
1.26
$\Delta E_C A^{1/3}/Z$
5.5
6.0
6.5
7.0
7.5
$Z/A^{1/3}$
present data
Teranishi [5]
semiempirical formula [Eq.2]
^{51}V
^{52}V
^{55}Mn
^{60}Co
^{65}Ni
^{59}Co
^{57}Co
^{66}Cu
^{77}Ge
^{54}Fe
^{47}Sc
^{50}Cr
^{58}Ni
^{46}Ti

Fig. 3

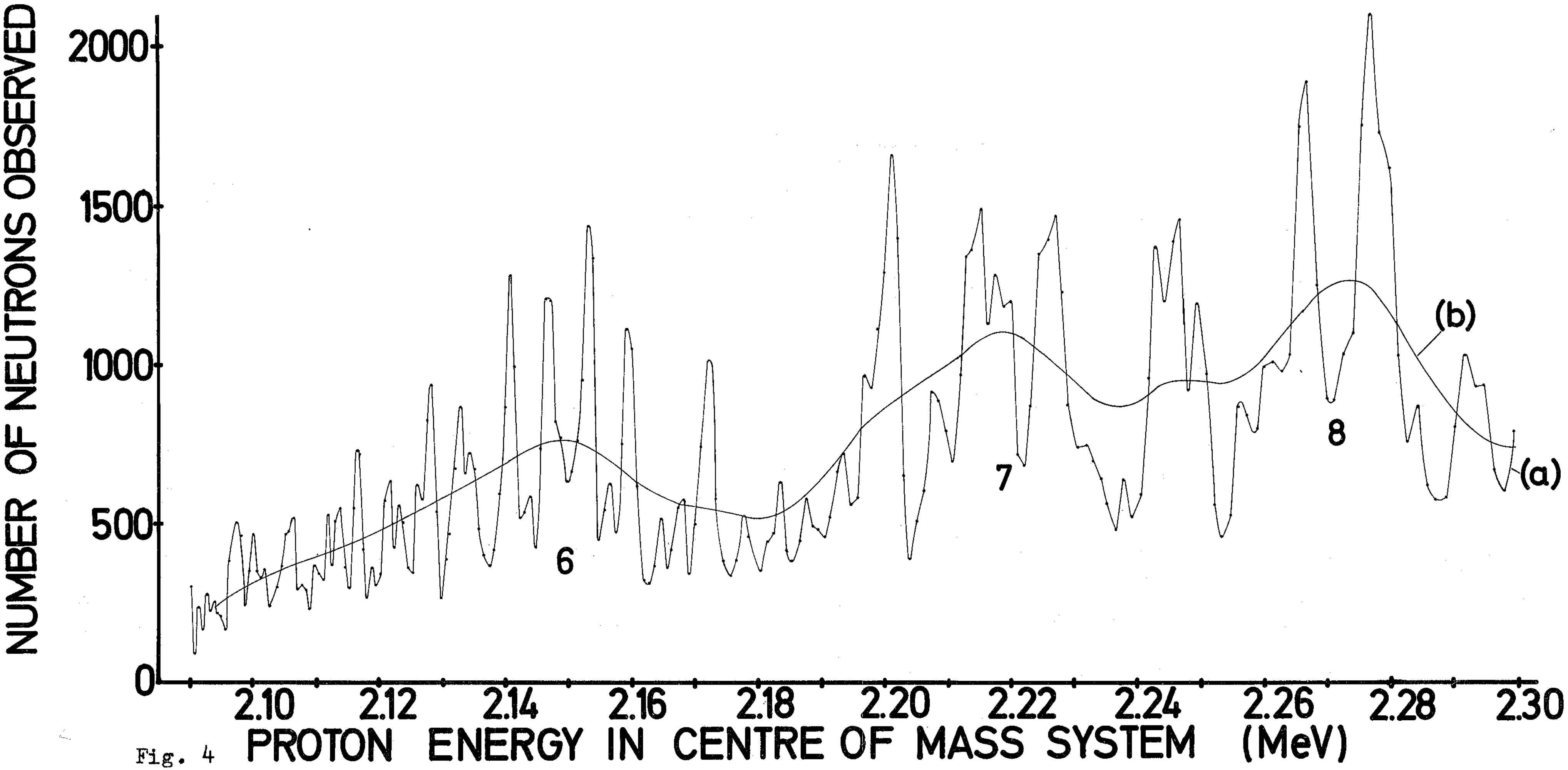
NUMBER OF NEUTRONS OBSERVED
2000
1500
1000
500
0
2.10
2.12
2.14
2.16
2.18
2.20
2.22
2.24
2.26
2.28
2.30
PROTON ENERGY IN CENTRE OF MASS SYSTEM (MeV)
6
7
8
(a)
(b)

Fig. 4

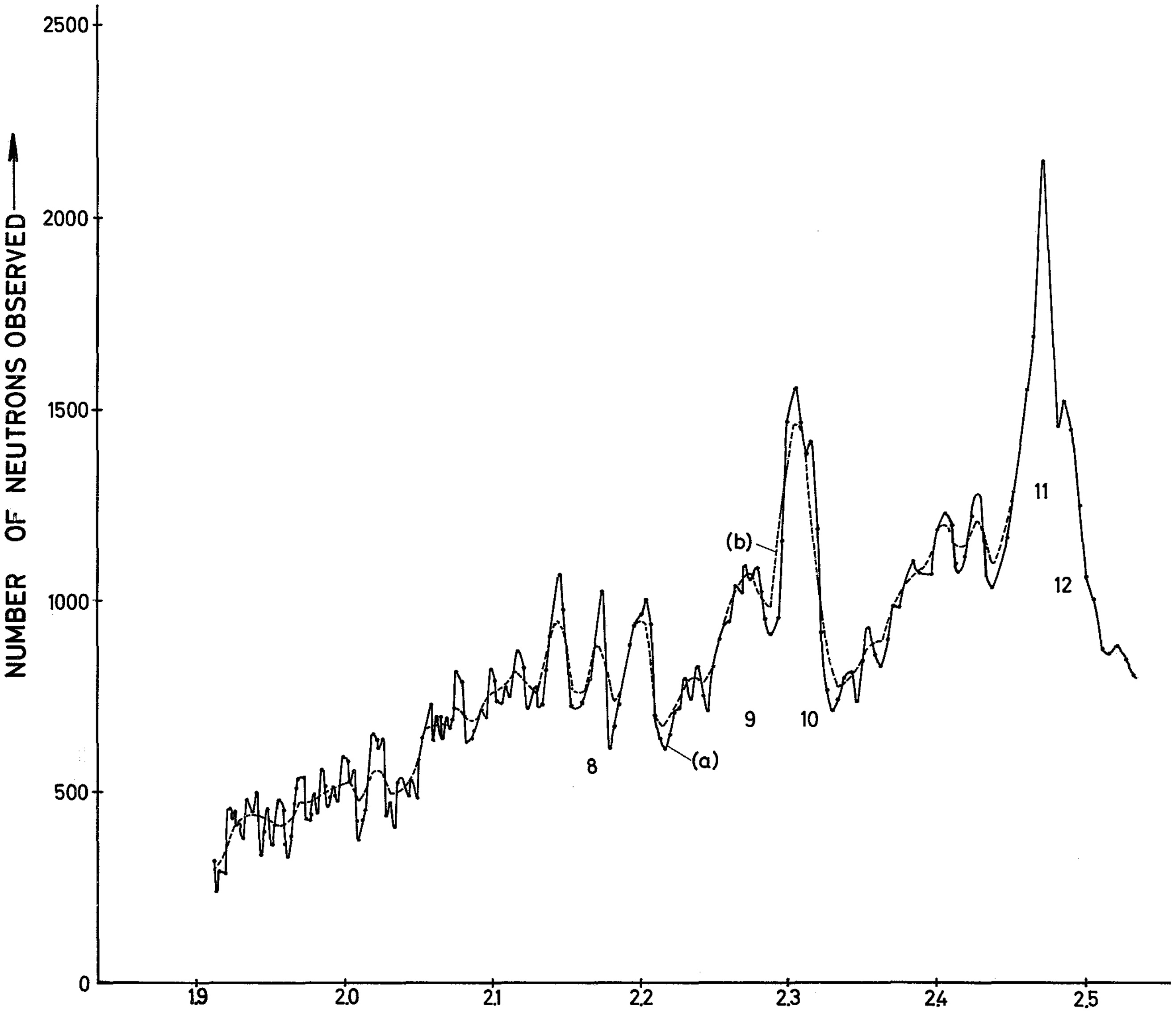

Fig. 5 PROTON ENERGY IN CENTRE OF MASS SYSTEM (MEV)