ОБЪЕДИНЕННЫЙ ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ
ЛАБОРАТОРИЯ ЯДЕРНЫХ ПРОБЛЕМ

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THE (p, pn) AND (p, n) REACTIONS ON Sc^{45} INDUCED BY HIGH-ENERGY PROTONS

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1. Introduction

The present paper proceeds with our work on the study of simple nuclear reactions on complex nuclei, in particular, of the influence of the target-nucleus structure upon them. The $_{21}Sc^{45}$ nucleus close by A and Z to $_{20}Ca^{48}$, already studied /1/ by ourselves, was used as a target. The chosen target gave also the possibility of determining the relative yields of isomers from the reaction (p, pn).

2. Experimental Procedure

2.1. The target and the conditions of irradiation

The target was pressed in the form of a rectangular tablet ($15 \times 4 \times 1\ mm^3$) of scandium oxide. The conclusion on the proper degree of the target material purity was drawn basing on the fact that in the scandium fraction separated after the irradiation no isotopes with mass numbers > 44 have been found. Those isotopes would be inevitably produced in the presence of heavy admixtures.

Targets were irradiated in the internal proton beam of the Joint Nuclear Research Institute synchrocyclotron during 15-20 minutes. The thickness of the target along the beam was $\approx$ 1 mm. The variation of the incident proton energy was achieved by suitable choice of target radius. The determination of the proton beam intensity was made by the yield of the reaction Al^{27} (p, 3pn) Na^{24} .

The contribution of the reaction (n, 2n) to the cross-section of the reaction (p, pn) was neglected, the earlier estimates /1/ being taken into consideration.

2.2. Chemical treatment of the target

The major mass of the irradiated target was dissolved in the concentrated hydrochloric acid saturated with gaseous HCl, 15 mg of the titanium carrier being present. In order to speed up the process of the complete target dissolution scandium and titanium chlorides and the undissolved fraction of the scandium oxide were transformed into sulfate by evaporating with concentrated H_2SO_4 . The sulfates Sc and Ti, thus obtained, were easily dissolved in hot water. Scandium and titanium hydro-oxides were precipitated from the solution by adding NH_4OH. The precipitation washed was dissolved in hot concentrated HCl. A small amount of 30% H_2O_2 was added to the solution and Sc was extracted by tributilphosphate /2/. Then radiochemical purification of scandium and titanium fractions was made.

The purification of the scandium fraction consisted of two operations: the precipitation of scandium ftoride with the aid of Na_2SiF_6 and the extraction of scandium by tributilphosphate from the concentrated solution of HCl in the presence of H_2O_2 and some milligramms of titanium as holdback carrier. Finally scandium was precipitated in the hydroxide form. On completing the measurements scandium hydroxide was heated and weighed in the Sc_2O_3 form.

The purification of titanium fraction consisted of three operations: the precipitation of titanium hydroxide in the presence of the complexon III and iron ions; the scavenging by the iron sulfide in the presence of tartaric acid; the extraction of titanium cupferronate from IN HCl by chloroform. Finally titanium was precipitated in the hydroxide form. On accomplishing the measurements titanium hydroxide was heated and weighed in TiO_2 form.

2.3. Measurements of activity

The measurements of the sample activity were perfomed with a scintillation γ – spectrometer/1/. Radioactive characteristics of isotopes /3,4,5/ used in the calculation of the cross-sections of the reactions under study are given in Table 1.

Table 1.

Nucleus	Half-life	Energy of the specific γ – line (KeV)	Number of γ-rays/decay %
Na^{24}	15,0 h	1368	100
Sc^{44m}	59 h	1160	100
Sc^{44g}	3,9 h	1160	100
Ti^{45}	3,09h	511	100

The decay scheme of Sc^{44} is shown in Fig. 1. The law of changing with time I_{1160}, the intensity of the 1160 KeV γ - line, is as follows:

$$I_{1160} = \left(A^{\circ}_{g} - A^{\circ}_{m} \frac{\lambda_g}{\lambda_g - \lambda_m} \right) e^{-\lambda_g t} + A^{\circ}_{m} \frac{\lambda_g}{\lambda_g - \lambda_m} e^{-\lambda_m t}$$

where A° is the activity at the end of irradiation,

λ is the decay constant,

t is the time passed from the end of irradiation, and the subscripts m and g refer to the isomeric and ground state of Sc^{44} respectively.

The activity $A^{\circ}_{m} = \lambda_m N^{\circ}_{m}$, where N^{0}_{m} is the number of Sc^{44m} nuclei produced for the time of irradiation, i.e. the value necessary for calculating the cross-section. The activity A^{0}_{g} involves also the term taking into account the accumulation of Sc^{44g} from Sc^{44m}, during irradiation. However, in our case this contribution can be neglected. The error introduced into the cross-section under study σ_g is not larger than 0.2%.

Thus, the measurements of I_{1160} provide all the necessary information for the determination of σ_m and σ_g.

As for the detection of annihilation radiation of Ti^{45} one may say that under the conditions of our measurements positron annihilation occured mainly on the crystal surface and only one 511 KeV gamma-ray per decay should have been registered. However, due to annihilation in the surrounding shielding etc. this number was somewhat larger than unity and was determined experimentally with the Na^{22} isotope, the decay scheme of which is well known.

3. Experimental Results

The values of the cross-sections of the reactions Sc^{45} (p,pn) and Sc^{45} (p,n) in mb, the ratios of the cross-sections of Sc^{44g} and Sc^{44m} productions and the cross-sections of the monitor reaction /6/ in the energy range of incident protons from 120 to 670 MeV are enlisted in Table 2. For the sake of comparison the cross-sections of the reactions (p, pn) and (p, n) on Ca^{48} , taken from ref. /1/ are also given in the same Table.

Table 2

E_p,MeV	I20	200	300	400	500	600	670
Sc^{45}(p,pn)	70,I ± I,8	50,4 ± I,2	48,5 ± I,2	47,7 ± I,0	43,I ± I,0	42,0 ± 0,7	39,4 ± 0,7
Sc^{45}(p,n)	3,80 ±0,07	2,29 ±0,03	I,82 ±0,04	I,40 ±0,07	I,I4 ±0,09	I,07 ±0,09	0,83 ±0,02
Sc^{44g}/Sc^{44m}	2,I0 ±0,06	2,2I ±0,03	2,I9 ±0,0I	2,22 ±0,0I	2,I9 ±0,06	2,I8 ±0,02	2,20 ±0,04
Ca^{48}(p,pn)	II8±2	106±10	106±4	101±4	104±1	110±8	110±2
Ca^{48}(p,n)	7,8 ± 0,3	4,7 ±1,2	4,1 ±0,3	3,6 ±0,1	3,9 ±0,2	2,2 ±0,2	2,6 ±0,1
Al^{27}(p,3pn)	10,2	9,1	11,0	11,3	11,1	11,0	10,9

The above values are average from three or four determinations, with standard errors. The total accuracy of the cross-section determination is $\approx$ 10% according to our evaluation. In our estimation as well as in calculation of the cross-sections and standard errors possible systematic errors due to the inaccuracy in the decay schemes and in the cross-section of the monitor reaction were not taken into consideration.

It is worth noting that the evaluation of the accuracy of the determination of the isomeric cross-section ratio is about 5% and depends, mainly, upon the accuracy of the decay curve resolving.

4. Discussion of the Results

4.1. Excitation functions

As is seen from Table 2 and Fig. 2, the cross-sections of the reactions under study decrease monotonously with increasing energy of the incident proton. The cross-section of the reaction (p,n) is reduced more sharply than that of the reaction (p, pn).

The behaviour of the excitation functions of the reactions Sc^{45} (p, pn) and Ca^{45} (p, pn) differ from each other. In the case of Ca^{48} the cross-section of the reaction (p, pn) beginning from 200 MeV remains practically constant. This difference appears to be due to a possible contribution of the reaction Ca^{48} (p, 2p) to the value of the reaction (p, pn)[1]. The values of the (p, 2p) reaction, judging by the published data[7,8] tend to increasing with increasing incident proton energy, which may give rise to the constancy of $\sigma_{p,pn}$ observed.

4.2. The absolute values of $\sigma_{p,pn}$

First of all, one should note a considerable difference in the values of the cross-sections of the reactions (p, pn) on nuclei close by A and Z (see Table 2). This circumstance directly shows the strong influence of the target-nucleus structure.

At present such reactions are supposed to take place by direct interaction of the incident proton with the nucleons of the nuclear diffuse surface. This assumption was explicitely discussed and treated experimentally for the GeV incident particle energy range by Benioff[9] and a number of other authors e.g.[10, 11]. According to our assumptions[1], this mechanism becomes predominating even in the proton energy range of the order of 200 MeV. Remsberg[12] has drawn the analogous conclusion. According to his evaluation at least 90% of the (p,pn) reaction occurs by the direct knock-on mechanism at E_p = 370 MeV. Then the cross-section of the (p,pn) reaction should be proportional to the number of neutrons the knocking on of which from the nucleus does not give rise to excitation exceeding the nucleon binding energy.

Thus, for the (p, pn) reaction those neutrons are available which are in a shell whose distance below the topmost occupied level is smaller than the binding energy of the least bound particle in the product nucleus. The least bound particle in the Sc^{44} nucleus is a neutron with the separation energy of 9.7 MeV[5]. According to the scheme of nucleon energy levels in the nucleus which was calculated by Ross et al.[13], in the case of Sc^{45} neutrons situated on the levels $1f_{7/2}(4)$, $1d_{3/2}(4)$, $2s_{1/2}(2)$ satisfy this condition. In brackets is given the number of neutrons on the appropriate level. Now if one makes use of the calculation scheme and parameters, quoted in ref.[9], then for the proton energy of 3 GeV the cross-section of the (p, pn) reaction is determined by the expression

$$\sigma_{p,pn} = 36 \; \Sigma \; NM ,$$

where N is the number of neutrons on the given levels and M is their fractional availability for the (p,pn) reaction. Summation is performed over all the available levels. The calculation gives the value of the Sc^{45} (p,pn) reaction cross-section to be 39.5 mb. In our calculation we used the value of M for the half density radius parameter r_0 = 1.07 f.

Taking into consideration weak energy dependence $\sigma_{p,pn}$, one may say that the above evaluation is in good agreement with our data. This confirms once more the assumption on the primary role of the mechanism of direct neutron knock-on process in the energy region of the order of a magnitude of hundreds MeV.

In the case of Ca^{48} the same levels $1f_{7/2}$ (8), $1d_{3/2}$ (4), $2s_{1/2}$ (2) appear to be available. The increase of the number of available neutrons from 10 to 14 should give rise to the proportional* increase of the cross-section of the (p,pn) reaction. As is seen from Table 2, the cross-section of the reaction Ca^{48} (p,pn) is larger than it might be expected from the above considerations. However, this excees may be explained by the contribution of the (p,2p) reaction. Thus, for E_p = 400 MeV the cross-section of the reaction Ca^{48} (p,pn) should have been about 70 mb. With this proton energy the cross-sections of the reaction Si^{30} (p, 2p) and Zn^{68} (p, 2p) are about 20 mb[8] while in the reaction Zr^{96} (p,2p) it is about 40 mb[7]. The excess of the experimental cross-section of the reaction Ca^{48} (p,pn) over the expected one is about 30–35 mb, which agrees fairly well with the quoted cross-sections of

* Coefficients *M* for Sc^{45} and Ca^{48} are practically equal.

the reaction (p, 2p). We confined ourselves to the evaluation of the contribution of the reaction (p, 2p) only at 400 MeV, since at larger energies of incident protons there is no information on the cross-section of the reaction (p,2p), while at lower energies the comparison would not be so convincing due to the reduction of relative role of the direct knock-on mechanism.

4.3. Comparison of the reactions (p,pn) and (p, n)

In our previous paper/1/ it has been noted that the ratio $\sigma_{p,pn} / \sigma_{p,n}$ is strongly dependent upon the incident proton energy and practically is independent of the number of nucleons in the target-nucleus. As is seen from Fig. 3, the corresponding ratios for Sc^{45} agree well with the previous situation.

However, if one takes into account that $\sigma_{p,pn}$ for Ca^{48} and Th^{232} contains a noticeable contribution from the reaction (p, 2p) , then one should, evidently, divide all the available data into two groups which are somewhat different by the value of the ratio $\sigma_{p,pn} / \sigma_{p,n}$. One group consists of Sc^{45} and Ga^{69} nuclei, and the other consists of Ca^{48} , Y^{89} , Th^{232} with smaller values of $\sigma_{p,pn} / \sigma_{p,n}$. Such a difference is due, most likely, to the fact that the previously made assumption/1/ on the equal number of neutrons available for the reactions (p, pn) and (p, n) is justifiable only in the first approximation. Indeed, taking into account the contribution of the reaction (p, 2p) , it can be seen from Table 2 that $\sigma_{p,n}$ from Sc^{45} to Ca^{48} changes considerably sharper, than $\sigma_{p,pn}$. This may be accounted for the fact that a smaller number of neutrons is available for the reaction (p,n), namely, only neutrons of the highest level completely or partially populated. It is natural that in future this assumption should be checked experimentally.

4.4 Mechanism of the reaction (p, n).

It is natural to think that the mechanism of the reaction (p, n)consists in scattering at a large angle of the incident proton on the neutron of the target nucleus. The neutron leaves the nucleus carrying away a larger fraction of energy and the proton is captured by the nucleus.

By assuming that this mechanism is valid the energy dependence of the cross-section of the reaction (p, n) should be analogous to the energy dependence of the differential cross-section of elementary n-p scattering at angles corresponding to the scattering particle energy $\lesssim$ 8 MeV (in the laboratory system). It should be noted that the change of the upper energy limit of the scattering particle from 8 to 10 MeV influences upon the absolute value of the differential cross-section ($\sim$ 10 %) and does not affect practically the character of energy dependence.

Fig. 4 shows the energy dependence of the differential cross-section of n-p scattering calculated in the above way by the data of/17-20/. Also the relative values of $\sigma_{p,n}$ for Sc^{45} and Ca^{48} are given. For the convenience of comparison all the data are normalized to unity with E_p = 300 MeV. It is seen that at $E_p \gtrsim$ 300 MeV the energy dependence of the differential cross section of n-p scattering and that of the cross section of the reaction (p, n), in fact coincide. A certain spread of points for Ca^{48} can be accounted for, evidently, by experimental difficulties in observing the reaction (p, n). Thus, from the analysis of Fig. 4 one may arrive at the conclusion that the reaction (p, n) may proceed direct interaction beginning from $E_p \cong$ 300 MeV.

4.5. Production cross-section of the isomers Sc^{44g} and Sc^{44m}.

The dependence of the isomeric cross-section ratios upon the incident proton energy is shown in Fig. 5. From $E_p \approx 200$ MeV the ratio σ_g / σ_m becomes constant. Its average value in the energy range 200-670 MeV is 2.20 ± 0.01. This value is consistent with the value 2.1 obtained by Remsberg/12/ for $E_p = 370$ MeV. At the same time the total cross-section of the reaction Sc^{45} (p, pn) according to his data amounts to (34.5 ± 1.6) mb, while according to our results at this proton energy the production cross-section of only Sc^{44g} is about 33mb. The reasons of such a divergence are not clear.

The isomeric cross-section ratio in the reaction (p, pn) can be calculated by assuming the mechanism of direct neutron knock-on as it has been done by Porile and Tanaka/11/. The calculation scheme is as follows. As a result of neutron knock-on from the levels $1f_{7/2}$, $1d_{3/2}$, $2s_{1/2}$ (available for the reaction) of Sc^{45} (7/2) a set of states is formed with the angular momenta j, ranging from $|\frac{7}{2} - j_1|$ to $\frac{7}{2} + j_1$ and the relative weights proportional to $(2j+1)$. Here j_1 is the angular momentum of the ejected neutron. The de-excitation of these states takes place as a cascade of γ-rays.

Further consideration of the process is performed in the manner of Huizenga and Vandenbosch /21/. It is suggested that γ-radiation is of a dipole character and the branching ratio of the transition from the state with spin j to the state with spin $j_f = (j-1), j, (j+1)$ is given by the expression:

$$P_{(j_f)} \approx (2j_f + 1)\ \exp[-(j_f + ½)^2 / 2\sigma^2]^*$$

The average number of γ-rays emitted per cascade in the case of (n, γ)-reactions is equal to 3-4. It may be expected that multiplicity of γ-rays in neutron knocking-on in the reaction (p, pn) is not larger than the above number. Various spin states of the residual nucleus produced as a result of gamma-ray emission enter either into isomeric or ground states of Sc^{44} depending on which transition requires smaller spin change. Thus, the states with spin $j_f \geq 6$ give rise to the production of Sc^{44m} (7 +), the states with spin $j_f \leq 4$ give rise to the production of Sc^{44g} (3 +), and the state with $j_f = 5$ is distributed between them equally.

Taking into account different contributions of the neutron levels available for the reaction, one may write the expression for the isomeric cross-section ratio in the following form:

$$\frac{\sigma_g}{\sigma_m} = \frac{\Sigma_{j_1} NM\ \Sigma_j\ w_g\ p}{\Sigma_{j_1} NM\ \Sigma_j\ w_m\ p}$$

Here $p = \dfrac{2j+1}{\sum\limits_{j=|7/2 - j_1|}^{7/2+j_1} (2j+1)}$ is the weight of the state with spin j,

w_g and w_m are the production probabilities of the ground and the isomer states, respectively, calculated in the above way.

*Here σ is a known parameter entering into the expression for nuclear level density. Both this parameter and the cross sections of nuclear reactions are denoted by σ, what is so customary, that we considered it possible not to change them.

The results of calculation for various values of the parameter σ and for various γ -ray multiplicity are listed in Table 3. It is easily seen that the experimental value σ_g / σ_m agrees best of all with calculation when the value of the parameter σ is close to 4. The assumption on the γ -ray multiplicity influences weakly upon σ_g / σ_m

The value of the parameter σ may be estimated also theoretically by the formula, suggested by Bloch[22]:

$$\sigma^2(0) = \Sigma_\alpha \; g_{n,\alpha} m_\alpha^2 \left(e^{a/2} + e^{-a/2} \right)^{-2},$$

where $\sigma(0)$ is the value of the parameter with zero excitation energy;

$g_{n,\alpha}$ is the number of nucleons in the given state;

m_α is the set of constants characterizing the projection of the nucleon angular momentum in the given state;

a is obtained from the condition that e^a should be equal to the ratio of the number of nucleons at the highest level (for the given nucleus) to the number of the remaining vacancies at the same level.

The summation refers only to the upper totally or partially populated level.

Table 3

Levels and the number of emitted γ-rays		Parameter σ 3	4	5
$1f_{7/2}$, $1d_{3/2}$, $2s_{1/2}$	$N_\gamma = 2$	2.75	2.07	1.82
$1f_{7/2}$, $1d_{3/2}$, $2s_{1/2}$	$N_\gamma = 3$	3.16	2.10	1.74
$1f_{7/2}$, $1d_{3/2}$, $2s_{1/2}$	$N_\gamma = 4$	3.57	2.13	1.69
$1f_{7/2}$, $1d_{3/2}$, $2s_{1/2}$	*$N_\gamma = 2$, $N_\gamma = 3$	2.74	1.98	1.70
$1f_{7/2}$, $1d_{3/2}$, $2s_{1/2}$	$N_\gamma = 3$, $N_\gamma = 4$	3.16	2.04	1.66

The values of the sum $\Sigma_\alpha \; g_{n,\alpha} m_\alpha^2$ up to the values which are of interest to us are given in Table 4 for two cases. In the left hand side they are given without spin-orbital interaction being taken into account and for the total number of nucleons[22]. In the right hand side they are given for one sort of nucleons with the account of the spin-orbital interaction. In the latter case $\sigma^2(0)$ has the form of the sum of similar items referring to neutrons and protons, respectively. The configuration of external nucleons Sc^{45} can be presented as $(1f)^5$ for the first case and as

Table 4

States	$1s$	$1p$	$1d$	$2s$	$1f$	$1s_{1/2}$	$1p_{3/2}$	$1p_{1/2}$	$1d_{5/2}$	$2s_{1/2}$	$1d_{3/2}$	$1f_{7/2}$
$\Sigma_a\, g_{n,a}$	4	I2	20	4	28	2	4	2	6	2	4	8
$\Sigma_a\, g_{n,a}\, m_a^2$	I	II	45	I	II9	I/2	I0/2	I/2	35/2	I/2	I0/2	84/2

$p(1f_{7/2})^4$ and $n(1f_{7/2})^4$ for the second case. The calculated values of the parameter σ amount to 4,2 and 3,9 respectively. It is seen that the consideration of the spin-orbital interaction allows to obtain perfect agreement of the calculation value with the experimental data.

It appears to be of interest to check the applicability of comparatively simple presentations which form the basis of the formula for $\sigma^2(0)$ /22/ for other nuclei as well, in particular for heavier ones.

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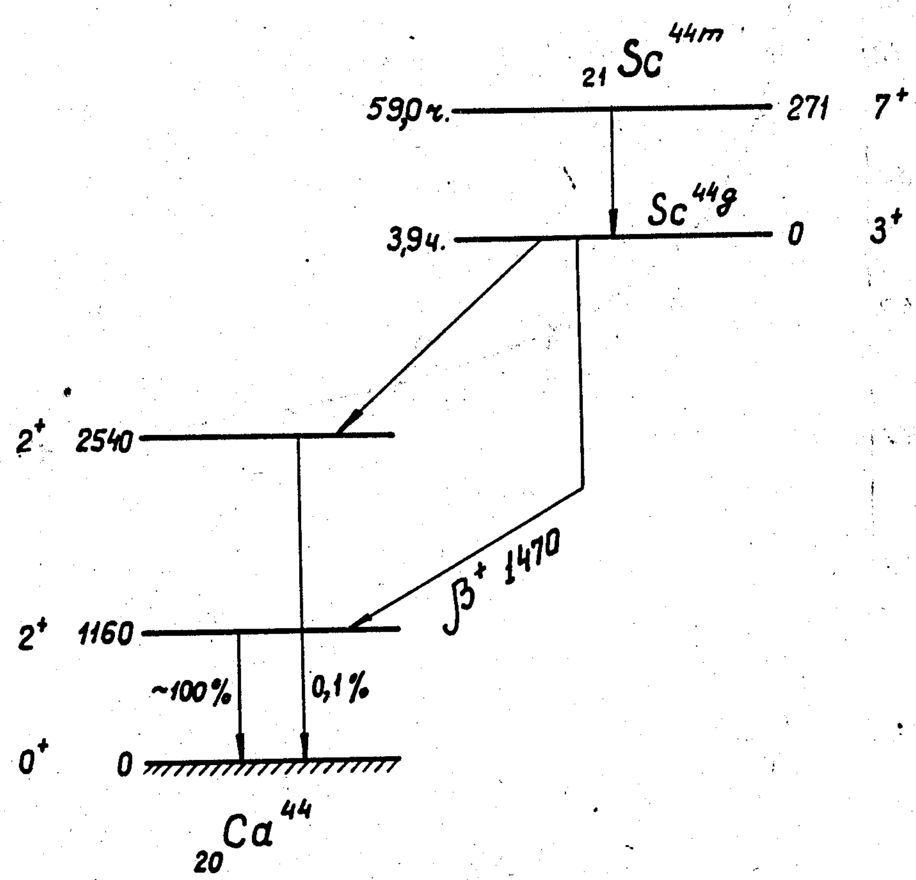

Fig. 1. Decay scheme of Sc^{44}.

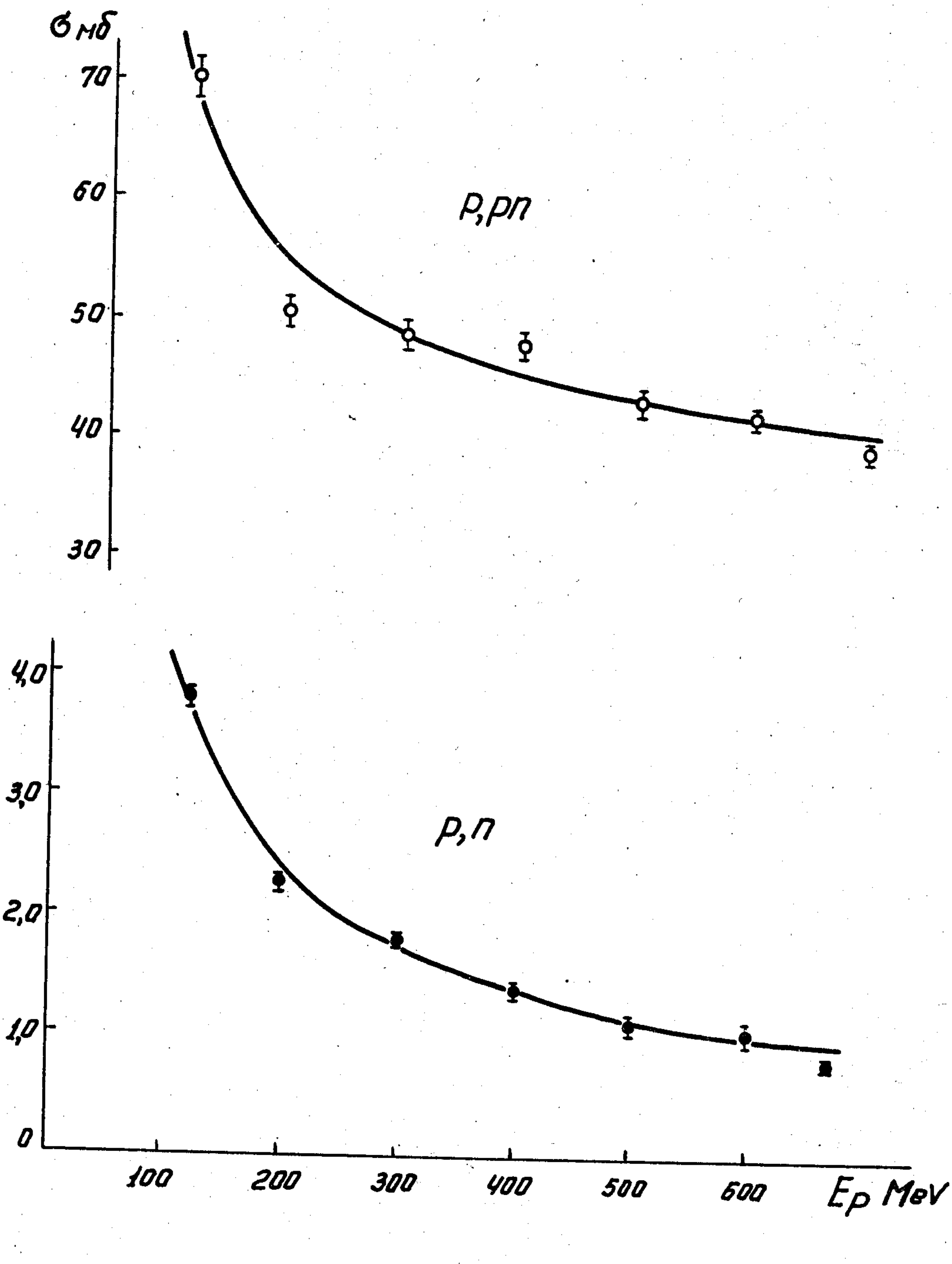

Fig. 2 Excitation functions of the reactions Sc^{45} (p, pn) and Sc^{45} (p,n).

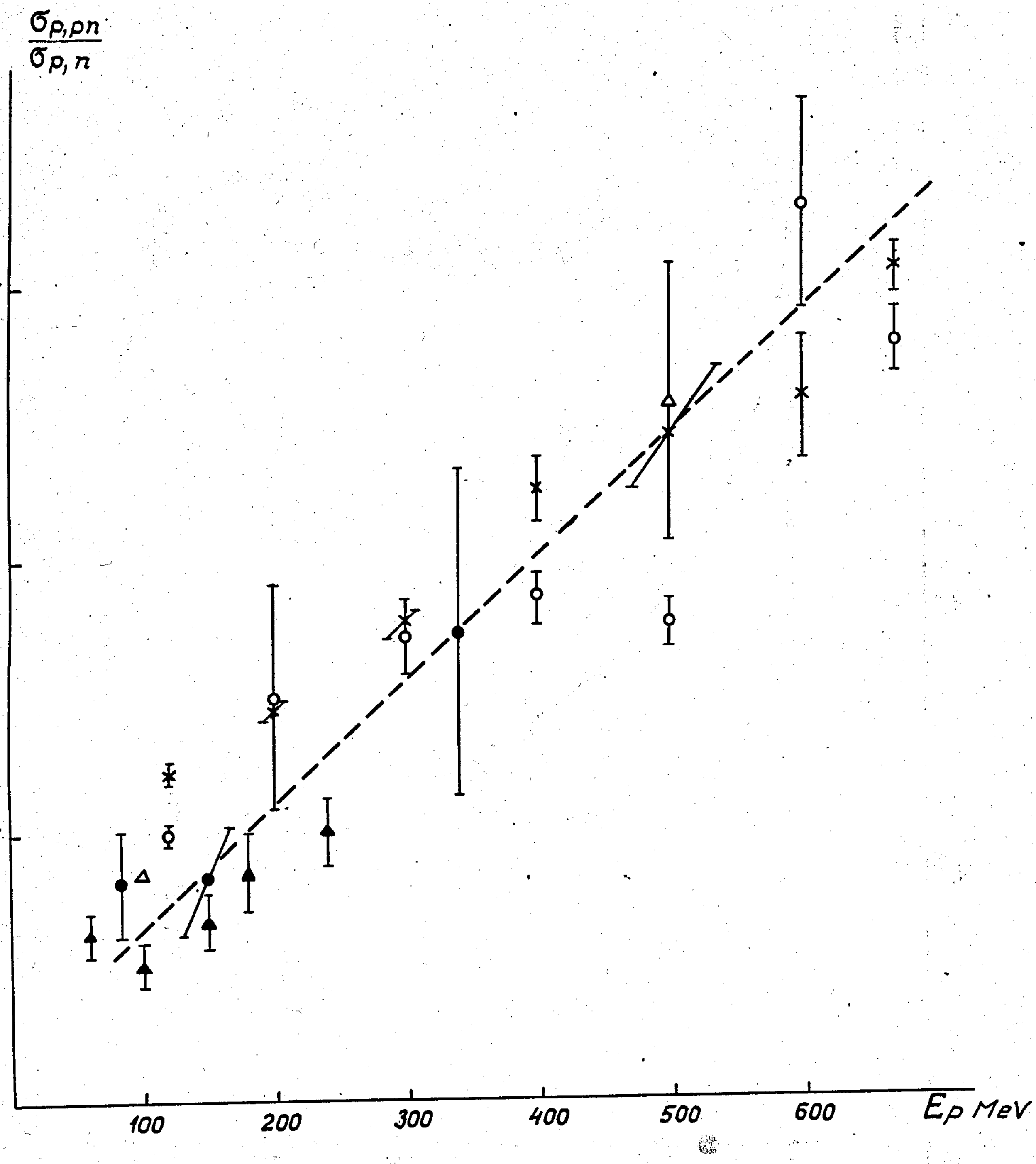

Fig. 3 The dependence of the ratio $\sigma_{p,pn} / \sigma_{p,n}$ upon the energy of incident protons. Crosses correspond to Sc^{45} (the present paper), open circles to Ca^{48} /1/, open triangles to Ga^{69} /10/, black triangles to Y^{89} /14/, black circles to Th^{232} /15, 16/.

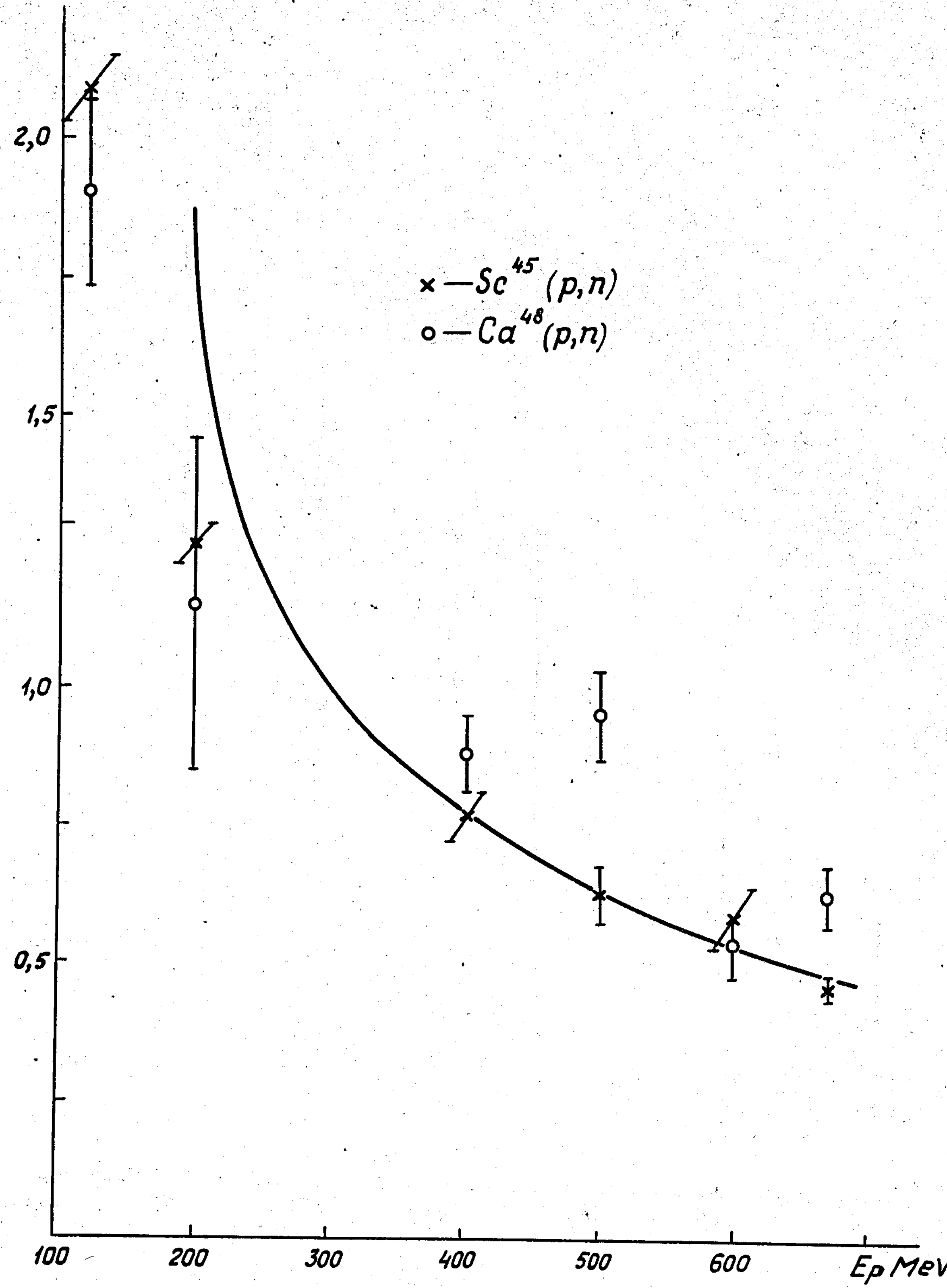

Fig. 4. Energy dependence of the differential cross-section of n-p scattering and $\sigma_{p,n}$. The solid curve correspond to the differential cross-section of n-p scattering at large angles (see the text), crosses to $\sigma_{p,n}$ for Sc^{45} , open circles to $\sigma_{p,n}$ for Ca^{48} .

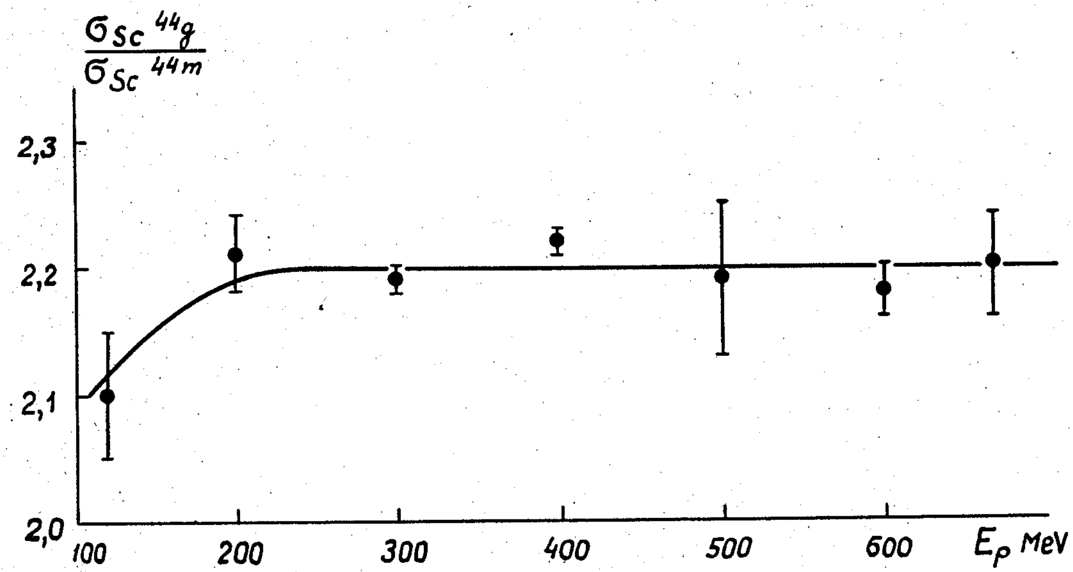

Fig.5. Dependence of the ratio of Sc^{44g} and Sc^{44m} production cross-section upon incident proton energy.