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PRODUCTION OF ^{2}H, ^{3}H, ^{3}He and ^{4}He ISOTOPES IN $p + {}^{12}C$ REACTIONS AT A PROTON ENERGY OF 660 MeV

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1. INTRODUCTION

The experimental and theoretical study of inelastic interactions between high energy particles and light nuclei is of great importance for science and its applications. So far the role of the internuclear correlations of nucleons in various nuclear processes has not been explained, and questions concerning the reaction mechanism have been insufficiently studied. At the same time, in the last few years the problem of prolonged cosmic flight has brought forward the practical necessity of using the whole sum of knowledge concerning the nuclear reactions of high energy particles.

From the point of view of the existing ideas on the mechanism of the nuclear interactions of high energy particles, on the basis of the known N-N scattering cross sections and the nucleonic density of nuclear material, it can be expected that when high energy nucleons pass through a light nucleus the incident particle undergoes a small number of collisions (in practice about one) with the nucleons of the nucleus. However, experimental results show that in such interactions there arises a complex mass spectrum of particle products; all the known stable and unstable isotopes of nuclei lighter than the target nucleus appear with varying probability. This may be understood either by assuming that the highly excited states occuring in such interactions are of a cluster type, or by supposing the possibility of direct interactions between the incident particle and associated nucleon groups in the nucleus. There are a large number of papers (see for example the references in (2)) devoted to explaining the question of the production of complex particles resulting from the disintegration of light nuclei by high energy protons. In a series of papers (3-7) it was shown that the experimental results on the production of α-particles in inelastic interactions between high energy particles and light nuclei can be explained by taking into account when calculating the cascade process the possibility of direct quasi-elastic scattering of the incident particles on intranuclear α-clusters. Such an analysis was mainly carried out for ^{12}C nuclei, for which it was found that about 20 to 30% of the protons passing through the nucleus at an energy of 660 MeV must be connected with their scattering on α-substructures.

Direct confirmation of the assumption concerning the quasi-elastic scattering of the incident particles on associations of intranuclear nucleons was obtained from experimental investigation into reactions of the type (p, pd), (p, pα) and (α, 2α)[8-10] and also from the study of the high energy regions of the spectra of the secondary particles ^{2}H, ^{3}H, ^{3}He, and ^{4}He emitted at small angles with respect to the direction of the incident protons in interactions with light nuclei [11-14].

Unfortunately, attemps to show by direct experimental observation that a significant part of the low-energy α-particles ($E_{\alpha} \leqslant$ 30 MeV) in the disintegration of light nuclei result from their quasi-elastic expulsion from the nucleus did not meet with success. The method of obtaining the α-particle spectra of the expulsion by subtracting the distribution $d^{2}\sigma_{\alpha}/dEd\Omega$ when $\Theta_{lab} = 90° + \delta$ from the distribution $d^{2}\sigma_{\alpha}/dEd\Omega$ at an angle of $\Theta_{lab} = 90° - \delta$ used in (15) and (16) cannot be deemed justified. Owing to the momentum distribution of the α-clusters in the nuclei and the re-scattering effect in the final state it is certain that at angles of $\Theta_{lab} > 90°$ there is also a contribution from the expulsion of α-particles if quasi-elastic scattering of the incident particles on the clusters take place. Moreover, the discrepancy found in two differential cross sections comprises an uncontrolled difference in the background distributions at two Θ_{lab} angles.

The work described below for the purpose of explaining the role of the nucleon association in the interaction of high energy protons with light nuclei included experimental investigation of the production of ^{2}H, ^{3}H, ^{3}He and ^{4}He isotopes in p + ^{12}C reactions at a proton energy of 660 MeV. A study of the kinematic characteristics of secondary particles was made in the 2-8 MeV nucleon region, which comprises a significant part of the total cross section of their production in the assumed direct reactions in clusters.

2. EXPERIMENTAL METHOD

In the extracted proton beam of the NPL synchrocyclotron at the JINR a remote-controlled vacuum chamber was installed, in the centre of which was placed a thin polystyrol target (1.23 mg/cm^2). The particles produced by the interaction between the proton beam and the nuclei of the target were recorded, their charge and mass identified and their energy measured by means of a telescope consisting of three semiconductor silicon detectors; the dE/dx detector 23, 40 or 120 μm thick, the E detector 800 or 2,000 μm thick and the anticoincidence detector 500 μm thick.

The main part of the electronic measuring circuit is a digital computing device, described in (17). The high background level when working in the synchrocyclotron proton beam and the small time extension of the beam (160 μsec) made it necessary to change the input device to include a fast coincidence and anticoincidence circuit (2g = 70 nsec) and a dead time measuring circuit.

The proton flux was monitored by means of a three-electrode ionization chamber filled with argon and calibrated according to the reactions ^{12}C (p, pn)^{11}C and ^{27}Al (p, 3pn)^{24}Na. Repeated calibration of the ionization chamber during the experimental measurements showed that the absolute proton flux was determined with an error of less than 10%.

In order to determine the absolute production cross sections of the particles studied in the reactions, measurements were made of the solid angles of detection of the particles from the extended target with an operational telescope using an α-source whose activity was known with an accuracy of better than 1% and whose configuration was similar to the shape of the beam cross section in the target. For a beam of a diameter of 20 mm the solid angle measured was 1.99×10^{-3}cp and it remained constant within limits of 1% when the telescope was rotated in relation to the target from 20 to 160°.

III. EXPERIMENTAL RESULTS

The computing device used made it possible to obtain immediately during the experiment the mass and charge distribution of the recorded particles, which with the method of identification used have a value of $f(M, Z) = (E + 0.5\,\Delta E)^{0.74}\,\Delta E$, where ΔE and E are the values of the energy left by the particles in the dE/dx and E detectors. In order to illustrate the M and Z resolution in the experiment, Fig. 1 shows the distribution of hydrogen, helium and lithium isotopes in p + ^{12}C reactions when observed at an angle of $\Theta_{lab} = 90°$, obtained by means of a telescope with a 40 μm thick dE/dx detector. It can be seen from the diagram that the relative probability of production of the different isotopes corresponds to the following particle energy ranges: 4-11 MeV for ^{1}H; 5-14 MeV for ^{2}H; 6-17 MeV for ^{3}H; 7-33 MeV for ^{3}He; 8-33 MeV for ^{4}He, and 16-36 MeV for ^{6}Li and ^{7}Li.

The computing device made it possible to carry out scaling transformation of the mass scale when studying one or other of the isotopes of the particle products. For instance, Fig. 2 shows the distribution according to f(M) for hydrogen isotopes, which was used when measuring the kinematic characteristics of ^{2}H and ^{3}H.

Reliable identification of secondary particles in p + ^{12}C reactions made it possible to measure the differential energy spectra and angular distribution of ^{2}H, ^{3}H, ^{3}He and ^{4}He isotopes in inelastic interactions between 660 MeV protons and carbon nuclei. Figs. 3-6 give a series of distributions measured at different Θ_{lab} angles. In order to facilitate examination of the general characteristics of the differential spectra of the hydrogen and helium isotopes, the experimental results are given in these diagrams without reference to the absolute cross sections. For particles in the measured energy range the differential spectra have the following characteristics: the $d^2\sigma/dEd\Omega$ functions of all the isotopes studied are exponential; the spectra "soften" at a given angle when changing from ^{2}H to ^{3}H and ^{4}He; the "hardest" spectra at an energy $E \gtrsim 2$ MeV/nucleon have ^{2}H fragments; the shape of the spectra for ^{3}H and ^{3}He coincides.

The angular distributions of ^{2}H, ^{3}H, ^{3}He and ^{4}He isotopes are given in Fig. 7 for several energy ranges. Errors in determining the absolute values $d\sigma/d\Omega$ are about 15%. The presence of a maximum in the region $\Theta_{lab} = 50° - 70°$ is characteristic of all the angular distributions.

A decrease in the differential cross sections $d\sigma/d\Omega$ in the angular region $\Theta_{lab} < 60°$ was subjected to repeated checks with repeated independent measurements and is a well established fact. Unfortunately at present nothing can be said about the behaviour of $d\sigma/d\Omega$ for hydrogen and helium isotopes in the region $\Theta_{lab} < 30°$. Measurements in this region were seriously hampered because the telescope was overloaded with background particles.

Integration of the angular distributions gave the following values for the production cross sections of hydrogen and helium isotopes:

$$\sigma_{^{4}He}(E=8 \div 33\ MeV) = 106\ mb$$

$$\sigma_{^{3}He}(E=7 \div 33\ MeV) = 43\ mb$$

$$\sigma_{^{3}He}(E=6 \div 33\ MeV) = 51\ mb$$

$$\sigma_{^{3}H}(E=6 \div 17\ MeV) = 20\ mb$$

$$\sigma_{^{3}H}(E=6 \div 33\ MeV) = 31\ mb$$

$$\sigma_{^{2}H}(E=5 \div 14\ MeV) = 49\ mb$$

It is known from the literature that the production cross section of ^{3}H isotopes in $p + {}^{12}C$ reactions at a proton energy of 660 MeV has a value of about 11 mb(18), which is very different from the cross section obtained in our work.

The measured values of the cross sections can be compared to the results of the determination of the mean number of singly and doubly charged particles in disintegrations of ^{12}C nuclei by 660 MeV protons. Direct measurement of the number of particles in the case of inelastic interaction of fast protons with nuclei (obtained by the track method) in conjunction with independent measurement of the total cross section of inelastic interaction gives the most reliable absolute production cross sections of secondary particles. According to the results given in (4) the mean number of doubly charged particles for one interaction in $p + {}^{12}C$ reactions is 1.3. For the value $\sigma_{inelastic} = 227 \pm 12$ mb [19] this gives a total production cross section for doubly charged particles of 296 mb. If the doubly charged particle cross section for the $\gtrsim 8$ MeV energy region is determined according to the energy spectrum given in (4), we obtain $(E \geq 8$ MeV$)$ = 151 mb. According to our measurements $\sigma_{{}^3He + {}^4He}(E \geq 8 \text{ MeV}) =$ 149 mb. Since it was possible to measure the mass distribution of hydrogen and helium isotopes simultaneously in the experiment in question, the relative probability of production of the different isotopes is a reliably determined value. As found in the experiment, $\sigma_{{}^3H}/\sigma_{{}^3He}$ is 0.61 when $E \geq 6$ MeV. It is interesting to note that for interactions between 660 MeV protons and ${}^4He$ nuclei the ratio between the production cross sections $\sigma_{{}^3H}/\sigma_{{}^3He} = \frac{28}{46} = 0.61$ [20].

IV. CONSIDERATION OF THE RESULTS

A description of multiparticle reactions resulting from inelastic interactions between high energy hadrons and light nuclei can be given in the frame of the cascade model in conjunction with the model of the subsequent decay of the excited states of the residual nuclei.

This investigation by model, which is unavoidable in the absence of a strictly valid theory, has a specific value: it makes it possible to trace the effects of nucleon association and the relative role of the various production mechanisms of secondary particles. Moreover, comparison of such results with experimental results may give an estimate of the different parameters characterising the cluster state in nuclei. Therefore it is very interesting to compare the results obtained with those of model calculations. A more detailed analysis of intranuclear cascades taking into account N-α-scattering in light nuclei has recently been carried out by Barashenkov and Ablinov (7, 21). Since in this work the calculations were made for several variants of the model, with considerable variation of the parameters and with better statistical accuracy than the similar calculations made by Combe (3), Zhdanov and Fedotov (4) and Gradshtajn (6), in what follows we shall use only the results from (7) and (21).

The results obtained by us on the production cross section of hydrogen and helium isotopes make it possible to choose between the two possible models of the decay of excited states of residual nuclei.

As the calculations in (21) show, the multiparticle decay model gives a much higher probability ratio for the production of ^{3}He and ^{4}He isotopes than the evaporation model (^{3}He/^{4}He = 0.33 and 0.13 respectively) and a more similar probability of ^{3}H and ^{3}He production, which corresponds more closely to the experiment. A similar conclusion was drawn earlier from a comparison of the experimental results on the production cross section of ^{6}Li, ^{7}Li, ^{7}Be from ^{12}C with the calculations in (22) and (23).

The experimental results given above also make it possible to choose between the different variants for calculating the cascade process in the ^{12}C nucleus.

The most suitable for comparison with the experiment is the variant of the model taking into account the variation of the nucleon density in the nucleus during the development of the cascade process. The calculated angular distribution for α-particles knocked out in the cascade process reaches a maximum in the region $\Theta_{lab} < 90°$ only if the decrease in nucleon density in the nucleus is taken into account. Figs. 8 and 9 show the experimental and calculated $d\sigma/d\Omega$ and $d\sigma/dE$ distributions of ^{3}He and ^{4}He isotopes in p + ^{12}C reactions.

For comparison with the experiment, the following variants of the spatial distribution of α-clusters in the ^{12}C nucleus (21) were used:

Variant A: Number of α-clusters 1.03, distributed in spherical layers 0 ÷ 1.14f -0.1, 1.14 ÷ 2.93f-0.1 and 2.93 ÷ 4.53f -0.56.

Variant F: Number of α-clusters 1.76, distributed in spherical layers 0 ÷ 1.14f - 0.2, 1.14 ÷ 2.93f -1.0 and 2.93 ÷ 4.53f -0.56.

which was not mentioned earlier when studying inelastic interactions between high energy protons and light nuclei (4, 5). The maximum in the angular distribution of ^3He and ^4He moves into the smaller angle region when their energy increases. The mean number of "cascade" and "decay" α-particles obtained in the calculations is respectively:

Variant A-$\bar{n}$ cascade = 0.16, $\bar{n}$ decay = 0.37
Variant F-$\bar{n}$ cascade = 0.38, $\bar{n}$ decay = 0.32

The mean number of α-particles in one inelastic interaction obtained in our experiments can be determined from the relation $\frac{\sigma_\alpha}{\sigma_{inelastic}} = \frac{166}{227} = 0.73$, which is near to the variant F.

As can be seen from the figures, the calculations accurately represent both the shape of the energy spectrum and the typical angular distribution of ^4He, showing the decisive effect of direct interactions between the incident protons and the cascade nucleons and the α-substructures in the ^{12}C nucleus on the shaping of the kinematic characteristics of the α-particles observed.

It must be mentioned that the calculations carried out in (21) do not give all the results necessary for comparison with the experimental information obtained. The angular distributions in this paper were obtained with a large interval between the angles (30°) and can only show that the maximum in the angular distribution is in the 60-90° range. Moreover, there are no detailed angular distributions for the different energy ranges of ^4He. The angular distribution given for the α-particle energy range above 32 MeV, with the same interval between angles, also indicates a maximum in the 60-90° range. It can be deduced from the experimental results that the maximum of the angular distribution moves towards the smaller angles as the energy of the recorded α-particles increases.

The most interesting of the possible variants of the spatial distribution of α-clusters over the ^{12}C nucleus for which calculations were given in (21) is the one in which the α-clusters are more evenly distributed over the volume of the nucleus (variant F). This conclusion does not agree with that arrived at by the writers of (7) and (21) on the basis of comparing the calculated results with the experimental results of (4). As noted above, the experimental results obtained by means of the nuclear emulsion method do not make it possible to determine the kinematic characteristics of individual isotopes of secondary particles. The absence of discrimination between ^{3}He and ^{4}He in (4) increased the proportion of high energy α-particles (over 50% of the ^{4}He at $E > 20$ MeV are ^{3}He isotopes) and the difficulty of identifying short-range Li isotopes led to an increase in the cross section of doubly charged particles at small Θ_{lab} angles.

Thus the general characteristics of the production of ^{4}He isotopes can be understood in the frame of the cascade model taking into account quasi-free N-α interactions. As can be seen from the experimental results, a large part of the multiple products of multiparticle reactions resulting from the interaction of protons with ^{12}C nuclei are isotopes such as ^{2}H, ^{3}H and ^{3}He, the kinematic characteristics of which are near to the characteristics of ^{4}He. It is therefore natural to endeavour also to explain the production of ^{2}H, ^{3}H and ^{3}He in the frame of the same representation. Unlike the case of ^{4}He production, when we can apparently neglect the contribution from the inelastic interaction of incident protons with heavier clusters (such as ^{5}Li, ^{5}He etc.) owing to the large known width of ^{4}He clusters, in the case of ^{2}H, ^{3}H and ^{3}He production it is necessary to take into account not only the quasi-elastic scattering on ^{2}H, ^{3}H and ^{3}He clusters, but also the inelastic interaction of the incident and cascade nucleons with the ^{4}He clusters leading to the same products.

In (24) it was assumed that the production of such products as ^{3}H and ^{3}He (and also the production of slow ^{1}H and ^{2}H) upon the interaction of protons with ^{16}O nuclei is mainly the result of single inelastic collisions of the incident protons with α -substructures of the ^{16}O nucleus. The $\sigma_{^3H}/\sigma_{^3He}$ coincidence in reactions with ^4He and ^{12}C nuclei already mentioned agrees well with this assumption. However, the existing experimental evidence of direct quasi-elastic expulsion of ^3He, ^3H and ^2H from light nuclei (8-14) rules out such an assumption.

It should be noted that the $d\sigma/d\Omega$ dependences obtained in this work for ^2H, ^3H and ^3He also contradict the assumption that their production is basically connected with inelastic interaction with α -clusters. As is known from experiments in which the angular distribution of residual nuclei in (p, 2p) and (p, pn) high energy reactions were studied, although the $d\sigma/d\Omega$ distributions have a certain maximum in the angular region $\Theta_{lab} = 40-60°$, this increase in the cross section is insignificant and considerably less than that observed by us in the experiment for ^2H, ^3H and ^3He. Apparently the maximum in the $d\sigma/d\Omega$ distribution for these secondary particles is mainly due to quasi-elastic scattering. Therefore the cascade model appears to be more logical since it takes into account elastic and inelastic interactions between the incident particles and the nucleons and various clusters in the nucleus, and the corresponding calculations should be carried out.

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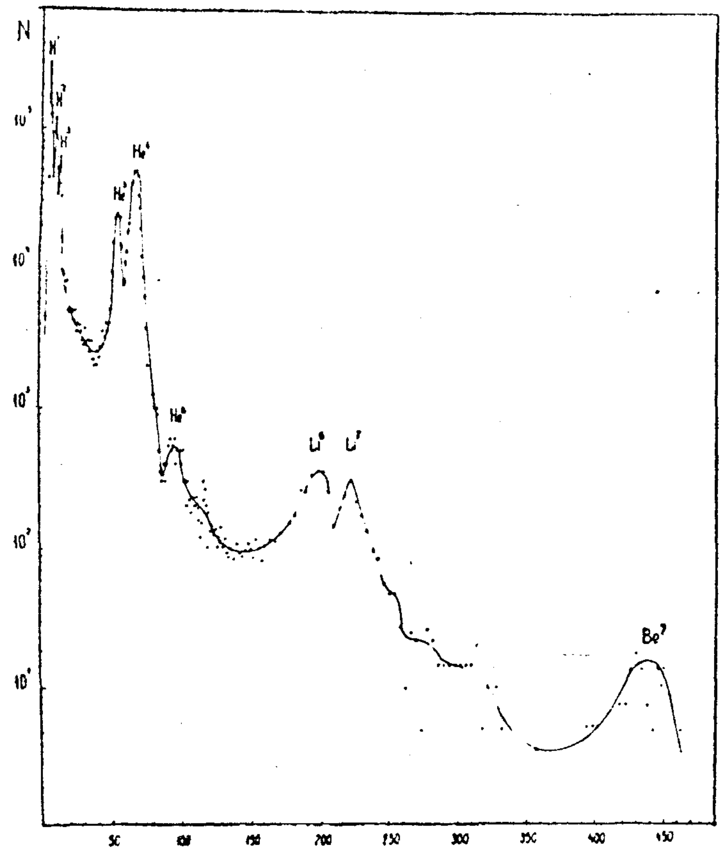

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Fig. 1 Distribution of hydrogen, helium and lithium isotopes resulting from interactions between 660 MeV protons and carbon nuclei. $\Theta_{lab}=90°$.

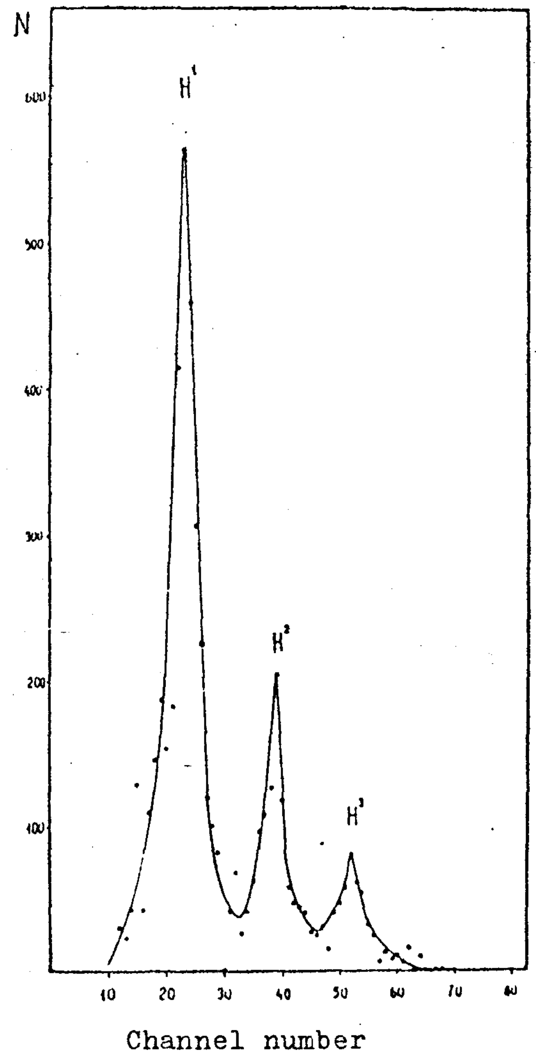


Fig. 2 Distribution of hydrogen isotopes in p + ^{12}C reactions, $\Theta_{lab} = 90°$.

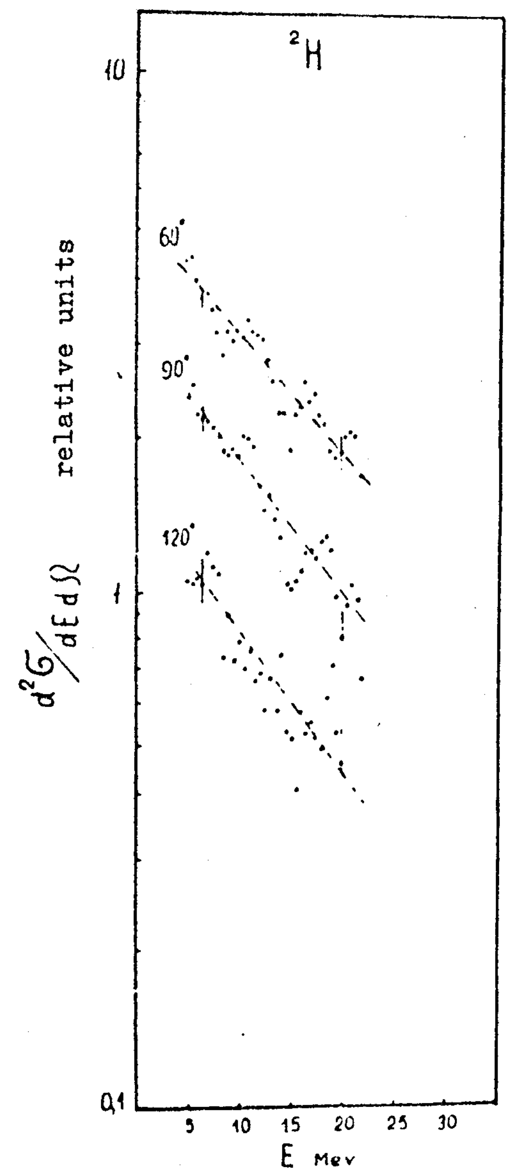
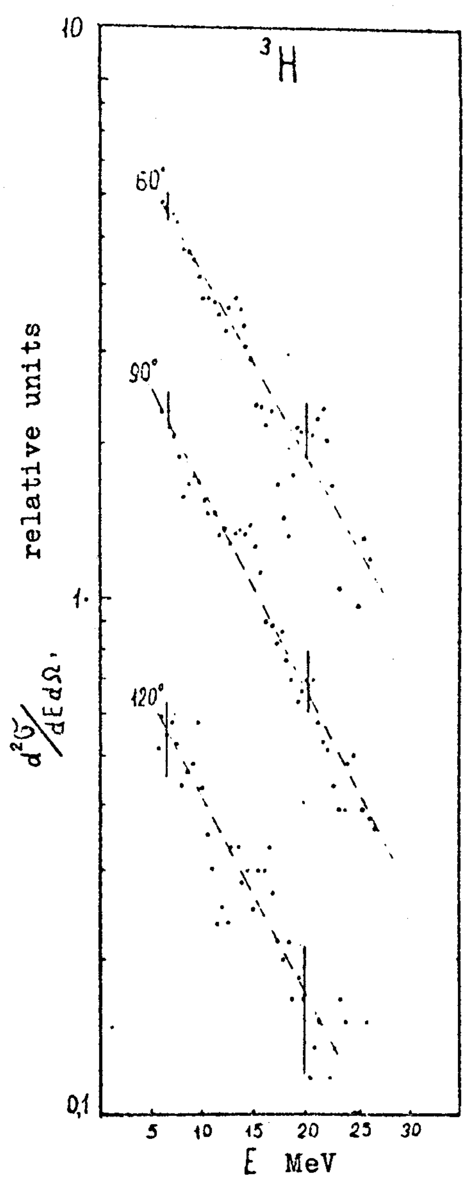
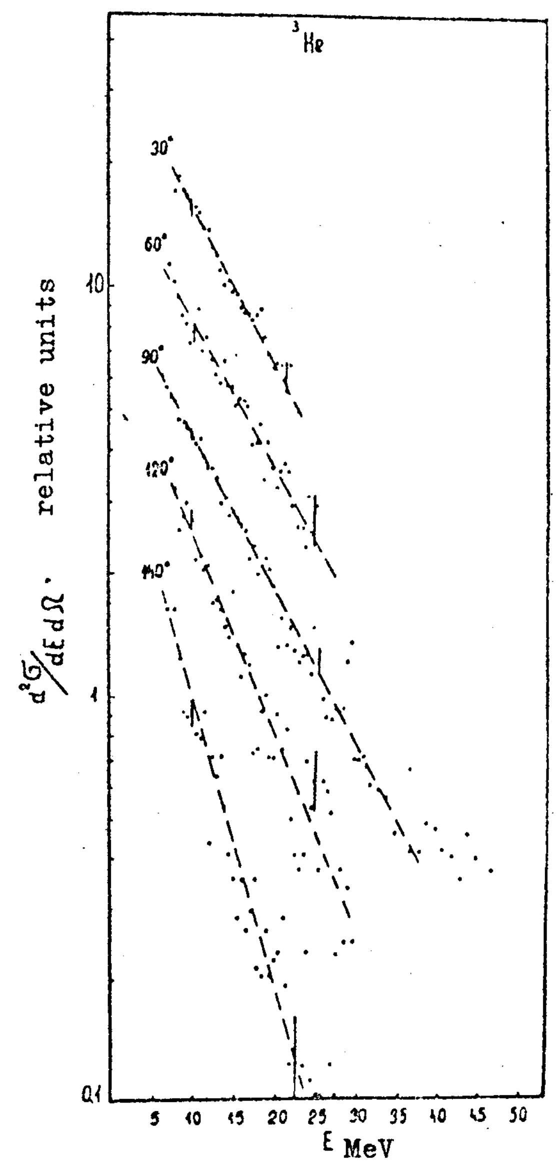


Fig. 3 Differential energy spectra of ^{2}H isotope in p + ^{12}C reactions, E_p = 660 MeV.



<u>Fig. 4</u> Differential energy spectra of ^3H isotopes in p + ^{12}C reactions, E_p = 660 MeV.



<u>Fig. 5</u> Differential energy spectra of ^3He in $p + ^{12}C$ reactions, $E_p = 660$ MeV.

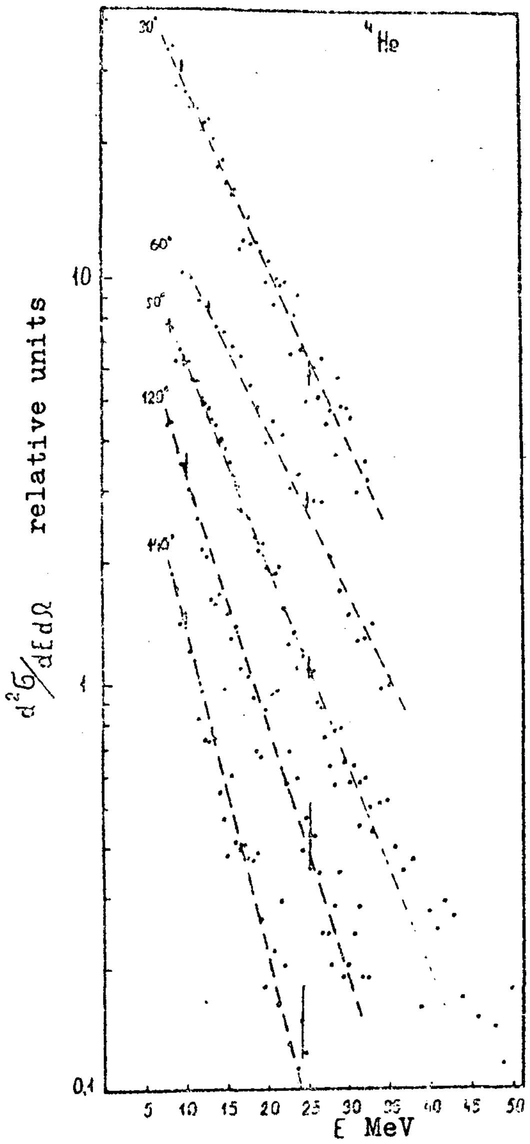


Fig. 6 Differential energy spectra of ^{4}He in p + ^{12}C reactions, E_p = 660 MeV. Dashed lines: linear approximation of experimental points.

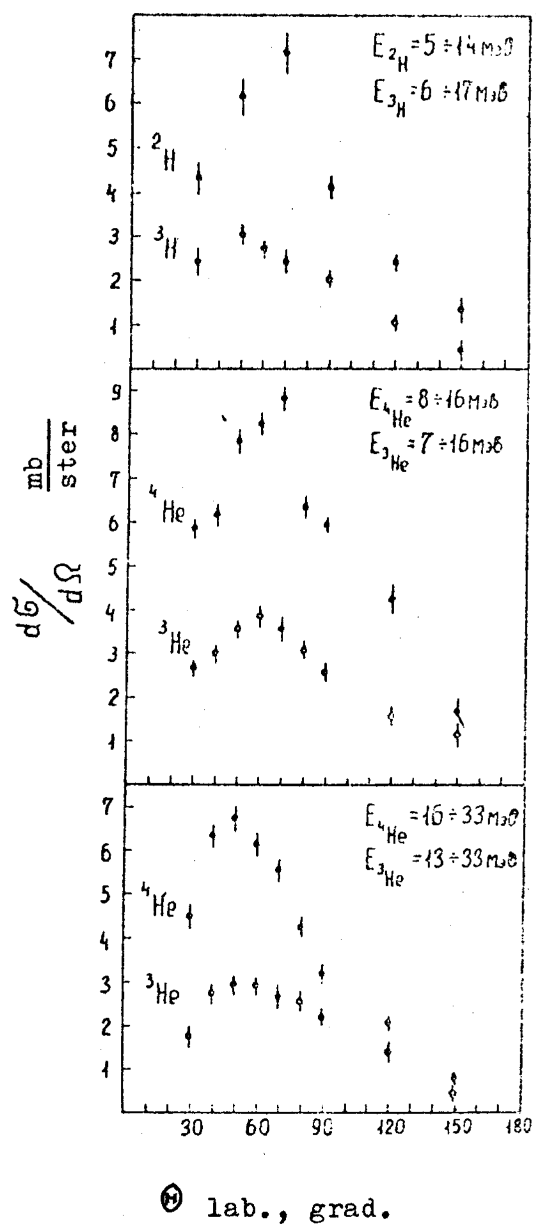


Fig. 7 Angular distributions of ^{2}H, ^{3}H, ^{3}He and ^{4}He in $p + {}^{12}C$ reactions. Statistical errors indicated.

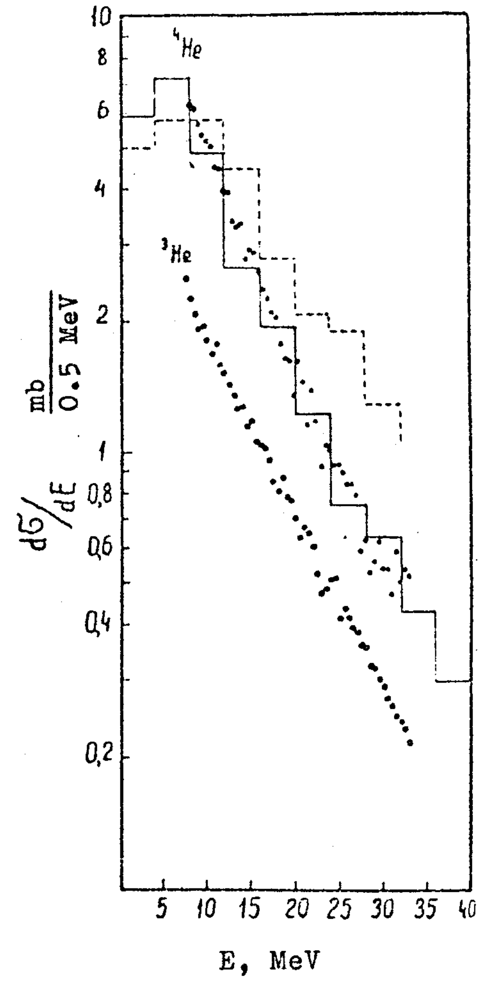


Fig. 8 Total energy spectrum of ^4He and ^3He isotopes in $p + {}^{12}C$ reactions.

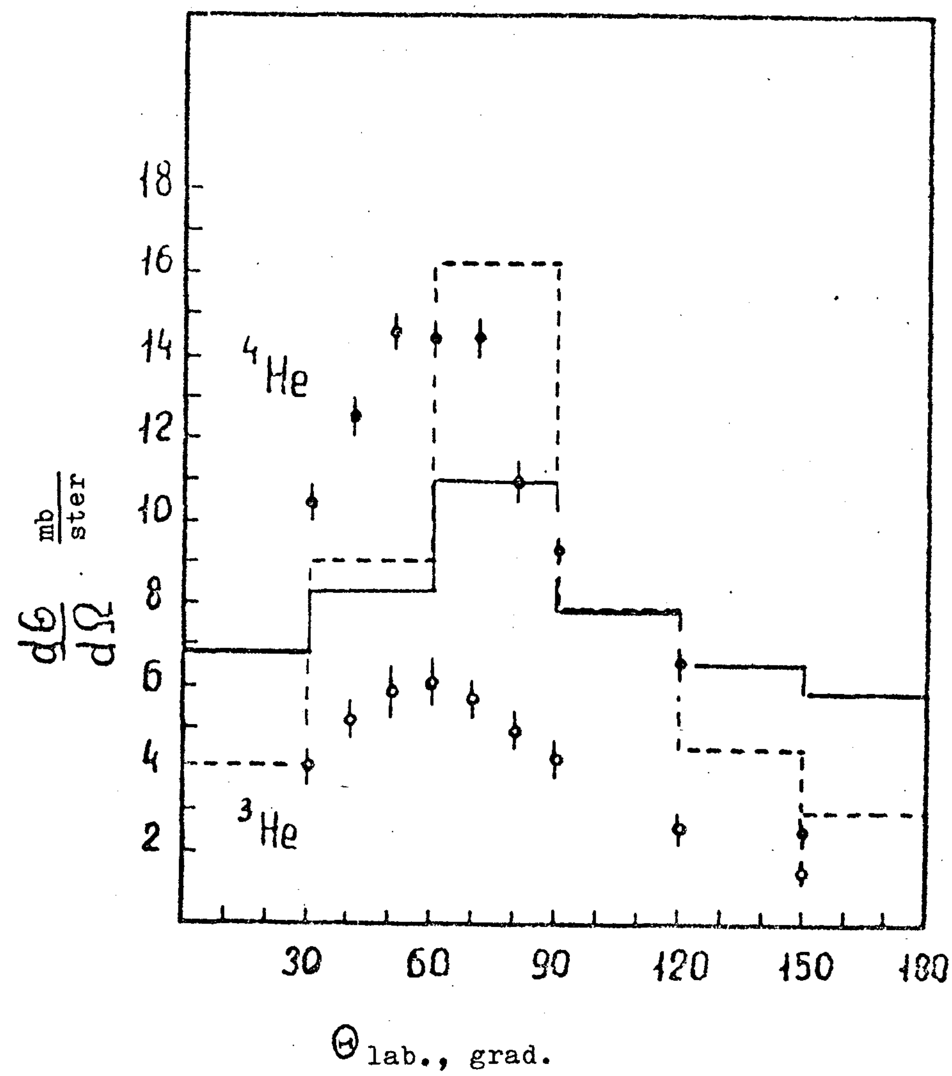


Fig. 9 Angular distribution of ^{3}He and ^{4}He isotopes in p + ^{12}C reactions. Histogram: calculations. Unbroken line: Variant A. Dashed line: Variant F.