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E7-81-355

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MULTINUCLEON TRANSFER REACTIONS AND THE FORMATION OF LIGHT CHARGED PARTICLES IN THE SYSTEM $^{nat}Ag + ^{40}Ar$ (285 MeV)

Submitted to "Zeitschrift für Physik A"

1981

1. INTRODUCTION

The interactions of the ^{40}Ar ions with silver at an energy of about 300 MeV have been studied in a number of papers. The fission and formation of products as a result of nucleon evaporation after the complete fusion of initial nuclei have been investigated /1/. The formation of products with atomic numbers $6 \leq Z \leq 30$ has been studied in ref. /2/. The activation technique /3/ was used to obtain the formation cross sections for the heavy products of the interaction $^{109}Ag + ^{40}Ar$. The products of nucleon evaporation from a compound nucleus have been investigated in ref. /4/. Some data have been obtained on the elastic scattering, the total reaction cross section, fusion cross section, and the cross section for formation of the evaporation residues /5/. By measuring the circular polarization of γ-rays it was shown that the products of deep inelastic nucleon transfer reactions with $11 \leq Z \leq 27$ are emitted in the region of negative angles /6/.

Taking into account a large amount of experimental information obtained for the system $Ag + ^{40}Ar$, it seems appropriate to try to get additional data on the formation of light charged particles in this system. A comparison of all the available data on the yields of elements and individual isotopes in the system $Ag + ^{40}Ar$ can give a better understanding of the general picture of the interaction between complex nuclei. In particular, we believe that these data may be of value for verifying the hypothesis that the multinucleon transfer reactions are the main contributors to the formation of light charged particles and, primarily, α-particles in reactions with ^{40}Ar ions /7,8/.

2. EXPERIMENTAL TECHNIQUE

Experiments were carried out using the 310-cm heavy ion cyclotron of the JINR. A natural silver target 4.4 mg/cm^2 thick was bombarded with 300 MeV ^{40}Ar ions. The ion energy in the middle plane of the target was equal to 285 MeV. All the results obtained and transformation of data to the centre-of-mass system are referred to this energy. The energy spectra and cross sections for formation of the H to Cl isotopes for an emission angle of 40° were measured using a $\Delta E, E$ detector telescope placed in the exit focus of the magnetic spectrometer. The measurements at different angles were performed using a rotating telescope without a magnetic spectrometer. A gridded ionization chamber served as a ΔE detector operated in the focal plane of the magnetic spectrometer. Silicon surface-barrier detectors 15, 38 and 100 µm thick were employed as ΔE detectors in the movable telescope. In both telescopes, the E detectors were drift Si(Li) detectors with a thickness of 2.5 mm and 4.5 mm. The amplified and coded pulses from the ΔE and E detectors were recorded on magnetic tape using a Minsk-32 computer. The experiment was controlled by displaying information in the form of two-dimensional spectra 128(ΔE) x64(E) channels by means of a digital printer. The calibration of cross sections was performed according to the elastically scattered ^{40}Ar ions. The energy calibration of the detectors was done by means of α-particles of ^{241}Am and the products of nuclear reactions of fixed energies, separated by the magnetic spectrometer. The energy spectra of reaction products in experiments with the magnetic spectrometer were obtained by measuring the yields at different magnetic rigidities. The yields of products in different charge states were summarized.

3. RESULTS OF MEASUREMENTS AND DISCUSSION

3.1. Energy Spectra

The energy spectra of ^{1}H, ^{2}H, ^{3}H, ^{3}He, ^{4}He and ^{6}He for an emission angle of 40° both in the laboratory and centre-of-mass systems are presented in Fig. 1. Transformation to the centre-of-mass system was performed assuming the two-body mechanism of the reaction proceeding according to the scheme $A_1 + A_2 \rightarrow A_3 + A_4$, where A_i is the mass number of the nucleus. In fig. 1, the energies corresponding to the Coulomb barriers for protons and α-particles, calculated using the formulae cited in ref.[9] are indicated by arrows. An interesting peculiarity of the energy spectra in Fig. 1 is the presence of particles with a kinetic energy per nucleon much higher than that of the projectile.

Typical energy spectra of the isotopes of the heavier elements Li, C, Na, Si, and Cl, also obtained at 40°, are presented in Fig. 2. In this case the Coulomb barriers were calculated in the approximation of nuclear shapes by spheres with a distance between the centres

$$R = (1.225(A_3^{1/3} + A_4^{1/3}) + 2) \times 10^{-13} \text{ cm.} \qquad (1)$$

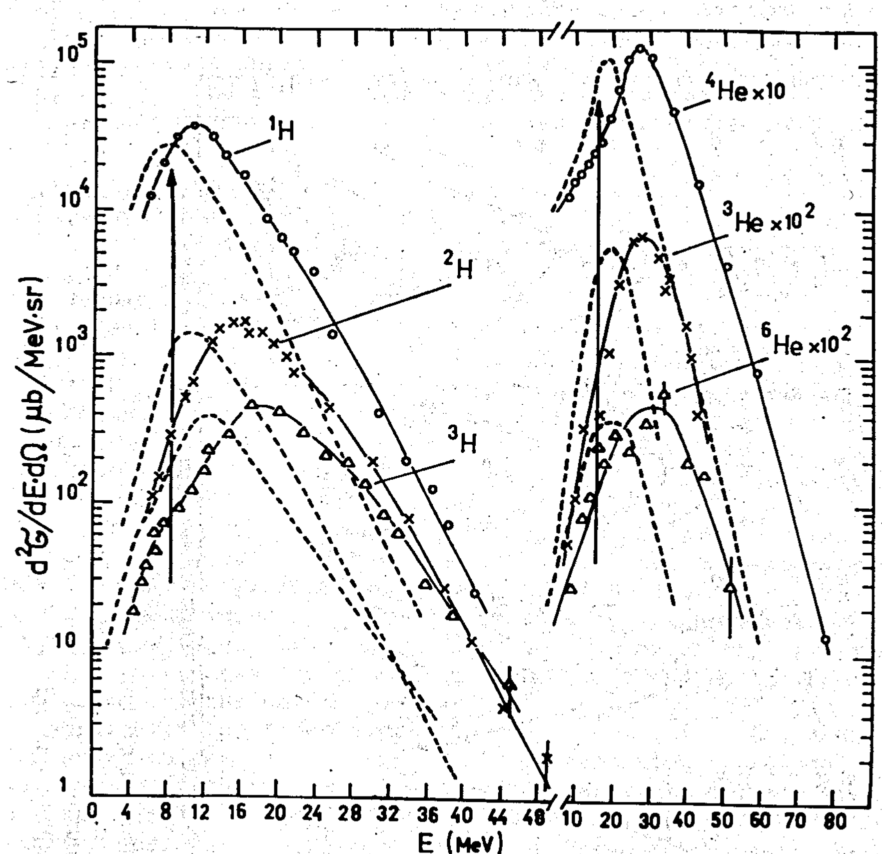

Fig. 1. The laboratory energy spectra of the isotopes ^{1}H, ^{2}H, ^{3}H, ^{3}He, ^{4}He, and ^{6}He($\theta_{lab} = 40°$). The c.m. energy spectra are shown by dashed lines. The arrows show the c.m. Coulomb energies for protons and α-particles. The curves for He isotopes have been multiplied by the coefficients shown in the figure.

We note that the difference between the Coulomb energies calculated using relation (1) and following formula from ref.[9] amount to 1.1 MeV for protons and 0.8 MeV for α-particles.

The energy spectra of ^{1}H, ^{2}H, ^{3}H and ^{4}He in the c.m. system for different emission angles are presented in Fig. 3. The Coulomb barriers following ref.[9] are indicated with arrows. For deuterons and tritons, the Coulomb barriers are accepted to be identical with the barriers for protons. The α-particle energy spectra are represented by pairs for the angles cor-

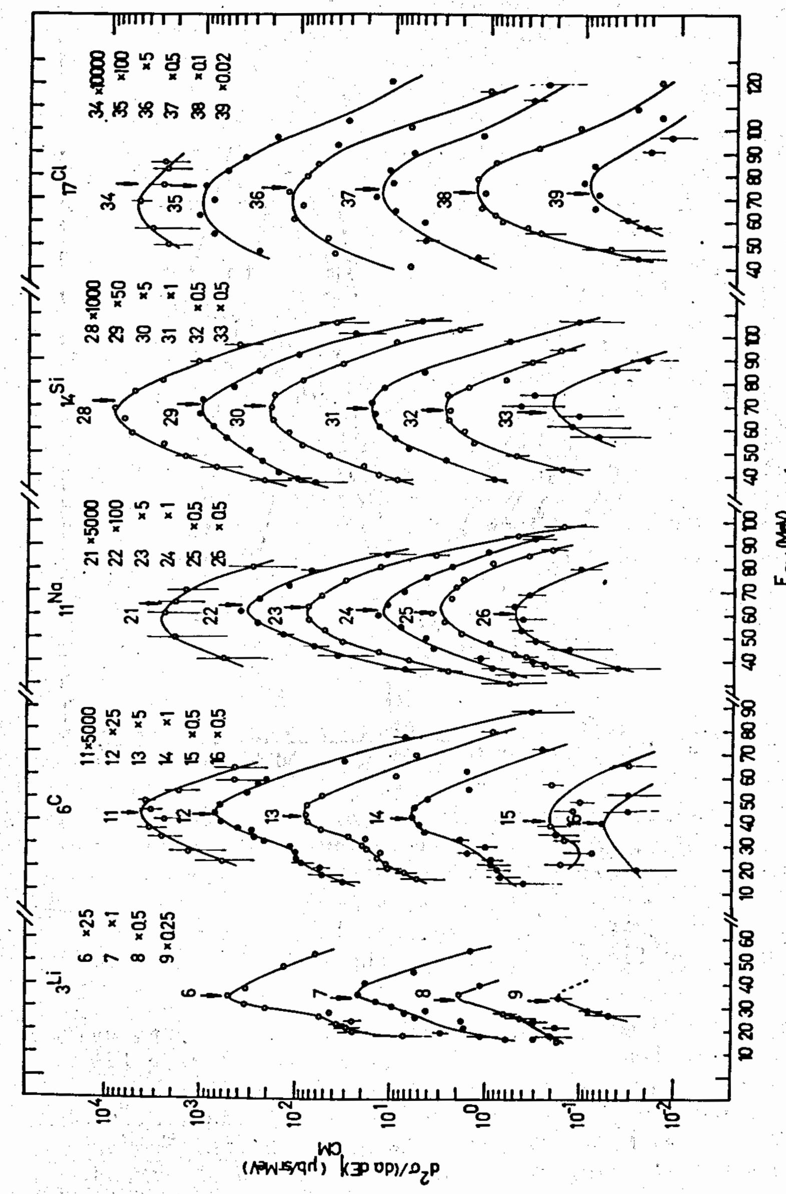

Fig.2. The c.m. energy spectra of the isotopes of Li , C , Na , Si , and Cl(θ_{lab} = 40°). All the curves have been multiplied by the coefficients shown next to the isotope mass number. The arrows show product energies for the system decaying into two spherical nuclei from the Coulomb barrier height.

responding to the energy averaged angles in the forward and backward hemispheres symmetrical relative to 90°. The c.m. values of these angles are 20° and 159°, 26° and 144°, 52° and 128°, and 77° and 110°, respectively. The difference between the spectra for forward and backward angles is shown by dashed lines.

For particles with Z=1, the relative contribution of the excess yield at forward angles is substantially smaller than that for α-particles. Therefore, in subtracting the spectra at forward and backward angles it is possible to obtain only the integral effect.

It can be noted that in fig 3 the maxima of the proton spectra well coincide with the values of the Coulomb barriers. For the heavier particles, we observe the deviation of the maximum from the Coulomb barrier to the higher energy. The maxima of the dashed spectra of α-particles considerably exceed the Coulomb barriers and are shifted as the observation angle changes. This is a characteristic feature of the particle emission from a source that moves in the c.m. system. The low energy parts of the spectra of both the α-particles and the heavier products (see Figs. 2 and 3) need to be specially investigated. Control experiments on the bombardment of a carbon target have shown that these parts of the spectra, as well as the rest of them, cannot be explained by the contamination of the carbon.

Apparently the total energy spectra of ^1H , ^2H , ^3H , and ^4He shown in Fig. 3, are the result of summation of several mechanisms of their formation. Nevertheless, all of them have a shape similar to that of the particles evaporated from an excited nucleus. According to this, we tried to describe the high-energy parts of the spectra by the known relation

$$\sigma \sim E \cdot \sigma_{inv}(E) \cdot \exp(-E/T), \qquad (2)$$

where $\sigma_{inv}(E)$ is the inverse reaction cross section, and T is the temperature parameter. To define $\sigma_{inv}(E)$ we used the optical model calculations using a somewhat revised program "ALICE" [10,11], as well as analytical expressions from ref.[12]. Both methods used in the treatment of energy spectra by the least-squares method lead to close values of T. The T values for p, d and α-particles, as a function of the observation angle, are presented in Fig.4. For protons, T=2 MeV at all angles. This value is close to the temperature obtained from the neutron energy spectra for compound nuclei with A~100 and excitation energy of several tens of MeV [13,14]. For deuterons and especially α-particles, a substantial dependence of T on the detection angle is observed in the forward hemisphere. In the backward hemisphere T for α-particles is practically

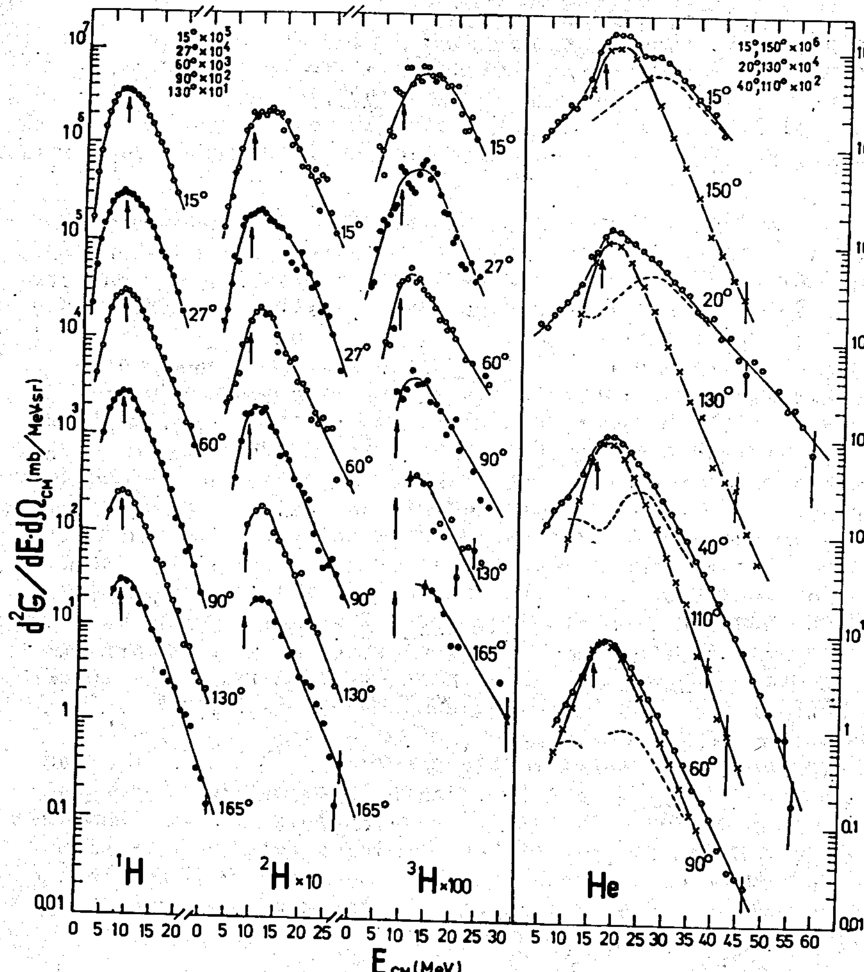

Fig.3. The c.m. energy spectra of ^{1}H, ^{2}H, ^{3}H, and He. The lab. values of the detection angles are shown next to the curves. The curves for different detection angles have been multiplied by the coefficients shown at the top of the figure. The curves for ^{2}H and ^{3}H have been multiplied additionally by the coefficients shown in the lower part of the figure.

constant, but the absolute value of T ~ 3 MeV substantially exceeds T for protons. Similar results for the difference in the temperature obtained from the energy spectra of protons and α-particles in the case of other target-projectile combinations were also obtained in refs.[15,16]. It is noteworthy

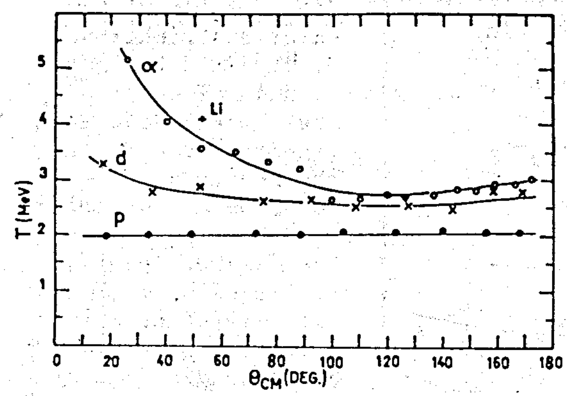

Fig.4. Nuclear temperature calculated from the energy spectra of protons, deuterons, α-particles and Li-particles as a function of the detection angle.

that the calculations of the proton and α-particle energy spectra for the system Ag+^{40}Ar (285 MeV) within the framework of the statisticall consideration of the compound nucleus de-excitation process according to ALICE code[10,11] lead to a difference in the T value for α-particles and protons within only 0.1 MeV.

3.2. Angular Distributions

The angular distributions of ^{1}H, ^{2}H, ^{3}H, He, Li, Be, B and C are presented in Fig. 5. The angular distributions for ^{2}H, ^{3}H at backward angles were corrected for the cutoff of the part of the energy spectrum by the ΔE detector 100 μm thick. It was supposed that the low-energy parts of the spectra in forward and backward angles coincide in shape. The angular distribution for carbon, obtained by us well agrees with the data of paper[2]. Thus the data of the present paper and ref.[2] taken together allow one to see the evolution of the angular distributions of the products from protons to chlorine in the system Ag+^{40}Ar (~ 300 MeV). In Fig. 5, there attracts attention the increasing symmetry of the angular distributions relative to 90° as one goes from carbon to the lighter products. This tendency is characterized quantitatively in the inset of Fig. 5. It shows the ratio of cross sections in the forward and backward hemispheres, integrated in equal angular intervals, located symmetrically with respect to 90°. For products with Z > 6, the data of ref.[2] are employed.

The angular distributions shown in Fig. 5 can be presented as a superposition of two distributions: the one symmetrical relative to 90° and the asymmetrical one that contributes to the cross section in the forward hemisphere. The shape of the asymmetric parts of the angular distributions is presented in Fig. 6. All of them are similar in shape and are characterized by the exponential growth of the cross section with decreasing emission angle.

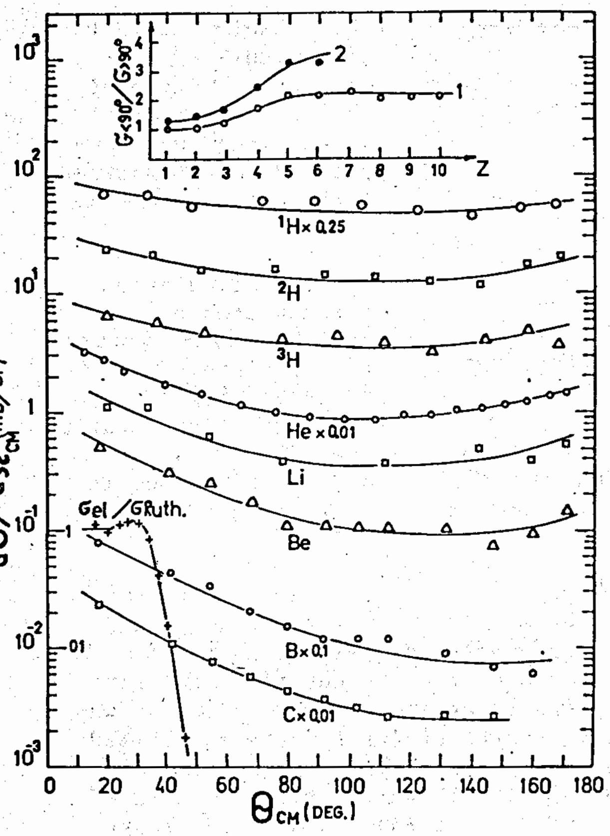

Fig.5. The c.m. angular distributions of ^{1}H, ^{2}H, ^{3}H, He, Li, Be, B, and C. The ratio of the elastic scattering cross section to the Rutherford one is shown in the left-hand bottom part of the figure. The ratio of yields of products with different Z in forward and backward angle ranges symmetric to 90° c.m. is shown at the top of the figure. Curves 1 and 2 give the ratios $\sigma(40^\circ-90^\circ)/\sigma(90^\circ-140^\circ)$ and $\sigma(10^\circ-90^\circ)/\sigma(90^\circ-170^\circ)$, respectively.

The similar shape of the forward directed angular distributions of particles with $1 \leq Z \leq 6$ can serve as evidence for a similar mechanism of their formation. In the case of α-particles we have data on energy spectra (see Fig. 3), which indicate that the main contributor to the cross section for formation of α-particles with a forward directed angular distribution are particles with energies considerably above the Coulomb barrier. The dependence of the energy of these particles on the observation angle allows one to admit that they are emitted from a source moving with respect to the centre of mass. In accordance with this, it is possible that part of the forward directed particles with $Z \leq 6$ is also formed at the stage of interaction until the total dissipation of the initial kinetic energy occurs. Similar conclusions concerning the time of formation of the forward directed protons, α-particles and neutrons in other target-projectile combinations have been made, e.g., in refs./16–19/.

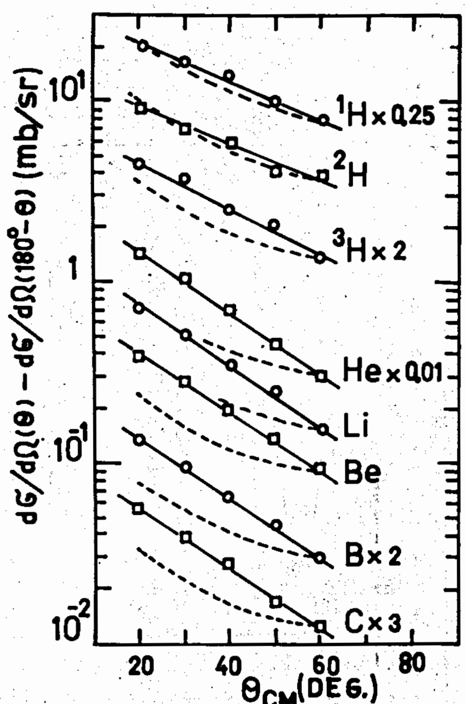

Fig.6. The asymmetric parts of angular distributions of products with $1 \leq Z \leq 6$. The dashed lines correspond to $1/\sin\theta$.

3.3. Cross Sections for formation of Isotopes and Elements

The differential cross sections of the isotopes of elements from hydrogen to chlorine at an emission angle of 40° are presented in Fig. 7. The dependence of cross sections on the proton number Z and neutron number N indicates the pronounced effects of nuclear structure of fragments on their yield. The Table presents the total cross sections for the formation of ^{1}H, ^{2}H, ^{3}H, ^{4}He and elements from lithium to carbon. They have been obtained by integrating the differential cross sections over the angle range 15°–168° (lab.system). The relation between the cross sections of products with an angular distribution symmetric relative to 90° (c.m.) and the forward peaked angular distribution is presented in the table too.

Table

Cross sections (mb) for formation of light particles in the system ^{nat}Ag + ^{40}Ar (285 MeV)

Particle	^{1}H	^{2}H	^{3}H	He	Li	Be	B	C
σ_{total}	2700	180	50	1450	6.1	2.0	2.4	6.9
$\sigma_{symm.}$	2500	160	45	1200	4.7	1.2	1.0	1.5
$\sigma_{forward}$	200	20	5	250	1.4	0.8	1.4	5.4

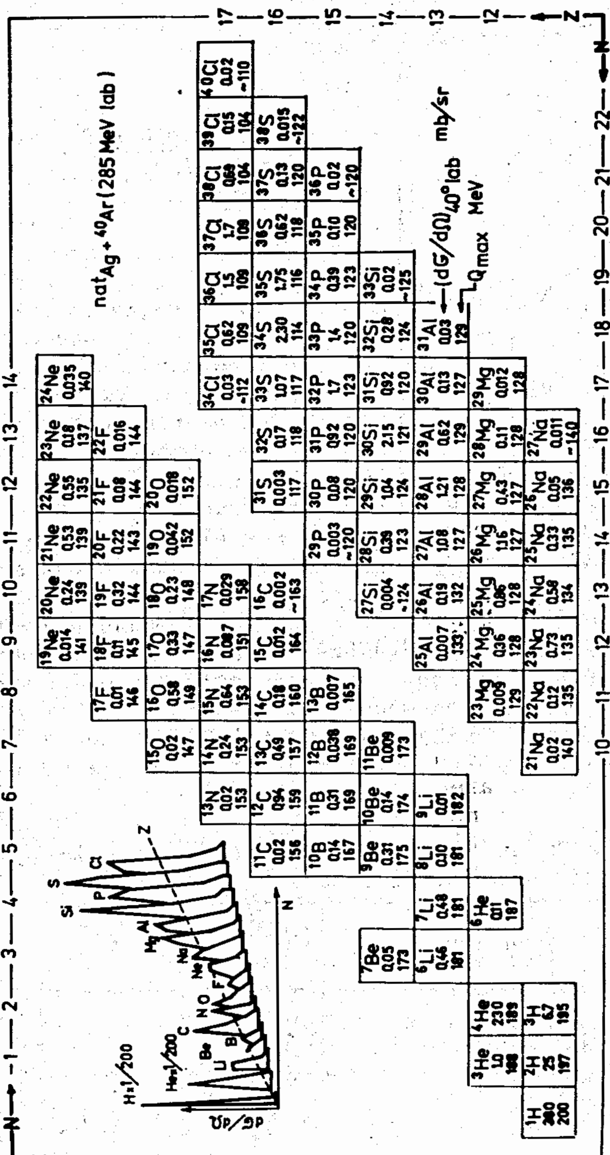

Fig.7. The cross sections for formation of different isotopes and Q-values for the maxima of the energy spectra in the system $Ag+{}^{40}Ar$ (285 MeV) at a detection angle of 40°.

As is seen from the table, the total cross section for formation of protons and α-particles exceeds 4 barns. The total cross section of the nuclear reaction, determined from the elastic scattering data presented in Fig. 5, amounts to 2.2 barns. The procedure of determining the total cross section is similar to that used in ref./5/ and gives results that agree with that paper. From the balance of cross sections it follows that most of the protons and α-particles are formed in processes involving the emission of more than one light particle in one event of interaction. This fact is in agreement with the charge distribution of heavy products, obtained by the activation technique in ref./3/.

As is seen from the table, the cross sections for formation of forward directed α-particles and protons constitute a small part of the total formation cross sections. Therefore, the main contribution to the multiple production of α-particles and protons is made by the processes leading to their symmetrical emission relative to 90° in the centre-of-mass system.

If Fig. 8 one can see the dependence of cross sections for the formation of the isotopes detected at an angle of 40° on the difference of masses of the initial and final nuclei, Q_{gg}. In calculating Q_{gg} the average values were taken for ${}^{107}Ag$ and ${}^{109}Ag$ with a weight proportional to their contents in natural silver. It is notworthy that the difference in the Q_{gg} values for these silver isotopes lies within about 1 MeV. The exponential dependence on Q_{gg} of cross sections for formation of the isotopes of a given element is satisfied up to the isotopes of oxygen. For elements with larger Z values the exponential Q_{gg} dependence of the isotopic yields being measured is violated, apparently because of the effects of the excitation of primary nuclear reaction products. The problem of nucleon evaporation by the excited products of the reaction $Ag+{}^{40}Ar$ (285 MeV) has been considered in ref./20/.

In Fig. 8 the cross sections for formation of isotopes of different elements are presented also as a function of Q_{gg} with pairing corrections. The pairing corrections were taken equal to the sum of the pairing energies of the total number of proton and neutron pairs, transferred to the acceptor nuclei. It is seen that the introduction of these corrections allows one to improve the systematization of the initial experimental data. The slopes of the straight lines and the distance between them are practically identical. The slope parameter interpreted as the temperature of the double nuclear system/21/ is equal to 2.2 MeV, this value being close to the value of T=2 MeV, obtained from the data on the energy spectra of protons (see Figs. 3 and 4).

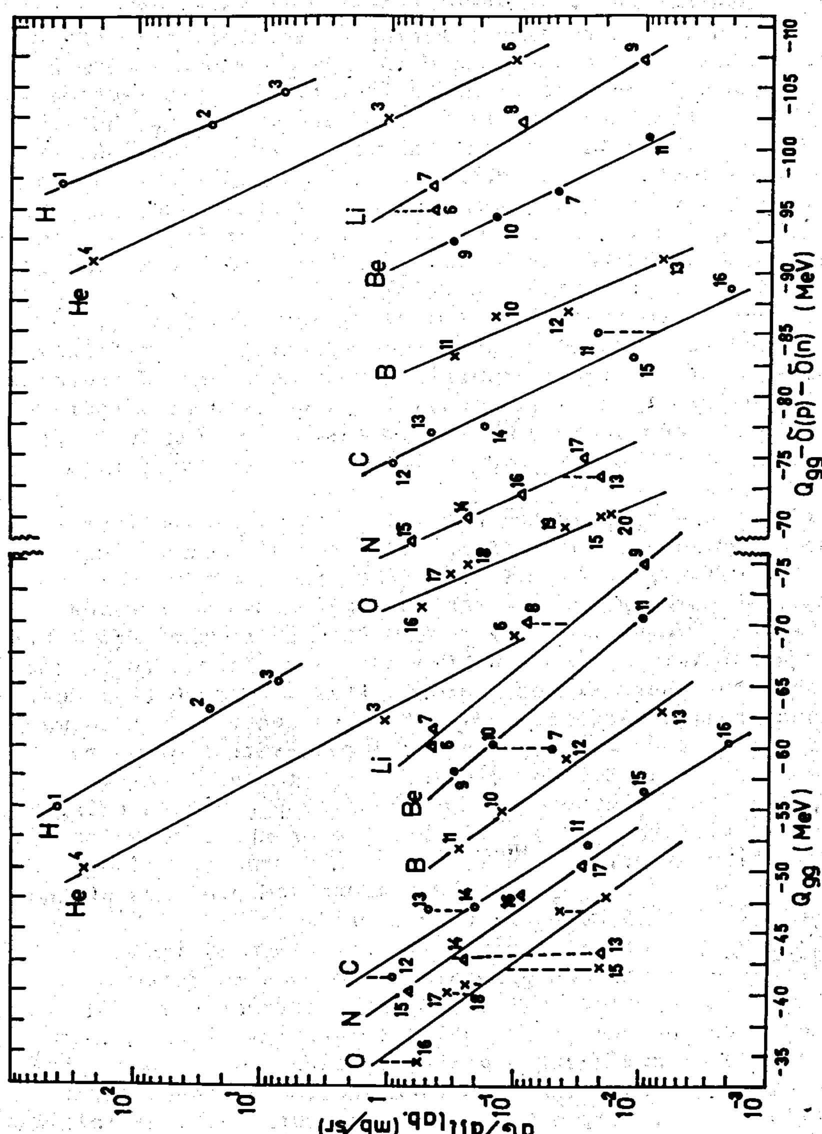

Fig.8. Q_{gg}-systematics of differential cross sections for the production of isotopes from H to O at a lab. angle of 40°.

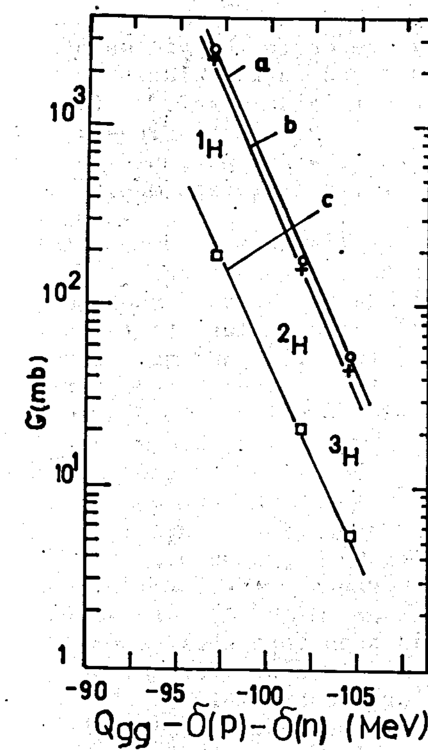

Fig.9. Q_{gg}-systematics of cross sections for the production of hydrogen isotopes: (a) total cross sections; (b) cross sections for formation of particles with an angular distribution symmetric relative to 90° c.m.; (c) cross sections for formation of products with a forward peaked angular distribution.

Figure 9 shows the Q_{gg} dependence of the total cross sections for formation of hydrogen isotopes. It is seen that this dependence is satisfied well. It is seen in the same figure that the Q_{gg}-systematics with pairing corrections are satisfied for the cross sections for formation of products having a symmetric relative to 90° (c.m.) angular distribution and a forward peaked angular distribution. In the Q_{gg}-systematics, the deviations of the experimental values of the cross sections for formation of the isotopes of a given element from the straight line drawn using the least-squares method, lie mainly within a factor of 2-3. For the whole range of the change of cross sections by several orders of magnitude this spread of points weakly influences the slope and position of the straight line. Therefore, the multiplicity of the formation of α-particles and protons of about 2 should not substantially influence the position of the straight lines for helium and hydrogen in Fig. 8 and 9.

The statistical model calculations according to ALICE code/11/ for the system Ag + ^{40}Ar (285 MeV) give the reaction cross section of 2.1 b, the compound nucleus production cross section of 1.1 b, the proton evaporation cross section of 1.1 b, the α-evaporation cross section of 0.8 b, and the fission cross section of 0.55 b. These calculations for the reaction cross section, cross sections for compound nucleus formation and fission coincide within about 10% with the experimental data of refs./1,4,5/. However, they are incapable of explaining all the observed α-particle yield and proton yield with a symmetrical angular distribution. A similar, but still stronger (a factor of ≈100) difference in the yields of light charged particles in experiments and in calculations using the evaporation model has been obtained in ref.[17] for the system $^{197}Au + ^{40}Ar$ (340 MeV). Thus the question arises about another mechanism of formation of light charged particles with a symmetrical angular distribution, a different one from evaporation from a compound nucleus.

It is possible to advance the hypothesis that a substantial part of light charged particles with an angular distribution symmetrical relative to 90° (c.m) can be a result of nucleon transfer reactions which proceed during the evolution of the initial double nuclear system of the projectile and the target nucleus. The nucleon diffusion model calculations[22] performed in paper[8] with real nuclear masses confirm this conclusion. The physical reason leading to the considerable excess of proton and α-particle yields over the yields of the heavier multinucleon transfer products is a strong decrease in the potential energy of the double nuclear system as it transforms to the configuration involving a proton or a particle. As seen from Fig. 7, there occurs a continual distribution of products from the atomic number of the projectile to protons. From Figs. 1 and 2 it is seen that their energy spectra are similar in shape. The cross sections for formation of products with Z from 8 to 1 are describable by the Q_{gg}-systematics which manifest themselves most vividly in multinucleon transfer reactions. Hence it is possible to assume that mechanism of their formation can also be similar for at least a part of the total yield. The tendency of changing the T value in going from protons to the heavier particles (see Fig. 4) also confirms, in our view, the hypothesis that a considerable part of light charged particles are formed at the expense of multinucleon transfer reactions. In this case complete fusion can be considered to be the limiting case of multinucleon transfer reactions.

4. CONCLUSIONS

1. Data on the differential cross sections for the formation of the isotopes of elements with $Z \leq 8$ at an angle of 40° are described satisfactorily by the Q_{gg}-systematics with pairing corrections.

2. The yields of hydrogen isotopes are described by the Q_{gg}-systematics with pairing corrections both for the differential cross sections at 40° and the total cross sections. In the case of hydrogen isotopes, the Q_{gg}-systematics with pairing corrections are satisfied for both parts of cross

sections that correspond to the angular distribution symmetric relative to 90° c.m. and for forward peaked angular distribution.

3. The substantial part of light charged particles with an angular distribution symmetric relative to 90° c.m. can be a result of nucleon transfer reactions which proceed during the evolution of the initial double nuclear system of the projectile and the target nucleus.

4. The similar shape of the forward directed angular distributions of particles with $Z \leq 6$ can serve as evidence for a similar mechanism of their formation. It is possible that part of the forward directed particles with $Z \leq 6$ is formed at the stage of interaction preceding the total dissipation of the initial kinetic energy.

ACKNOWLEDGEMENTS

The authors express their thanks to Yu.A.Muzychka and B.I.Pustylnik for performing the statistical calculations of the processes of formation and de-excitation of a compound nucleus in the system $Ag + ^{40}Ar$ (285 MeV). The authors express their deep appreciation to Academican G.N.Flerov for his stimulating interest in the present study.

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Received by Publishing Department
on May 27 1981.