Interaction of Nitrogen Nucleus with Nuclei in an Emulsion

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The results of an experimental investigation of the interaction between nitrogen nuclei, accelerated to an energy of 100 mev, and nuclei in an emulsion are presented. The range-energy relation for nitrogen nuclei in the emulsion is determined. The angular and energy distributions for protons and α-particles produced in the reactions are examined. The experimental results reveal a number of interesting features in the emission of charged pasticles which characterizes the interaction of the nitrogen nuclei with the nuclei of the emulsion.

NUCLEAR reactions involving nuclei heavier than α-particles have received little attention until recently. This situation is a result of the technical difficulties associated with the acceleration of heavy ions to high energies and the desire to deal with as simple an interaction as possible, the latter suggesting the use of elementary particles as bombarding particles. However, study of the interaction of more complicated nuclei should yield valuable data on nuclear deformation, the structure of the nuclear surface, nucleon exchange, and so on[1].

In the small amount of work which has been carried out in this field several interesting features of this type of reaction have been observed. In the bombardment of aluminum by nitrogen nuclei and carbon nuclei[2,3] with energies of 50-80 mev, a considerably greater number of charged particles was produced than had been predicted by the analysis based on evaporation of nucleons from a compound nucleus. In spite of the fact that the bombarding nuclei were comparatively slow--3 to 5 mev per nucleon--the authors assumed that a "stripping" reaction was possible. On the other hand, in Ref. 4, a study was made of the excitation function for reactions occuring in bombardment Mg^{25} by protons and C^{12} by nitrogen nuclei. The excitation functions were similar: this finding indicates that both reactions proceed via the same compound nucleus, Al^{26}.

In the work cited above a radiochemical method was employed; this method does not permit detailed observation of the interaction. A more comprehensive picture of the interaction can be obtained through the use of photographic emulsions, since in these it is possible to determine the identity as well as the energy and angular distribution of all charged particles produced in the reaction.

Below are described the experimental results obtained in a study of the interaction of nitrogen nuclei with nuclei in an emulsion.

The emulsions were bombarded by nitrogen nuclei accelerated in a 150 cm cyclotron. The acceleration of the nitrogen nuclei to high energies was accomplished as follows: The cyclotron was adjusted to accelerate sextuply-charged nitrogen ions ($e/m = 6/14$); it is also possible for doubly-charged ions to be accelerated under these conditions. The ion source was of the usual type and yielded singly- and doubly-charged nitrogen ions. The doubly-charged ions, having been accelerated to an energy of 4-5 mev, subsequently lost four more electrons to atoms of the residual gas in the cyclotron chamber. These ions were then accelerated as sextuply-charged nitrogen ions acquiring thereby an energy of 120-130 mev. A similar acceleration mechanism has been described by Walker[5].

However, since the electron-loss process can occur anywhere in the volume of the cyclotron chamber, the energy spectrum for nitrogen ions in the last orbit (70 cm) ranges from 0 to 130 mev. Furthermore, the beam is comprised of ions of different charge. To obtain monochromatic ions in the emulsion, the beam was extracted from the cyclotron chamber and passed through an analyzing magnet. In front of the analyzer there was an aluminum foil 2μ thick in which the nitrogen ions were completely stripped of electrons. By varying the magnetic field in the analyzer it was possible to obtain nitrogen nuclei with energies up to 130 mev. The analyzer resolution was about 3 mev.

In order to investigate the interaction of nitrogen nuclei with the nuclei of the emulsion at any energy, the range-energy relation for nitrogen nuclei in the emulsion must be known. This relation was determined with the magnetic analyzer. It was found, after a careful check, that the magnetic field in the analyzer was a linear function of the current in the winding. Thus, by measuring, at a given value of the analyzer current, the deflection of deuterons of known energy, it is possible to determine the energy of the nitrogen nuclei from the relation

$$E_N = \left(\frac{Z_N}{Z_d}\right)^2 \frac{M_d}{M_N} \left(\frac{i_N}{i_d}\right)^2 E_d ,$$

where Z is the charge, M is the mass and i is the current in the analyzer winding. The emulsions were exposed to nitrogen nuclei of various energies and the range measured with a microscope. The results obtained are shown in Fig. 1.

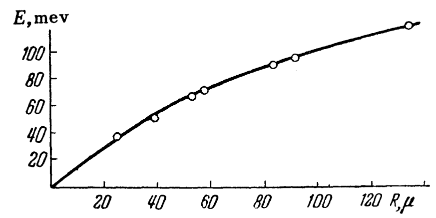

FIG. 1. The range-energy relation for nitrogen nuclei in an emulsion.

The range-energy relation in an emulsion for nitrogen nuclei with energies from 4 to 30 mev has been measured by Zucker and his collaborators[6]. In the region ~30 mev the results of the present work are in agreement with those of Zucker.

In the experiments an Ilford E-1 plate was bombarded by nitrogen nuclei with an energy of 115 mev. 25 cm^2 of the emulsion was scanned and 198 events were found in which an interaction took place with the emission of charged particles. Because of the complicated constitution of the emulsion it is impossible to determine exactly with which element the nitrogen nucleus interacts. It was possible, however, to distinguish cases in which the nitrogen nucleus interacted with "light" nuclei--carbon, oxygen and "heavy" nuclei--bromine and silver. The nitrogen nucleus, having an energy of several tens of mev, has a large momentum; hence, the constituent nuclei has a considerable range. Estimates indicate that for collisions of the nitrogen nuclei with silver or bromine nuclei the range of the constituent nuclei is 2-5 μ and in collisions with "light" nuclei erect this range is 10-15 μ. It should be noted that in each case it was necessary to take into account the momentum imparted to the residual nucleus by the emitted particles. If there is a preliminary emission of several particles the range of the "light" residual nucleus can be reduced to 5-8 μ. Hence, the cases in which the range of the residual nucleus was of the order 5-8 μ were attributed to interactions with carbon or oxygen nuclei.

Out of 198 cases 70 were assigned to interactions with "heavy" nuclei and 128 with "light" nuclei.

Knowing the initial energy of the nitrogen nucleus, by measuring the length of track from the beginning to the "star" it is possible to determine the energy at the point of interaction.

Using photographic plates it is possible to distinguish between tracks of protons, particles and heavier fragments but it is not possible to identify these heavier fragments.

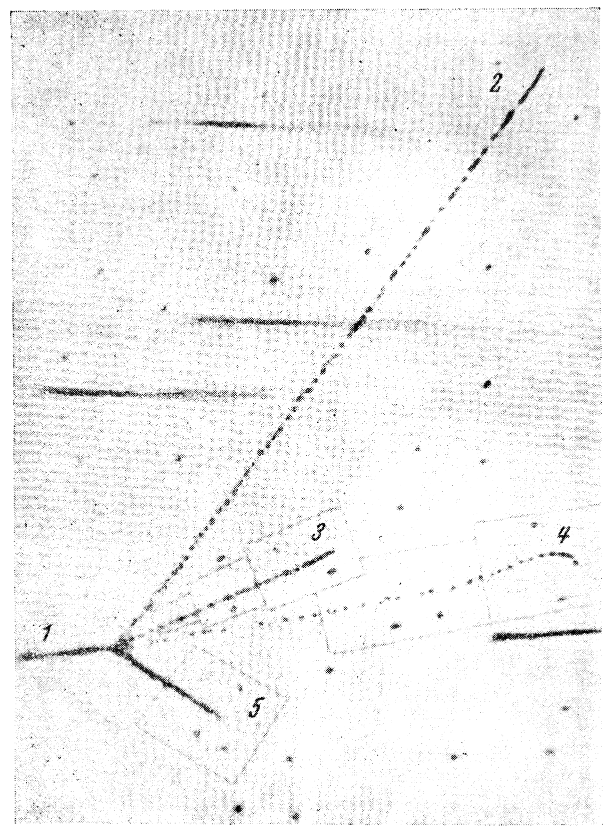

FIG. 2. Photograph of an interaction between a nitrogen nucleus and a "light" nucleus. The following tracks are visible: 1 – incoming nitrogen nucleus, 2, 3 – α–particles, 4 – proton and 5 – recoil nucleus.

In Fig. 2 is presented a photograph of a star which shows the emission of two α – particles and

TABLE

Reaction	Number of events	
	Nitrogen on carbon, oxygen	Nitrogen on bromine, silver
N; p	2	7
N; $2p$	5	5
N; α	6	14
N; α, fragment	4	1
N; α. p	8	10
N; α, p, fragment.	3	1
N; α, $2p$	2	0
N; 2α	9	11
N; 2α, fragment.	2	0
N; 2α, p	12	11
N; 2α, p, fragment	2	1
N; 3α	6	7
N; 3α, p	4	1
N; 4α	1	0

a proton. In the Table are listed stars with different numbers of emitted charged particles (interactions with "light" and "heavy" nuclei are shown spearately). In this Table are included all reactions induced by nitrogen nuclei with energies from 30 to 110 mev. The number of interactions of nitrogen nuclei with carbon and oxygen is normalized to the number of interactions with bromine and silver (70).

All charged particles produced in the reactions are listed; the recoil nuclei are omitted.

The considerable preponderance of α – particles merits attention. On the average, in all stars the α – particles are found to be twice as numerous as protons both for "light" and "heavy" target nuclei. In the interaction of nitrogen nuclei with carbon and oxygen, in 25 percent of the cases emission of fragments heavier than α – particles was observed. Out of 70 cases of interaction of nitrogen nucleus with bromine and silver only 3 cases of fragment omission were observed.

In Figs. 3 and 4 are shown the angular and energy distributions for α – particles in the center-of-mass system. In converting to the center-of-mass system, the mass of the target nucleus was taken to be an average between that of carbon and oxygen (14) and bromine and silver (94). Because of the small amount of data it is not possible to determine accurately the angular and energy distributions for the α – particles at different nitrogen energies. In Figs. 3 and 4 are shown the distributions as summed over all cases in which the incident nitrogen nuclei had an energy from 70 to 110 mev.

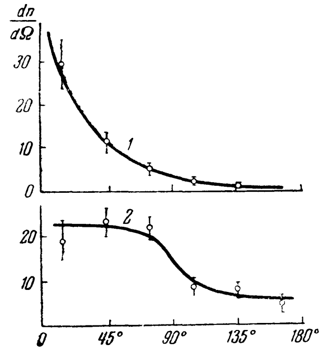

FIG. 3. Angular distribution for α – particles in the center-of-mass system. The interactions are between a nitrogen nucleus and 1 – Br, Ag nuclei; 2 – C, O nuclei.

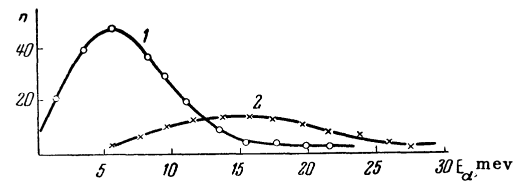

FIG. 4. Energy distribution for α – particles in the center-of-mass system. The interactions are between a nitrogen nucleus and 1 – C, O nuclei; 2 – Br, Ag nuclei.

The α – particle angular distribution is characterized by a noticeable directional effect in the forward direction, particularly in the case of "heavy" target nuclei . In the energy spectra, attention is directed to the considerable number of low-energy α – particles, having energies below the Coulomb barrier for a nitrogen nucleus. Within the limits of experimental error, the proton angular distribution for "light" nuclei, presented in Fig. 5, is isotropic. The number of proton-emission cases in the "heavy" nuclei was not large enough to permit plotting of the angular distribution. However, the proton distribution is approximately isotropic. Out of 31 protons, 17 were emitted in the forward direction and 14 in the backward direction.

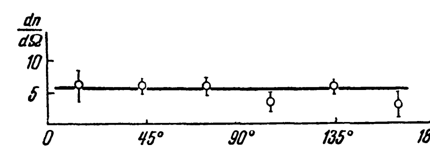

FIG. 5. Proton angular distribution in the center-of-mass system in the interaction of a nitrogen nucleus with C, O nuclei.

The results presented here are not in accord with the notion of the formation of a compound nucleus with the subsequent emission of particles. According to a calculation given by Le Couteur[7], at an excitation energy of the order 50-100 mev in nuclei such as silver or bromine, the number of evaporated protons should be twice the number of α – particles. In the experiment, it is found that there are twice as many α – particles as protons. The average number of α – particles emitted per disintegration is 1.3--this is 3 times larger than that predicted by evaporation theory; moreover, the α – particles are emitted chiefly in the forward direction while the angular distribution predicted by evaporation theory is isotropic.

In Ref. 2 there has been presented a qualitative picture of the interaction between nitrogen and aluminum nuclei which may explain the large number of charged particles. The height of the Coulomb barrier for penetration of the nitrogen nucleus into the aluminum nucleus is 17.4 mev in the center-of-mass system; this is close to 19.7 mev, the energy required for splitting the nitrogen nucleus into three α – particles, a proton and a neutron. Thus, in its approach to the aluminum nucleus, the nitrogen may be split into separate particles, some of which penetrate the aluminum nucleus and some of which are scattered by the Coulomb field. In this case, conditions are most favorable for the penetration of the neutron, since it sees no potential barrier. The next most favored is the α – particle since its energy is 4 times larger than the proton energy, although the barrier it sees is only 2 times larger; the proton will have the highest probability for being scattered. The angular distribution for all particles should be characterized by a predominance in the forward direction.

The isotropic proton angular distribution observed in the experiment is not in agreement with this hypothesis.

It may also be assumed that the nitrogen nucleus undergoes disintegration into individual particles only after penetration into the target nucleus. If the α – particles are maintained as individual objects, the probability of their being emitted at the moment of collision is large, since each α – particle has an energy of 25-30 mev. The emission of protons is less probable, since these are emitted by evaporation following the heating of the nucleus. The existence of a large number of low-energy α – particles would seem to indicate that a considerable deformation of the nucleus occurs during the time of collision; this deformation causes a reduction in the potential barrier.

It would be of interest to study the interaction of carbon nuclei or oxygen nculei, consisting of α – particles only, with nuclei in an emulsion. If the picture given in Ref. 2 is correct, a considerably smaller number of protons should be observed. On the other hand, if the hypothesis presented here is valid, the number of protons should not vary to any great extent. If a more complete picture of the interaction of nitrogen nuclei with nuclei in the emulsion is to be obtained we shall require a detailed explanation of the dependence of the angular and energy distributions for protons and α – particles on the energy of the incident nitrogen nucleus; the relation between the proton and α – particle angular distributions and energies also requires study.

In conclusion, we wish to express our gratitude to the cyclotron crew and particularly to Iu. M. Pustovoi for providing reliable cyclotron operation in the course of the work.

Note added in proof: The interaction of accelerated oxygen nuclei with nuclei in an emulsion has been studied in a recent experiment. The emulsion was bombarded by a monochromatic beam of oxygen nuclei accelerated to an energy of 110 mev. The results have been analyzed in the same way as in the nitrogen experiments.

The ratio between the number of α – particles and the number of protons, averaged over all reactions, has been found to be 2 $\pm$0.5. Thus the probability for the emission of protons is virtually the same in reactions induced by nitrogen nuclei and oxygen nuclei. This would seem to corroborate the assumption that, in general, the reactions proceed via the formation of a conglomerate nucleus.

[1] Breit, Hull and Gluckstern, Phys. Rev. **87**, 74 (1952).

[2] Chackett, Fremlin and Walker, Phil. Mag. **45**, 173 (1954).

[3] Chackett, Chackett and Fremlin, Phil. Mag. **46**, 1 (1955).

[4] Cohen, Reynolds and Zucker, Phys. Rev. **96**, 1617 (1954).

[5] D. Walker and J. H. Fremlin, Nature **171**, 189 (1953).

[6] H. L. Reynolds and A. Zucker, Phys. Rev. **96**, 393 (1954).

[7] K. J. Le Couteur, Proc. Phys. Soc. **63A**, 259 (1950).

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