Tritium production in iron by protons
at energies between 50 and 177 MeV

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ABSTRACT. Tritium produced in iron by high energetic protons has been separated from the target material and its activity was determined in a GM counter. The tritium production by protons between 50-177 MeV was compared with the He** activity in aluminum foils induced by the same proton beam. A cross-section of 6.6 mb at 177 MeV was obtained, at the lower energies the tritium yield decreases slowly and is about 6 mb at 50 MeV. These results can be compared with the prediction of the evaporation theory. It turns out that the evaporation effect does not explain the magnitude of the observed tritium cross-section. The possibility of other production mechanisms such as fast fragmentation and double pick-up process is described and other experiments in this field are discussed.

1. Introduction

In the interactions between incident high energetic particles* and nuclei (target nuclei) of zero momentum, a wide variety of products results. The process is generally thought to consist of a fast nucleon cascade in the target nucleus followed by a dissipation of energy deposited in the nucleus in the fast cascade. The excited nuclei might undergo evaporation of single nucleons or groups of nucleons, fission processes or fragmentation. These effects - with exception of fission - can be responsible for the tritium production in iron which, in particular, has been studied because of the possibility of a comparison with the tritium production in iron meteorites induced by cosmic radiation in outer space.

The products with lowest mass number are generally emitted with kinetic energies ranging from zero** to nearly the incident energy. To study these ejected particles nuclear emulsions or photographs from diffusion or bubble chambers are very often used. In this type of experiment much information is obtained, because all charged particles in a wide momentum range can be observed. Sometimes, however, it is difficult to distinguish tracks

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* The validity of the compound nucleus model is limited by an energy of 20 MeV. The reactions considered here are above this limit, but the fast processes might also take place at lower energies, e.g. pick-up or stripping processes (see Nudras [1976]).

** The minimum kinetic energy for charged particles emitted by high energy interactions depends on the Coulomb barrier of the nucleus in question.
from different isotopes, e.g. deuterons and tritons. In addition, heavier fragments are often not easy to identify because of their short range in the emulsion. If such particles have a favourable half-life or a high neutron capture cross-section, it is preferable to measure the activities in order to obtain their production rate in spallation processes.

The yield of tritium in high energy interactions can be determined in this way using its $\beta$-activity which has a half-life of 12.3 years.

The abundance of tritium in the atmosphere gave rise to special interest in the determination of its production rate in the main process induced by cosmic ray particles: the cross-section of $N(p,t)$ and $O(p,t)$ at 2.2 GeV was found (Fireman and Rowland [1955]) to be $28 \pm 4$ and $33 \pm 4$ mb respectively, while for the production of secondary neutrons ($E \geq 4.4$ MeV) in nitrogen $N(n,t) = 11 \pm 2$ mb was obtained (Fireman [1953]). These results together with the primary flux of cosmic ray particles and an estimation of the energetic secondaries allow the calculation of the world wide production of tritium in the atmosphere.

In helium determinations in meteorites a high abundance of $\text{He}^3$ especially in smaller bodies was found (Chackett, Reasbeck and Wilson [1953]). It has been assumed that the $\text{He}^3$ and a considerable part of the $\text{He}^4$ is produced by cosmic irradiation of the meteorite during its flight in outer space. This implies that the $\text{He}^3$ is partly produced as tritium which decays afterwards in $\text{He}^3$. At the time of fall the tritium in a meteorite is in equilibrium between decay- and production rate, and should be found in material from recent falls. Up to now it has been possible to measure the tritium content in two stone (Begemann, Geiss and Hess [1957]) and two iron (Fireman and Schwarzer [1957]) meteorites. To clarify the question of direct production of tritium in iron, measurements at proton energies of 0.45, 2.05 (Currie, Libby and Wolfgang [1956]) and 2.20 GeV (Fireman [1955]) have already been carried out. For the production of tritium in meteorites it was of interest to study how the production rate behaves in dependence on the depth. In recent measurements Fireman and Zähringer [1957] could show that at high energies of 3 and 6 GeV a transition effect exists.

In the present work the tritium production rate has been measured at energies between 50 and 170 MeV. This energy is of interest for the discussion of secondary processes in thick targets or meteorites and for primary interaction near the surface of the meteorite if the cut-off of the cosmic ray energy does not exist in outer space. Considering the difficulties that
arize in the explanation of the tritium cross-section at higher energies (Currie, Libby and Wolfgang [1956]), it seemed justified to make further measurements at lower energies, where meson interactions do not occur*. Furthermore, in the chosen energy region more experimental data of the (p,t) reaction are available for discussion.

2. Experimental procedure

The measurements of the tritium production cross-section were carried out by irradiation of thin iron targets in the internal beam of the Uppsala Synchro-cyclotron. Energies between 50 and 177 MeV (maximal energy of the machine) were chosen at 50, 75, 93, 100, 135, 150, 177 MeV. The tritium was directly measured by its beta-radio-activity in a GM-counter.

2.1 Irradiation of the Iron

In the standard target holder of the cyclotron stacks of thin iron sheets were mounted, covered with 40 \( \mu \)-Al monitor foils in front and in the rear of the beam. In order to ensure that all foils and target sheets were hit by the same number of protons, the whole target was carefully aligned at the edges exposed to the beam. As could be checked by the activity of the monitor foils, the number of protons traversing the different sheets and foils was the same within a maximum error of 10%. Using for the tritium measurements only the inner sheets of the stack, it was possible to compensate for losses due to the kinetic energy of the tritons. The targets were irradiated at different radii corresponding to the chosen

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* Lindenbaum, in a lecture given at CERN in Geneva in November 1957, emphasized that the meson interaction might be responsible for the production of heavier fragments. (see also Wolfgang et al. [1956]).
energies. The irradiation time was 25 minutes, which was long enough to induce tritium activities which could be measured over a normal counter background.

2.2 Monitoring

In front and in the rear of the beam four Al-foils were placed. For the measurements of the beam intensity only the inner two foils numbered 2,3 (front) and 6,7 (rear) were used. In this way errors induced by recoil losses of the produced Na$^{24}$ could be avoided. The irradiated foils were fixed on a holder in such a way that no backing was underneath the irradiated edge of the foils. The holder and the end window beta-counter were fixed in a standard counting arrangement (Pappas [1953] and Zumwalt [1950]). The cross-section of the used monitor reaction Al$^{27}(p,3pn)$ Na$^{24}$ was taken from the data in the literature (Hintz and Ramsay [1952], Marques [1952], Chackett et al. [1956], Friedländer, Hudis and Wolfgang [1955], Hicks, Stevenson and Nervik [1956]). The values of Hicks, Stevenson and Nervik for the relative cross-section of the monitor to the C$^{12}(p, pn)$ C$^{11}$ reaction combined with the absolute value of the latter given by Crandall et al. [1956] seemed to be the most accurate ones. In Column 3 of the following table, these values are given. The beta-counting rates were corrected for self-absorption. Measurements for the different source sizes (point source and ring source of 10 mm $\phi$) showed that the geometrical factor in our arrangement does not change more than 1%.

Corrections due to our source are contained in the geometric factor. For all targets the maximum difference between the beta-activities of the different foils of the target is 12%.
The mean error of the measured proton intensity lies between 5% and 8%. The values of the average proton intensity per minute can be seen for the different irradiations from Column 4 in the table.

2.3 The tritium measurement

The irradiated iron sheets were rendered molten under vacuum in a graphite crucible. A high frequency generator provided the heat. Normally a temperature of 1800°C was used. During seven hours of heating the gas coming from the sample was pumped by means of a mercury diffusion pump through a cracking unit to a palladium diffusion thimble. In the cracking unit the chemical compounds of the hydrogen, the hydrocarbons, water, etc. were cracked to hydrogen. In the vacuum line behind the palladium tube another diffusion pump provided constant vacuum conditions for the diffusion of the hydrogen through the palladium. An automatic Toepler pump pumped the hydrogen into a reservoir of the GM-counter.

The counters used (see fig. 3 below) has already been filled with "Tracerlab-Q-gas" or normal argon-alcohol or argon-ethyl-acetate quenching gas and had been checked for low background and a good plateau. By opening the thin glass bulb between counter and storage vessel, the tritium could enter the counter. After each trial a test run was made and, if necessary,
the sample degassed for another period. This was continued until all tritium had been separated within the limits of error of the whole procedure (10%). In spite of the fact that the tritium activities were rather high (maximum counting rates about 500 cpm), the use of a low level counting facility was very practical for many test trials by which traces of tritium could be followed in all treatments of the gaseous samples. The low level counting equipment consists of a normal anti-coincidence arrangement with a double ring of 20 GM-counters, whose pulses close an electronic gate for the pulses from the inner counter. The counters were surrounded by a 20 cm thick iron shield. The background of all counters lies between 1.6 to 3 cpm (counts per minute). In some of the trials where H₂-carrier was added, the H₂ pressure in the counter was remarkably high. From about 15% of H₂ upwards the background started to rise slowly. This effect limited the carrier quantity if the necessary corrections for the background were made. Because of the comparably low background (1% of the effect) the rise of the background, due to a higher partial pressure of the hydrogen, was not important.

3. Results

In the table the results for the tritium production cross-section in iron are presented. From the highest energy of 177 MeV the cross-section drops slowly with decreasing energy. The errors of all determinations are relative to the Al-Na²⁴⁺ cross-section maximum of 20%. Because of the steep rise of the Al-Na cross-section in the energy region of 50 MeV the production rate of tritium at 50 MeV is not very well defined.

<table>
<thead>
<tr>
<th>Target No.</th>
<th>Proton energy MeV</th>
<th>Al²⁴⁺(p,3p) cross-section mb</th>
<th>Proton flux per minute x 10⁻¹²</th>
<th>Tritium decays per minute⁵⁴</th>
<th>Tritium production cross-section mb</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>177</td>
<td>8.9</td>
<td>0.41</td>
<td>902</td>
<td>6.6 ± 1.2</td>
</tr>
<tr>
<td>2</td>
<td>150</td>
<td>9.2</td>
<td>0.71</td>
<td>988</td>
<td>6.1 ± 1.1</td>
</tr>
<tr>
<td>3</td>
<td>135</td>
<td>9.7</td>
<td>0.84</td>
<td>1200</td>
<td>6.4 ± 1.2</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>10.6</td>
<td>0.74</td>
<td>795</td>
<td>4.3 ± 0.9</td>
</tr>
<tr>
<td>5</td>
<td>93</td>
<td>10.7</td>
<td>0.83</td>
<td>948</td>
<td>5.9 ± 1.0</td>
</tr>
<tr>
<td>6</td>
<td>75</td>
<td>8.2</td>
<td>0.73</td>
<td>720</td>
<td>4.3 ± 0.8</td>
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<tr>
<td>7</td>
<td>50</td>
<td>(2-3)</td>
<td>0.87</td>
<td>860</td>
<td>(4.2)</td>
</tr>
</tbody>
</table>

a) All irradiations last 25 minutes, with the exception of Target 1 which was irradiated for 20 minutes.

b) The counting rates at the end of irradiation are corrected for the counting efficiency of the GM - counters.

* According to Marques [1932] the absolute value of the cross-section of our monitor reaction is certain within an
4. Discussion

4.1 Comparisons with other experimental data

In previous experiments of the same type a cross-section of tritium production of \(62 \pm 7\) mb was obtained at a proton energy of 2.2 GeV (Fireman [1955]). This is about one tenth of the geometrical cross-section. In the same experiments a depth dependence of the tritium production is found which shows a decrease of the tritium yield less rapid than the attenuation of the incident proton, due to an interaction of the geometrical cross-section. From another more extended examination (Currie, Libby and Wolfgang [1956]) the tritium production rates of many target nuclei (from C to Pb) for 450 MeV and for 2.05 GeV have been obtained. The tritium production in iron corresponds to a cross-section of \(28 \pm 5\) mb and \(53 \pm 8\) mb at 450 MeV and 2.05 GeV respectively.

During this work results as to the depth dependence of tritium and \(^{37}\)A\(^{37}\) production rates at high energies have been published (Fireman and Zähringer [1957]). A transition effect for tritium could be measured at 3 and 6 GeV, while for the lower energies (1 GeV and 0.16 GeV) only an exponential decrease of the tritium production could be found. The given cross-sections are: 7.2 mb at 160 MeV, 60 mb at 1 GeV, 100 mb at 3 GeV and 130 mb at 6.2 GeV (maximum values). At the lowest energy (160 MeV) the value of 7.2 mb agrees well (within the limit of error) with the cross-section obtained in this determination. In contrast to other cross-sections, e.g. the \(^{27}\)Al\(^{(p,3pn)}\) Na\(^{24}\), which do not change between 75 MeV and 2 GeV (Friedländer, Hudis and Wolfgang [1955]), the tritium cross-section rises up to 1 GeV and is nearly constant only from this energy upwards.

4.2 The mechanism of tritium production

In order to obtain theoretical values of cross-sections of high energetic interactions between nucleons and target nuclei one treats the complex process in two steps. First, it is assumed that a nucleon cascade is originated in a short period (\(10^{-22}\) sec.) after the first collision between the incident particle and the target nucleon. When the cascade has passed the nucleus, it is left in an excited state. The nucleus as a whole will then lose its energy by the evaporation of particles or by de-excitation by gamma-emission.
4.2a The cascade process. It has been first proposed by Server [1947] to assume a model for nuclear reaction with high energy particles in which the incident particle induces a nucleon cascade in the nucleus. In this model the interactions are regarded as collisions between free nucleons. The nucleus in this picture is thought to be a highly degenerated Fermi-gas of free nucleons. The Fermi-energy* (maximum energy for protons or neutrons in the lowest state zero temperature) for a medium weight nucleus \((N = 56)\) is about 25 MeV. The nucleons are free in a "square well" potential, the momentum exchange between the nucleons in this Fermi-gas is subject to the Pauli principle. Taking an average separation energy of 8 MeV, and for the protons a Coulomb barrier of 6 MeV**, a nucleon in a nucleus must have an energy of about 40 MeV to escape through the nucleus surface. Goldberger [1948] (see also Bernardini, Booth and Lindenbaum [1952]) has used a Monte Carlo calculation to follow the nucleon interactions in the cascade***. The calculation deals in the first stage with the collision between incident nucleon and the nucleon of the target nucleus. The result is a new momentum distribution between the two partners. In the next stage, the free nucleon-nucleon collisions (if they occur) of both partners are treated. By this process a certain statistical energy distribution is obtained for the nucleons inside the nucleus as well as for the ejected nucleons. This distribution and the distribution of the excitation energy of the residual nucleus depend very strongly on the assumption which can be made about the end of the cascade process. The extreme cascade model takes the particles as free moving in the nucleus until they escape from the nucleus or their kinetic energy is lower than the minimum energy for leaving the nucleus (Fermi energy + binding energy + Coulomb energy); then the nucleon is captured. Other models using the compound nucleus picture require a minimum energy for the free nucleon in the nucleus**** above this threshold.

The cascade model only includes reactions between single nucleons and can therefore not account for the production of tritium or other particles

\[ E_p = \frac{k^2}{2m} \left( \frac{4\pi N}{V} \right)^{2/3} \]

\( V \) = nuclear volume
\( M \) = nucleon mass
\( N \) = number of protons or neutrons

** The Coulomb barrier of about 9 MeV must be corrected for barrier penetrations. An effective barrier of 6 MeV is obtained.

*** In the different steps of the cascade a single interaction is determined by a number of parameters, e.g. the point of collision (free path in the nucleus), the collision partner, the momentum of the collision partner, the scattering angle, etc. All these parameters have a statistical distribution, each of these distributions must be divided in equally probable intervals. In an ordered sequence for each parameter an interval is chosen at random numbers. With this set of parameters the collision can be calculated and the procedure is repeated for each of the two partners, and so on.

**** The compound nucleus model is assumed to be valid up to 20 MeV "outside energy".
besides protons and neutrons. However, because the excitation energy of the residual nucleus influences the following evaporation and therefore the number of evaporated particles, the assumption about the cascade processes are of importance also for tritium production.

4.2b The evaporation process. After development of a nuclear cascade the nucleus is left in an excited state. In the statistical model of Weisskopf (LeCouteur [1950]) the excitation energy is thought to be statistically distributed amongst all nucleons of the Fermi gas like nucleus, with fluctuations between the nucleons. The energy fluctuations can accumulate energy in an individual particle to boil it off. The emission probabilities of the different particles can be calculated for a given excitation energy which corresponds in the thermodynamical picture with a certain nuclear temperature. By evaporation of the particles the nucleus is cooled down. Therefore, a mean nuclear temperature depending on the excitation energy must be defined which is valid for the duration of the whole evaporation process. The relation between initial and mean temperature can be deduced only from the experiment (see e.g. Heisenberg [1953]). In the paper by Currie, Libby and Wolfgang [1956] a comparison is made between the measured tritium multiplicities at proton bombarding energies of 450 MeV and 2 GeV and the calculated values according to the evaporation theory. The difficulty lies in the determination of the excitation energy. They chose 150 and 250 MeV respectively because at this excitation energy one gets the right numbers of evaporated protons and neutrons (Wilson [1952]).

They found that the predicted values of the tritium production are an order of magnitude higher than the experimental data. It seems quite well possible that this discrepancy is due to the difficulty of distinguishing cascade and evaporation nucleons in the above-mentioned determination of excitation energy. With a somewhat lower excitation energy agreement could be achieved.

Rudstam [1956] has made a very extensive calculation of cascade and evaporation processes at 170 MeV in nuclei of the atomic number 75 (As 75). He found a cross-section for tritium production of 1 mb and obtained the best agreement with experimental data for the residual nuclei by assuming that the extreme cascade model* is valid. In this case the mean excitation energy is 35 MeV, whereas under assumption of a compound

* Extreme cascade model: no formation of a compound nucleus, the cascade process continues until all particles have insufficient energy to escape.
nucleus it would be 48 MeV. The excellent agreement between calculation and experiment for the yield of the finally obtained nuclei lead us to suppose that the tritium cross-section which Rudstam evaluated gives the right amount of the evaporated tritium particles. As in our experiment we irradiated with the same energy and had a target whose atomic number does not differ too much from the arsenic used by Rudstam, the tritium cross-section of 1 mb should be compared with our results (6 mb). The discrepancy, however, obliges us to conclude that another mechanism of tritium production is responsible for the high experimental values. The fact, that a similar result for tritium has not been obtained in the stars, is only due to the comparatively very low abundance of tritium prongs, which does not allow statistically significant results. LeCouteur [1950, p. 276] pointed out that in the particular case of tritium the application of the evaporated theory must be subjected to certain precautions. In the expression for the evaporation probability a term is contained which controls the final nucleus to be near the stability line in the energy valley. Especially for tritium this term is dependent on the actual excitation energy. The normal simplification that the probabilities in question are taken as being constant for the whole evaluation induces an error for the tritium evaporation.

4.2c Direct production of tritium in fast processes. Only a small fraction of the (experimentally measured) tritium produced by interactions between high energetic protons and iron target nuclei can be explained by the statistical model of the evaporation process. However, from similar experiments, indication is given that tritium can also be produced by fast processes occurring when the incident energy is not yet statistically distributed amongst all the nucleons in the target nucleus. The possible model is either understood as a direct interaction of the incident particle (or fast secondaries in the cascade) with subgroups of the nucleus or by a pick-up process. In both cases the experimental proof can be effected by measuring the energy distribution of the ejected particles.

In the determination of the yield of the final nuclei from proton irradiation (100 MeV) of copper, Meadows [1955] and Meadows, Diamond and Sharp [1956] found agreement with the Goldberger-Serber model of nuclear cascade followed by an evaporation process for the \((p, 2p)\) and \((p, 2n)\) processes, but not for the \((p, p)\) and \((p, n)\). He mentioned that the model does not take into account the \((p,d)\) direct interaction which certainly brings up the yield of the
corresponding final nucleus*. Hardley and York [1950] measured the angular distribution and energy of deuterons obtained from 90 MeV neutron irradiation of C, Al, Pb. A very strongly forward peaked deuteron distribution resulted with energy higher than 27 MeV.

The cross-section for deuterons (E ≥ 27 MeV) in copper was measured to be 52 mb. At the same time tritium could be observed and its production cross-section has been determined as about 4 mb. With a proton beam of 100 MeV Selove [1953] found in the (p,d) reaction an energy distribution of the secondary deuterons with a pronounced peak at 70 - 80 MeV from Al, Si and C irradiations**. From cloud chamber data for charged particles (Brueckner and Powell [1949])** it follows that 202 protons (32 - 107 MeV), 162 deuterons (25 - 124 MeV) and 22 tritons (56 - 95 MeV) are emitted in a 90 MeV neutron bombardment of carbon. It corresponds to a production cross-section of this highly energetic particle of 10.3 mb, 7.4 mb and 1.2 mb for protons****, deuterons and tritons respectively.

All the mentioned results cannot be explained by the cascade and evaporation model. Chew and Goldberger [1950] gave theoretical consideration to the production of fast deuterons in high energy nuclear reactions. They pointed out that the pick-up process must not be thought of as taking place within the nucleus following a real collision of the neutron and the proton. (Their calculation is carried out for a neutron-proton pick-up only). The period of the deuteron is considerably longer than the time required for a 100 MeV neutron or proton to cross the nucleus and the "radius" of the deuteron is as large as the separation of the constituents of a heavier nucleus. The momentum requirements are different for this type of virtual "scattering" from the free proton-neutron collision. The outgoing wave function corresponding to the outgoing deuteron does not materialize as such until long after the nuclear event. They mentioned that the fast tritons (about one tenth of the fast deuterons) could be explained in the same way with somewhat more complicated assumptions about the re-arrangement in the nucleus.

The method of Butler [1951]***** has been used by Newns [1952] to

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* In the work of Ghoshal [1950] the same effect is found.
** Confirmation of the high energy deuterons 23 - 70 MeV in photographic plates: see Bradner [1949].
*** See also York [1949] who obtained very similar values with a counter-telescope (protons and deuterons from C, Cu, Pb irradiated with 90 MeV neutrons.)
**** The error of the cross-section is estimated to be ~ 50%.
***** With a non-perturbation method he calculated the (d,p) stripping reaction which can be used also in inverse pick-up processes.
calculate the angular distribution of the (d,t) reaction in Be (7.7 MeV) and Li (8 MeV). The agreement with the data of Holt and Marsham [1953] is good: nearly all tritons are in the centre of a mass system emitted under an angle of less than 20°.

Because of the fact that the cross-section of these (d,t) reactions are very high (Be(d,t)Be ca. 200 mb) one should expect a remarkable number of tritons also in a double pick-up process (p,t) which might occur when the protons of the nucleon cascade travel through the nucleus, especially if they move near the surface (see e.g. Eisberg and Igo [1954] and York [1949]). A direct measurement (see Cohen and Handley [1953]*) of the (p,t) reaction in Fe 54 shows in the lower energy (15 - 25 MeV) a very steep rise of the cross-section with energy. The value obtained is twice as high as the value predicted by the statistical theory (see Paul and Clark [1953]).

A very recent publication gives further confirmation of the high tritium production cross-section (Nade, Gonzalez-Vidal, Glass and Seaborg [1957]). With alphas of 48 MeV, deuterons of 24 MeV, and protons of 32 MeV, Au, Th and U targets have been irradiated; the tritium was directly measured by separating it from the target. The probability of the (p,t) reaction is in all targets 60% of the (d,t) reaction. As fission does not occur for U and Th, the conclusion must be drawn that the nucleus is not left in a highly excited state. The explanation for this is again a very probable double pick-up process. The cross-section measurements are 6.9 mb for Au, 24 mb for Th, and 13.7 mb for U (see also Glass, Carr, Cobble and Seaborg [1956]** and Cohen, Newman, Charpie and Handley [1954]).

An analysis of the secondaries from high energy proton reaction (330 MeV) in Be and C nuclei (see Barkas and Tyren [1953]) shows that tritium production was distinctly high, about 10% of the proton emission and more than half as much as the deuterium production. For heavier elements this percentage might be reduced***, but still the excess of d and t etc. against evaporation prediction is remarkable.

Another result of similar experiments in heavier targets (Deutsch [1953]) are the relatively high yields of heavy nuclear fragments. Be, Li,

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* A double pick-up process is influenced by the nuclear shell structure which can be derived from the comparison of the angular distribution of the ejected tritons in He(p,t)He(p,t)Ne reaction. In the case of Nb with two neutrons in an unclosed shell the triton angular distribution corresponds with the pick-up hypothesis more than in Be and Pd.

** In the reaction Pu 238 (4p2n) the high yield of the residual nucleus is probably due to tritium production. The fission is seldom indicating that the nucleus excitation is low; the tritium carries away a high fraction of the incident energy.

*** The tritium spectrum between 1.7 to 6.4 MeV is for heavier target nuclei suppressed by the Coulomb barrier.
B and C isotopes are emitted with high energies*. The alpha spectrum measured in the same experiment shows a long tail towards higher energies, which makes it conceivable that a fraction of the heavier fragments is produced by knock-on processes. To explain the behaviour of the light fragments with a fission process would not account for the fact that the fission is always exothermic whereas all these reactions in question are highly endothermic processes. This fragmentation is therefore regarded as a particular process taking place before the energy in the nucleus reaches an equilibrium distribution. The fragments immediately emitted have the same p/n ratio as the initial nucleus, they are normally neutron-rich. The process favours consequently a production of a particle such as tritium. There is, however, a continuous gradation, both in product mass and in time scale, between slow evaporation and fast fragmentation (Wolfgang et al. [1956]). The fact that the tritium production is higher than predicted in the evaporation theory, and that from other experiments it is evident that a great fraction of tritium is emitted with high energy, only proves that fast processes make a considerable contribution. It is, however, not possible to account separately for pick-up process and fragmentation.

5. Summary

Iron has been exposed in the Uppsala synchro-cyclotron to protons of energies between 50 and 170 MeV. The tritium produced in high energy interaction was separated from the target and tritium activity measured in a GM-counter. By comparison with the Na$^{24}$ activity induced in an Al monitor foil, the cross-section of the tritium production was obtained. It varies slightly from 4 mb to 6.6 mb as the proton energy changes from 50 to 170 MeV.

The experimental result was compared with calculated values (1 mb) from an evaporation process at the same incident energy. The Serber-Goldberger model, which does not include other processes than those between two nucleons according to a free nucleon interaction, gives a spectrum for the kinetic energy of the particles inside the nucleus ranging from the maximum incident energy to the minimum separation energy of the nucleon. Regarding this whole range of proton (or neutron) energies inside the nucleus, other processes such as pick-up, stripping or knock-on of fragments might occur. Some other experimental results show that a production cross-section for tritium higher than predicted from the evaporation process is obtained in all cases**. From

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* Compare also: Marques [1952]. (A high yield of F$^{19}$ from Al, Cu, Ag, Au targets was obtained in 340 MeV proton bombardment.)

** The assumption of a higher limit of the minimum energy of the cascade nucleon inside the nucleus, taking into account a compound nucleus, is unlikely.
those data a value between 3 to 7 mb should be expected for tritium production in iron. The 6.6 mb obtained in our determination as well as the 7.2 mb measured by Fireman and Zähringer agree with it in the limit of error. The process in question seems to be rather complex and it is therefore difficult to give a clear (theoretical) picture of the mechanism involved. It is obvious that the production by fast processes contributes more to the tritium cross-section than does the nuclear evaporation.

I am indebted to Professor W. Gentner for his encouragement and for stimulating discussions with him.

I would also like to thank the team of the Uppsala Synchro-cyclotron for their kind help in carrying out the irradiations.

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List of references


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