Correspondence

Neutron Emission from Nuclei Excited by High Energy Protons.

By D. M. SKyrME,
Atomic Energy Research Establishment, Harwell,
and
W. S. C. WILLIAMS,
University College, London*.

[Received August 1, 1951.]

Nuclear reactions induced by high energy protons are thought to take place in two stages (Serber 1947). In the first stage the incoming particle makes collisions with individual nucleons in the target nucleus, and some of the products of these collisions pass directly out of the nuclear field. These "prompt" particles have high kinetic energy and they are emitted predominantly in the direction of motion of the incoming particle. After their departure the residual nucleus is left highly excited, and in the second stage of the reaction the excitation energy is dissipated by the emission of neutrons, charged particles and eventually γ-rays. These "evaporation" particles have relatively low energies, and they are emitted isotropically because of the comparatively long lifetime of the intermediate nuclei. Evaporation protons have often been studied before (e.g. Harding, Lattimore and Perkins 1949), but there has been little investigation of the neutrons following high energy reactions. This letter reports preliminary results of an investigation of evaporation neutrons from carbon and tungsten targets bombarded in the Harwell cyclotron. Values have been obtained for the differential cross-section for neutron evaporation as a function of the kinetic energy of the emitted neutron. If some assumptions are made as to the value of the proton inelastic cross-section of the target nuclei, the average number of neutrons emitted per excited nucleus can be determined also.

The two targets were exposed in turn to the internal proton beam, whose maximum energy was calculated to be 171 MeV. Slowing down in the targets reduces the effective primary proton energy to about 157 MeV. in both cases. Neutrons emitted backwards (i.e. at 180° to the direction of the incoming proton beam) were collimated by 2 in. diameter holes in concrete blocks and entered photographic plates 18.9 metres from the target. The distributions in energy of these neutrons were determined by means of the tracks of recoil protons produced in the photographic emulsions (Champion and Powell 1944). The numbers of primary protons striking the targets in the two runs were determined by means of the tracks of recoil protons produced in the photographic emulsions (Champion and Powell 1944). The numbers of primary protons striking the targets in the two runs were determined by measuring the amount of 7Be produced by the 16C(p, 3p3n)7Be reaction, whose cross-section is known with an accuracy of 10 per cent (Dickson and Randle 1951). Several thin plates of carbon were incorporated in the tungsten target for this purpose. Two subsidiary experiments were carried out to check that the neutrons did, in fact, come directly from the target. Negligible numbers of recoil proton tracks were observed.

* Communicated by the Authors.
in the plates (a) when the target was out of line with the collimating holes, (b) when the target was realigned and the collimating holes were blocked with copper rods.

The differential cross-section, \( \sigma \), for neutron evaporation from the tungsten target is shown in fig. 1. The value given for neutrons with energy less than 0.5 MeV. may be as much as 30 per cent low (Nereson and Reines 1950). A change of this magnitude will not, however, significantly affect the integrated cross-section. The total cross-section, for neutron energies up to 11 MeV. is found to be \((6.0 \pm 0.9) \text{ barns}\) \((1 \text{ barn} = 10^{-24} \text{ cm}^2)\), and the mean energy of an evaporation neutron is 2.6 MeV. There are 675 tracks in the spectrum below 11 MeV.; only two tracks corresponding to neutron energies greater than this were observed. The shape of this spectrum agrees fairly well with that to be expected from evaporation theory (Weisskopf 1937), if account is taken of the fact that more than one neutron can be evaporated from each excited nucleus.

In order to calculate the average number of neutrons evaporated from an excited nucleus, it is necessary to know the cross-section for inelastic collisions of protons with the target nuclei. Such values are not available, but it is known that the total cross-section of carbon for 156 MeV. neutrons is \((0.330 \pm 0.003) \text{ barns}\) (Taylor, Pickavance, Cassels and Randle 1951 a), and that of tungsten for neutrons of the same energy is 3.1 barns (Taylor, Pickavance, Cassels and Randle 1951 b). If it is assumed that one-half the neutron total cross-section is inelastic, and that at these energies the inelastic neutron and proton cross-sections are equal,
the number of neutrons evaporated per excited nucleus in the tungsten target is equal to 4.0. If the binding energy of the most loosely bound neutron in a nucleus in the neighbourhood of tungsten is taken to be 6 MeV., the average energy lost in neutron evaporation by a nucleus in the tungsten target is 34.4 MeV. An estimate of the mean excitation energy of the evaporating nucleus may be obtained if it is assumed that one proton with an average kinetic energy of 10 MeV. is evaporated per nucleus, and that 7 MeV. are lost in other processes, including \( \gamma \)-emission (Le Couteur 1950). If the binding energy of the evaporated proton is taken as 7 MeV., the value \( (34+17+7)=58 \) MeV. is obtained for initial excitation energy—\( i.e. \) 0.37 of the energy of the primary protons. Goldberger (1948) calculates that the average excitation energy of a heavy nucleus when bombarded with 90 MeV. neutrons is 42.5 MeV.

It is hoped to investigate, by a method similar to that described here, the energy spectrum of the evaporated protons, and the cross-section for this process, in order to obtain more precise information on the average energy of the excited nucleus.

Results obtained with the carbon target are shown in fig. 2. Curve A shows the differential cross-section for neutron emission, assuming that the evaporating nucleus was at rest in laboratory space. In fact, on account of its small mass, it may have been recoiling with sufficient velocity to affect the observed spectrum. It is difficult to estimate an
average value for the recoil velocity, but this will certainly be much less than that corresponding to the full transfer of momentum from the incident proton to the nucleus as a whole. Curve C, in fig. 2, is derived on the basis of full momentum transfer, and is therefore greatly over-corrected for recoil. Curve B, calculated on the assumption of 30 per cent momentum transfer, probably represents a more reasonable corrected spectrum. The presence of a relatively large number of high energy neutrons makes it difficult to give unambiguous values for the total "evaporation" cross-section and for the mean neutron energy. The figures given below were obtained by cutting off the spectra at 14 MeV.

<table>
<thead>
<tr>
<th></th>
<th>Curve A</th>
<th>Curve B</th>
<th>Curve C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total cross-section for &quot;evaporation&quot; of neutrons (barns)</td>
<td>0.027</td>
<td>0.038</td>
<td>0.068</td>
</tr>
<tr>
<td>Mean kinetic energy of neutrons (MeV.)</td>
<td>4.5</td>
<td>4.6</td>
<td>5.4</td>
</tr>
<tr>
<td>Average number of neutrons per excited nucleus</td>
<td>0.16</td>
<td>0.23</td>
<td>0.41</td>
</tr>
</tbody>
</table>

The general conclusions to be drawn from these data are fortunately not affected by the considerable uncertainties in the corrections which have been applied to the observed spectrum. The average number of neutrons "evaporated" is less than one per excited nucleus, and there are relatively more high energy neutrons than would be expected from a nucleus in thermodynamic equilibrium.

ACKNOWLEDGMENTS.

We wish to thank Dr. J. M. Cassels for suggesting this problem, and Dr. T. G. Pickavance for helpful discussions during the course of the work. We wish also to express our thanks to the cyclotron operating crew for their co-operation. One of us (W.S.C.W.) would like to thank the Director of the Atomic Energy Research Establishment for allowing him to use the facilities at Harwell, and the Department of Scientific and Industrial Research for a maintenance grant.

REFERENCES.