Production of Hydrogen and Helium by 14-MeV Neutrons

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Introduction

The production of atoms of the isotopes of hydrogen and helium by 14-MeV neutrons will have an important effect on the physical properties of the materials in a fusion reactor, particularly on the first wall. The present report attempts to summarize available knowledge of the nuclear cross sections for the production of hydrogen and helium isotopes by 14-MeV neutrons. As an example, the case of the interaction of neutrons with ^{93}Nb will be discussed, partly because of the suggested use of Nb in fusion reactors, but also because Nb has only one stable isotope so that the situation for Nb is simpler than for other materials that are of interest, such as Fe, Ni, Mo, all of which have four or more stable isotopes. Nevertheless, the available information for Nb is typical for other intermediate nuclides.

Reactions

Reactions of ^{93}Nb with 14-MeV neutrons that can produce hydrogen and helium isotopes are listed in the table. Only reactions that have $-Q < 10$ MeV are included since the Coulomb barrier will inhibit emission of charged particles of less than 4 MeV energy. For other target nuclides reactions not included for Nb may be important.

Because of the effect of the Coulomb barrier reactions in which the second emitted light particle is charged will be less probable than those in which a neutron follows charged-particle emission.

Calculations of Cross Sections

In view of the importance of reactions induced by fast neutrons, Pearlstein[1] has calculated their cross sections. The calculations are based on the statistical model, but are normalized to measurements. As Pearlstein points out the calculations are quite uncertain, partly because of the poor agreement between measurements of the same cross section at different laboratories, partly because it is known that for 14-MeV neutrons direct and pre-equilibrium processes constitute a substantial fraction of the reactions. Pearlstein attempts to take such processes into account by adjusting the parameters in the statistical model to fit the measurements, but it is not obvious that such a procedure yields reliable results. Column 5 of the table presents the results of Pearlstein's calculations. A number of authors have summarized available data for the interaction of 14-MeV neutrons with various nuclides and have pointed out systematics that may permit predictions that could be used to estimate cross sections that have not been measured. Some of these estimates are listed in column 6 of the table. The values for the (n,t) and (n,^{3}He) cross sections are taken from reference 2, for the sum of (n,d) and (n,n'p) from reference 4, and for (n,p) and (n,α) from reference 3.

Methods for Measuring Reaction Cross Sections

The measurements of cross sections for producing H and He isotopes can be grouped in three categories: (A) Observation of radioactivity of the product nuclide; (B) Observation of the charged particles emitted in the reaction; (C) Collection of hydrogen or helium.

(A) Observation of Radioactivity

Most reported cross sections are based on this method because such measurements are easiest to perform, but this method is limited to reactions that produce observable radioactive products. As a consequence, very few cross sections that do not result in readily observable activities are known. In the example of ^{93}Nb, the (n,p) reaction results in an activity of about 10^6 years, which is very difficult to observe, so that it has not been used for measuring the (n,p) cross section.

A serious source of confusion is the fact that isomeric states may be observed, but the production cross section of the isomeric state is only a partial cross section for the reaction. An example of this confusion was the controversy about the value of ^{93}Nb(n,2n) cross section, which was measured by observations of the 10-day isomeric state in ^{92}Nb, but this measurement was used occasionally as if it were the entire (n,2n) cross section.

A similar situation arises in the ^{93}Nb (n,n'α) ^{89}Y reaction. This has been measured by observing the 16s isomeric state in ^{89}Y, but many reactions undoubtedly leave ^{89}Y in its (stable) ground state, so that the measurement gives only a partial cross section. The measured[5] value listed in the last column of the table is therefore only a lower limit.

Yttrium-91, the product of the (n,^{3}He) reaction, has a 51-min isomeric state for which a cross section of 6×10^{-5} b has been reported[5]. Unfortunately, reference 2 which shows a 1.5 mb cross section for the (n,^{3}He) reaction does not state which activity was observed.

Yttrium-90, the product of (n,α) reaction, has a 3.2 h metastable state which decays almost always to the 64h ground state. Both activities have been measured by several authors, but only the 64h activity is of interest here. The various measurements agree fairly well. Both the cross sections for the (n,α) and (n,2p) reactions are taken from reference 5.

(B) Observations of Charged Particles

The observation of charged particles produced by 14-MeV neutrons involves several problems: the need to identify what charged particle is observed, the low intensity, the anisotropic angular distribution, the large background.

The only observation of charged particles from 14-MeV neutrons on Nb is mentioned in a 1957 paper from the University of Pennsylvania[6]. In this experiment, only protons of energy greater than 6.5 MeV were detected. The method for integrating over energy and angle is not described clearly enough to permit evaluation of the realiability. The uncertainty in the cross section is given as 35%. Since few of the protons fron (n,n'p) will have energies above 6.5 MeV, the measurement should represent the (n,p) cross section. In this experiment, no attempt was made to reduce background by use of coincidence techniques, and the background was too high to observe protons of energies below 6.5 MeV.

Other authors have reported the observation of disintegration as protons, deuterons and α particles form other reactions down to energies of

2 MeV primarily by use of photographic emulsions, but also with counter telescopes.

(C) Collection of Hydrogen and Helium

In the case of hydrogen, this technique appears to have been used only for the radioactive isotope tritium[7]. Whether light hydrogen and deuterium could be detected also is not clear.

Farrar[8] has detected very small quantitites of ^{3}He and ^{4}He with a gas mass spectrometer. This method would permit the determination of (n,^{3}He) and (n,α) cross sections with sufficient accuracy using available 14 MeV neutron sources.

Another interesting method for detecting small quantities of ^{4}He in metals was developed by Katyal, Keesom and Cost[9]. They observe the anomaly at 4.2K in the specific heat in an annealed sample caused by the liquid-vapor transition of helium in bubbles.

Conclusions

On the basis of systematics of 14-MeV cross sections, by far the most probably process may be (n,d). It is not known in what fraction of cases the deuteron breaks up, since all the available measurements detect only the end product which is the same in (n,d) and (n,n'p) reactions. It is not clear why Pearlstein's calculations which are presumably normalized to experimental results differ so greatly from the systematics of the measurements. The cross sections from which the systematics in reference 4 is derived may, however, not be typical, since they are for the lighest isotope of each element.

For any material considered for a fusion reactor first wall, a knowledge of cross sections for charged particle production is needed. At present, very few cross sections that do not produce an observable radioactivity are known. It would appear to be important to perform measurements on those reactions that do not produce activities.

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Emitted Particles	Q (MeV)	Product	Half life	Calculated (mb)	From Systematics (mb)	Measured (mb)
p	+0.7	^{93}Zr	9.5 x 10^5y	29	18	22
d	-3.8	^{92}Zr	stable	21	300	
pn'	-6.0			3		
t	-6.2	^{91}Zr	stable		30	
2p	-8.9	^{92}Y	3.5h			<0.5
^{3}He	-7.7	^{91}Y	59d		3	1.5
α	+4.9	^{90}Y	64h	15	10	9
αn'	-1.9	^{89}Y	stable	0.9		>2.5
^{5}He	-2.8					
αp	-2.6	^{89}Sr	51d			
αpn	-9.0	^{88}Sr	stable			