Characteristics of the $^{50}V(n_{th},p)^{50}Ti$ reaction

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The $^{50}V(n_{th},p)^{50}Ti$ reaction has been studied at a very clean thermal neutron beam of the ILL's high flux reactor. An accurate cross section value of (0.71 ± 0.04) mb has been determined, as well as a value of $(0.002\,364 \pm 0.000\,008)$ u for the ^{50}V-^{50}Ti mass difference. Possible applications in nuclear astrophysics and in reactor technology are pointed out.

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Only two vanadium isotopes occur in nature, ^{50}V and ^{51}V, with isotopic abundances of 0.25% and 99.75%, respectively. The rare isotope ^{50}V has the peculiarity that it is one of the very few odd-odd isotopes existing in nature (above $A = 14$, only ^{40}K, ^{50}V, ^{138}La, ^{176}Lu, and ^{180}Ta occur). After neutron absorption in ^{50}V, the compound nucleus ^{51}V is formed with a magic number of neutrons ($N = 28$) and with an excitation energy [1] of 11.051 MeV, which stimulates the emission of the uncoupled proton. Moreover, in view of its high Q-value [1] (2.989 MeV), the $^{50}V(n,p)^{50}Ti$ reaction is one of the rare cases which can be studied with thermal neutrons.

To investigate this reaction, a series of measurements has been performed at the high flux reactor of the Institut Laue-Langevin (I.L.L.) (Grenoble, France).

Three different V_2O_5 samples were prepared by the Sample Preparation Group of the Institute for Reference Materials and Measurements (Geel, Belgium). The mass of the samples was determined in a first approximation by weighing, but the ultimate values were obtained with the x-ray fluorescence technique via the detection of the specific K_α line. The sample characteristics obtained are summarized in Table I.

The vanadium mass-values obtained with both methods were consistent for samples 2 and 3 (which were prepared during the same campaign), but very different for sample 1, which was prepared from another batch probably containing (hygroscopic?) impurities. A detailed discussion of the limitations of the weighing method to determine sample masses can be found in Ref. [2].

Finally, the samples were scanned with a collimated x-ray beam, which demonstrated that they were fairly homogeneous.

The measurements were performed at the end of the neutron guide H22D installed at the high flux reactor of the Institut Laue-Langevin. At this position, a thermal neutron flux of 5×10^8 n/cm^2 s is available with very low background, the fast neutron and γ-ray intensity of the direct beam being reduced by a factor 10^6.

The sample, inclined at an angle of 30° with respect to the incident neutron beam, was mounted in the center of a large vacuum chamber. Two types of experiments were performed, both in a low detection geometry.

In the first case, the reaction particles were detected with a single surface barrier detector (thickness 100 μm; active area 450 mm^2; resolution 20 keV for 5.5 MeV α's) mounted outside the neutron beam.

In a second series of experiments, the sample was viewed by a telescope assembly consisting of two gold-silicon surface barrier detectors. The fully depleted ΔE detector had a thickness of 15.6 μm, an active area of 200 mm^2 and an energy resolution of 60 keV for 5.5 MeV α's. The E detector had a thickness of 100 μm, an active area of 450 mm^2 and an energy resolution of 20 keV. After amplification, the coincident ΔE and E detector signals were coded and stored event by event in a HP1000 data acquisition system. Such a procedure considerably reduces the background and allows one to identify the particles via the relation [3] $T/a = (E+\Delta E)^{1.73} - E^{1.73}$, where T is the thickness of the ΔE detector, E, and ΔE the energy losses in the E and ΔE detectors, respectively, and a a constant specific for each particle. In this way, the protons can be separated from all other particles.

The energy calibration of the detectors was done using the well-known energies of the $^{14}N(n,p)$, $^{10}B(n,\alpha)^7Li$ and $^6Li(n,\alpha)t$ reaction products and of α particles emit-

TABLE I. Survey of the ^{50}V sample characteristics.

Number	$^{50}V/V$ [wt.%]	Amount of material/cm^2 by weighing [μg/cm^2]	V mass/cm^2 (μg/cm^2) Weighing	x-ray fluorescence
1	44.1	72.7	40.4±3.7	28.4±0.6
2	22.7	106.6	59.2±3.7	60.1±0.6
3	22.7	130.0	72.2±3.7	69.7±0.7

ted in the radioactive decay of ^{234}U and ^{235}U. The neutron flux calibration was performed by replacing the vanadium sample by a well-known ^{235}U sample, strictly maintaining the same geometry. For this purpose, the ΔE detector was replaced by a dummy detector ring in the second type of experiments. For the $^{235}\mathrm{U}(n_{\mathrm{th}}, f)$ cross section, the ENDF/B6 reference value of (584.25 ± 1.10) b was adopted.

The $^{50}\mathrm{V}(n_{\mathrm{th}}, p)^{50}\mathrm{Ti}$ reaction was first investigated using a single surface barrier detector. The pulse-height spectrum obtained with sample 1 is shown in Fig. 1, which indicates that a clean detection of the 2.92 MeV protons is hampered by the presence of a strong 2.73 MeV triton peak resulting from $^{6}\mathrm{Li}(n, \alpha)t$ reactions induced in ^{6}Li impurities in the sample. The situation becomes even worse when using samples 2 or 3, which are a factor two less enriched in ^{50}V. It is clear that under these conditions it is hard to determine a reliable value for the $^{50}\mathrm{V}(n_{\mathrm{th}}, p)$ reaction cross section. A calculation after a (very uncertain) correction for the underlying background yields $\sigma_p \approx 0.5$ mb. This cross section value is calculated in the usual way by means of the following expression:

$$\sigma_{p,\mathrm{th}}(^{50}\mathrm{V}) = \frac{N(^{235}\mathrm{U})}{N(^{50}\mathrm{V})} \frac{C(^{50}\mathrm{V})}{C(^{235}\mathrm{U})} \sigma_{f,\mathrm{th}}(^{235}\mathrm{U})$$

in which N is the number of atoms per cm^2, σ_{th} the thermal cross section value and C the counting rate after background subtraction of the respective reactions.

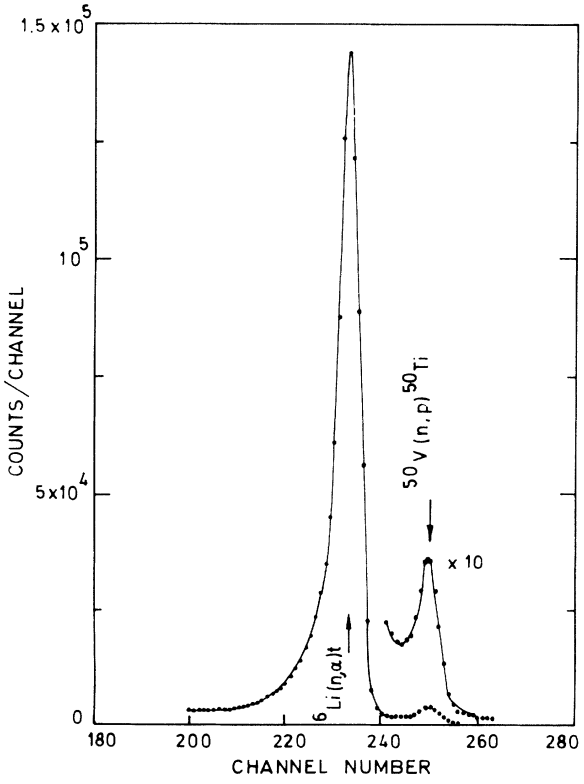

FIG. 1. Pulse-height spectrum of the $^{50}\mathrm{V}(n_{\mathrm{th}}, p)^{50}\mathrm{Ti}$ reaction obtained with sample 1 and using a single surface barrier detector.

A much more unambiguous detection of the protons is possible with the ΔE-E telescope set-up, the results of which are shown in Fig. 2 in the case of sample 2. Applying the identification relation mentioned above, a clear proton-triton separation is realized. The $^{50}\mathrm{V}(n_{\mathrm{th}}, p)$ counting rates obtained in this way for the three different samples yield coherent cross section values, using the accurate vanadium masses determined with the x-ray fluorescence technique. These values are: 0.73 mb (±1.1%), 0.72 mb (±1.9%), and 0.69 mb (±1.2%) for samples 1, 2, and 3, respectively. The errors quoted are purely statistical. Combining these data, an accurate $^{50}\mathrm{V}(n_{\mathrm{th}}, p)$ reaction cross section of (0.71 ± 0.04) mb is obtained.

The present value is significantly higher than the two other results reported in the literature. D'hondt *et al.* [4] obtained a cross section of 0.4 mb, using a sample with a ^{50}V enrichment of 22.7% and a single surface barrier detector.

Andrzejewski *et al.* [5] on the other hand reported a $^{50}\mathrm{V}(n_{\mathrm{th}}, p)$ cross section of $(277 \pm 42)\mu b$, obtained with a two-grid ionization chamber and a sample with a ^{50}V enrichment of 17%. In both cases, very important background corrections had to be performed, making the results not very reliable.

The $^{50}\mathrm{V}(n, p)^{50}\mathrm{Ti}$ reaction is important in three respects.

(i) Our present knowledge of atomic masses is derived from a combination of mass spectroscopic measurements and nuclear reactions [1]. In this respect, (n_{th}, p) reactions provide valuable information since the kinetic energy of the incident neutron is so small (0.0253 eV) that it can be fully neglected. Via the detection of the protons, accurate values can be obtained for the groundstate transition reaction energies Q_p, which are directly linked to the masses of the initial and the final nuclei $M(A, Z)$ and $M(A, Z-1)$, respectively, via the relation:

$$Q_p = M(A, Z) - M(A, Z-1) + M(n) - M(^{1}H).$$

Since the neutron and proton masses are very well known [1], the determination of Q_p provides a value for the mass difference between the initial and the final nucleus. From the energy of the proton peak shown in Fig. 1 (corrected for energy loss in the sample), a Q_p-value of (2.984 ± 0.010) MeV is deduced in good agreement with the corresponding value of (2.989 ± 0.003) MeV calculated from the mass-evaluation of Audi and Wapstra [1]. The present experimental Q_p-value yields a value of (0.002 364 ± 0.000 008) u for the $^{50}\mathrm{V}-^{50}\mathrm{Ti}$ *mass difference*, in good agreement with the evaluated value [1] of (0.002 3707 ± 0.000 0025) u and with the mass spectroscopic result of (0.002 376 ± 0.000 005) u obtained by Giese and Benson [6].

Although in the present case proton detection results in a slightly less accurate value for the $^{50}\mathrm{V}-^{50}\mathrm{Ti}$ mass difference than the one obtained via mass-spectroscopy, this example illustrates that the (n_{th}, p) reaction is a valid and simple alternative in cases where no mass-spectroscopic data exist (e.g., radioactive isotopes).

(ii) The $^{50}\mathrm{V}(n, p)^{50}\mathrm{Ti}$ reaction may also play a role in *nuclear astrophysics.* Indeed, up to now a zero value was

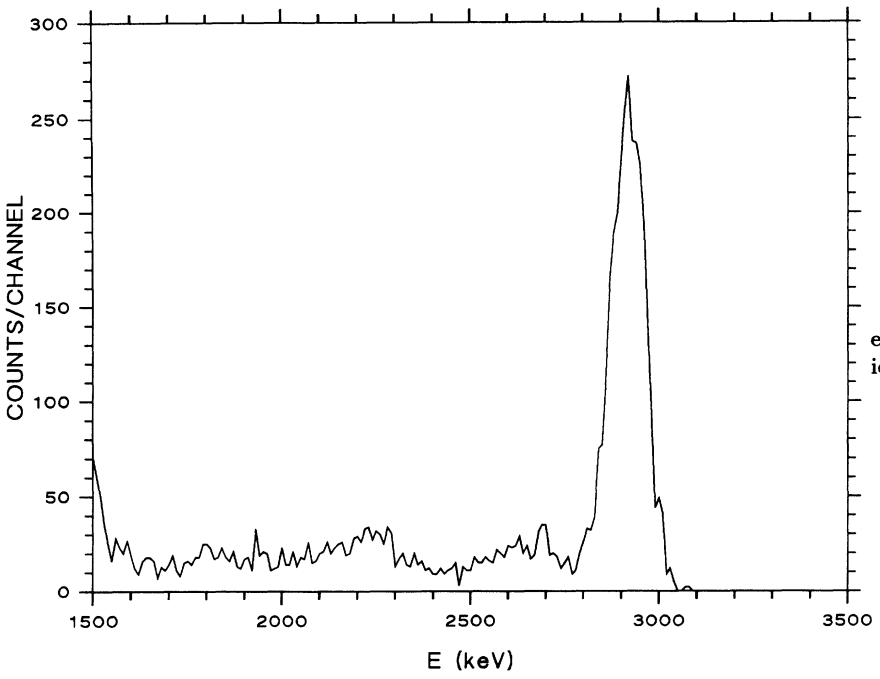

FIG. 2. Energy distribution of the protons emitted in the $^{50}V(n_{th},p)^{50}Ti$ reaction (after identification) using sample 2.

always adopted for the Maxwellian averaged (n,p) cross section, being defined as

$$\langle\sigma\rangle = \frac{2}{\sqrt{\pi}} \frac{\int_0^\infty \sigma(E_n) E_n \exp[-E_n/kT] dE_n}{\int_0^\infty E_n \exp[-E_n/kT] dE_n},$$

kT being the stellar temperature and E_n the neutron energy. The present result for the $^{50}V(n_{th},p)$ cross section indicates that this approximation might be too crude.

The $^{50}V(n,p)^{50}Ti$ reaction could also contribute to the understanding of the puzzle of Ti anomalies in meteoritic silicon carbide grains recently reported by Gallino *et al.* [7].

(iii) The present results finally indicate that canning materials containing vanadium should be avoided in nuclear reactors in order to limit the hydrogen production and to reduce metal embrittlement. Indeed, a small amount of, e.g., 1 mg $^{50}V/cm^2$ in a reactor core with a thermal flux of 10^{14} neutrons/cm^2 s would already produce about one million protons/cm^2 s.

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