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Vanadium Cross Section Measurements by the Activation Technique and Evaluations from Threshold to 20 MeV

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Cross sections for the reaction ^{nat}V(n,xα)^{47}Sc were measured from 11.7 to 20.5 MeV with the aim to improve the data base and resolve discrepancies. Simultaneously, new measurements were done for the ^{51}V(n,α)^{48}Sc reaction, and some additional experimental data were added to those obtained recently for the ^{51}V(n,p)^{51}Ti reaction. Calculations were performed using the STAPRE-H statistical model code with pre-equilibrium contributions that were estimated with a modified geometry dependent hybrid model. A physically consistent description of all pertinent experimental information was attempted. In most cases a description of the experimental data is obtained that is sufficiently accurate to consider adopting the new model calculations in evaluated data files.

KEYWORDS: nuclear reactions; measured cross sections; statistical model; preequilibrium emission; vanadium; gas production; evaluation; activation;

I. Introduction

Vanadium is of interest as a candidate low-activation structural material in devices with a hard neutron flux. Traditionally it was studied in connection with fusion reactors.[1)] Recently, structural materials studied for fusion reactors are also considered for Accelerator Driven Systems (ADS) and therefore the energy range of interest is extended up to a few GeV. Nonetheless, even in an ADS, neutrons with energies below 20 MeV play a considerable role with regard to hydrogen and helium gas production and the number of displacements per atom.[2)] It may be noted that (n,xp), (n,xα) and (n,xn) reactions above 15 MeV are often poorly studied and that the scatter of the data around 15 MeV is often large.[3,4)]

The data base of measured cross sections for hydrogen production on vanadium was reviewed recently,[5)] and GNASH model calculations were performed with an emphasis on estimating the cross sections for the (n,d+pn+np) and (n,t) channels for which few experimental values are available.[6)] For helium production, numerous measurements exist for the ^{51}V(n,α)^{48}Sc reaction, however, this is not the case for the ^{nat}V(n,xα)^{47}Sc reaction. In fact, benchmark irradiations of vanadium alloys showed discrepancies for ^{47}Sc production when measured data were compared with calculations based on the EAF-97 library. C/E values of 1.5 or more were obtained depending on the neutron spectrum used. These discrepancies were attributed to the evaluated cross section that was based on inconsistent measurements.[7–10)]

With the present measurements for the ^{nat}V(n,xα)^{47}Sc, ^{51}V(n,α)^{48}Sc, and ^{51}V(n,p)^{51}Ti reactions the experimental information with regard to the dominant neutron-induced reactions of vanadium up to 20 MeV incident energy is rather complete[11–18)] with the exception of the ^{51}V(n,np)^{50}Ti reaction.[5)] This makes vanadium an excellent test case for model calculations in the energy range up to 20 MeV. Here we present results of a statistical model calculation with pre-equilibrium contributions estimated with a modified GDH model using the latest version of the code STAPRE-H. The results are compared with the data and with evaluated cross section libraries for the reactions mentioned above. A full account of the experimental work and the modeling of reactions on vanadium is given elsewhere.[19)]

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II. Measurements and Calculations

Irradiations with neutrons of energies between 13.4 and 20.5 MeV were performed with the Geel 7 MV Van de Graaff accelerator using the T(d,n) neutron source for deuterons with energies between 1 and 4 MeV. The irradiation with 11.7 MeV neutrons was done at the Compact Cyclotron CV-28 at FZ Jülich. Samples were 350-450 μm 10-13 mm diameter foils of metallic vanadium arranged in stacks of 1 to 4 foils. The samples were sandwiched between monitor foils. Activities were determined by measurement of γ-ray yields with HPGe detectors. Cross sections were determined relative to the ^{27}Al(n,α)^{24}Na cross section and the ^{93}Nb(n,2n), ^{56}Fe(n,p) and ^{58}Ni(n,p) reactions were used to determine the contributions from low energy neutrons and multiple scattering. The details are reported elsewhere.[19)] The procedure followed closely an earlier work at our laboratory.[3)]

The model calculations were performed with a modified version of the STAPRE-H code[20–23)] which uses the statistical model approach of Uhl[24,25)] and an extension of the GDH model.[26–28)] Transmission coefficients were determined with the SCAT2 module[29)] of STAPRE-H. For alpha-emission the OMP of Avrigeanu *et al.*[30)] is preferred over that of McFadden-Satchler[31)] by comparison with the data for the ^{51}V(n,α)^{48}Sc reaction. The proton OMP was fixed by comparison with the reaction cross section data for the ^{48}Ti(p,n)^{48}V reaction and combines Perey's potential below 5 MeV proton energy[32)] with that of Kailas *et al.*[33)] above 5 MeV. The asymmetry dependence described by Hetrick *et al.* is used.[34)] The neutron OMP is that of Lawson *et al.*[12)] with

a modification to the energy dependence of the imaginary potential's diffuseness to obtain better agreement with recent total cross section measurements.

The level density model consists of two parts. In the low-energy part below the neutron binding energy B_n, discrete levels are used up to an excitation energy of about 3.5 MeV. Above this energy the back-shifted Fermi-gas (BSFG) model is used. An energy dependent effective moment of inertia is assumed. It's value divided by the rigid rotor moment of inertia (r_0=1.25 fm) is a smooth curve from 0.5 at the ground state energy to 0.75 at the neutron binding energy and 1 at 15 MeV excitation energy, while remaining constant at higher excitation energies.[19,35] The high-energy part uses the energy-dependent level-density parameter following Junghans *et al.*[36] above 15 MeV and a transition range between the binding energy and 15 MeV to interpolate between the value given by the BSFG at B_n and that at 15 MeV. The shell correction energy is determined following Koning and Chadwick[37]

Finally, the GDH model has no free parameters other than the pre-formation factor for α-particles which was taken to be 0.25. Further details are given elsewhere.[19,35]

III. Results and Discussion

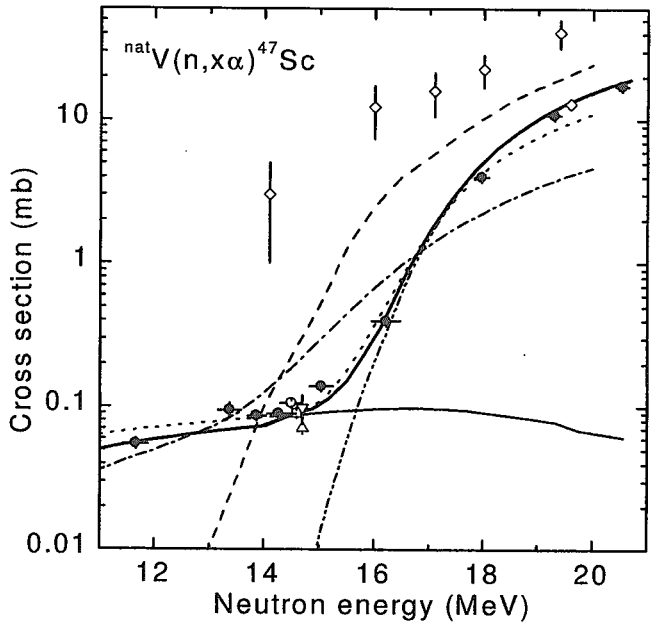

Fig. 1 Measured cross sections for the ^{nat}V(n,xα)^{47}Sc reaction compared to the new model calculations and excitation curves from evaluated cross section libraries: Present measurements (filled circles), Grallert *et al.*[38] (square), Wang *et al.*[39] (open circle), Qaim[40] (triangle down), Pepelnik *et al.*[41] (triangle up), Bormann *et al.*[42,43] (diamonds). The curves are from the present model calculation (full line), the JENDL Activation file (dotted line), ENDF/B-VI (dashed line) and EAF-99 (dash-dotted line). The present model estimates for the ^{50}V(n,α)^{47}Sc reaction (thin full line) and the ^{51}V(n,nα)^{47}Sc reaction (dash-double dotted line) are also shown.

In **Fig. 1** the new results for the ^{nat}V(n,xα)^{47}Sc reaction are presented together with earlier measurements, the new model calculation and excitation functions from evaluated data files. The newly measured data establish an excitation curve that is consistent with the recent measurements around 14.5 MeV and that exhibits the threshold behavior which is appropriate for the ^{51}V(n,nα)^{47}Sc channel. The present model calculations describe the data reasonably well. The data for energies below 15 MeV are slightly underestimated but the model clearly shows that it is the ^{50}V(n,α)^{47}Sc reaction that prevails at these energies. At 14.5 MeV this is confirmed by systematics.[44]

A comparison between the evaluated data files ENDF/B-VI,[45] EAF-99[46] and JENDL-3.2 (Activation)[47] shows that the latter is much closer to the data, whereas large discrepancies are observed for the former two. Below 15 MeV JENDL-3.2 (Activation) shows a somewhat better description for the ^{50}V(n,α)^{47}Sc reaction, whereas above 17 MeV it underestimates the data significantly and the new model calculation is preferred.

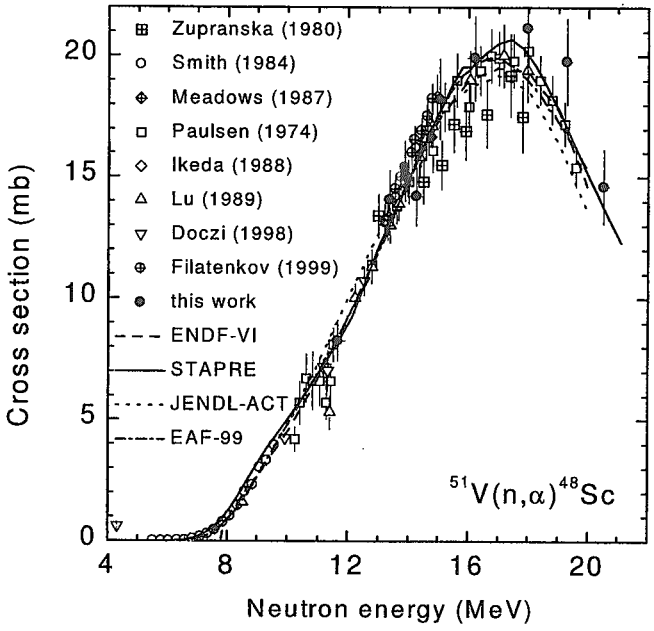

Fig. 2 Measured cross sections[48–55] for the ^{51}V(n,α)^{48}Sc reaction compared to new model calculations and excitation curves from evaluated cross section libraries.

Figure 2 shows the data, the model calculation and the evaluations for the ^{51}V(n,α)^{48}Sc reaction. Even if a firm data base exists, our data are only the second set above 18 MeV. The new values are slightly higher than those of Paulsen *et al.*,[52] which is most likely due to changes in the reference cross sections. The data are well described by the new model calculation except between 8 and 10 MeV where only the spin and parity assignments of the discrete low-lying levels play a role. A good description is also observed for the ENDF/B-VI,[45] EAF-99[46] and JENDL-3.2 (Activation)[47] files. Only above 18 MeV are the values in the latter file slightly low compared to the data and to the other curves.

Two new data points were determined for the ^{51}V(n,p)^{51}Ti

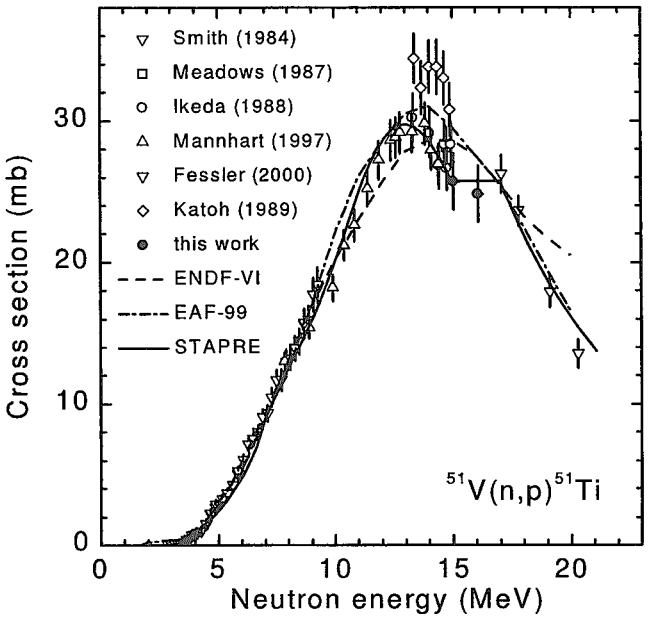

Fig. 3 Measured cross sections[3,49–51,56,57] for the ^{51}V(n,p)^{51}Ti reaction compared to new model calculations and excitation curves from evaluated cross section libraries.[45–47] The JENDL-3.2 (Activation) and EAF-99 evaluations coincide.

reaction that connect the recent measurements above 15 MeV[3] with the the lower cross section values around 14.5 MeV.[50,51,56] The results are at variance with the higher values of Katoh *et al.*[57] (**Fig. 3**). The new model calculation describes the excitation function well except between 5 and 7 MeV where discrete levels are important. The ENDF/B-VI evaluation[45] is low with regard to the data of Mannhart *et al.*[56] between 11 and 14 MeV and exceeds the data[3] considerably above 15 MeV. The JENDL-3.2[47] and EAF-99[46] evaluations coincide. They exceed the data between 9 and 12 MeV and again between 14 and 17 MeV.

Finally, it may be noted that the present model calculation gives a fair description of the proton emission spectrum measured at 14.8 MeV.[17] The measured (n,xp) cross section is 91±14 mb and the calculated value is 91.2 mb. The calculated cross section for the (n,p) reaction is 26.4 mb so that we deduce a cross section of 64.8 mb for the ^{51}V(n,np)^{50}Ti reaction at 14.8 MeV, in close agreement with the recommended value of 65.3 mb of Smith *et al.*[5]

IV. Conclusion

New measurements for the ^{nat}V(n,xα)^{47}Sc, ^{51}V(n,α)^{48}Sc and ^{51}V(n,p)^{51}Ti reactions were compared to statistical model calculations incorporating GDH-model estimates of pre-equilibrium contributions. For the first time an excitation function was established for the ^{nat}V(n,xα)^{47}Sc reaction. The reactions studied are well described with the model calculations that use one consistent set of parameters to describe the available experimental data. The evaluations[45–47] considered here need improvement for the ^{51}V(n,nα)^{47}Sc reaction. For the ^{51}V(n,p)^{51}Ti reaction fair agreement with the data exists but above 10 MeV discrepancies in excess of 10% occur. For the ^{51}V(n,α)^{48}Sc reaction these evaluations are close to the data although the new data favor higher values than are given by JENDL-3.2 above 18 MeV.

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