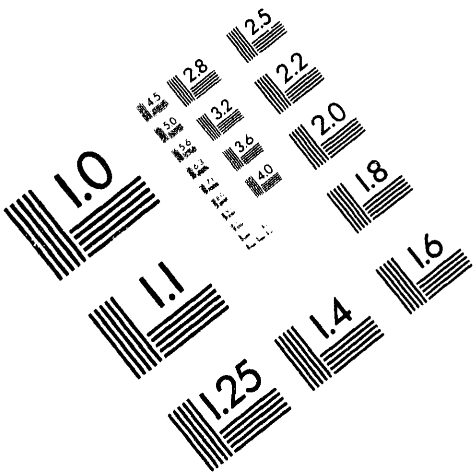
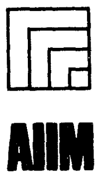
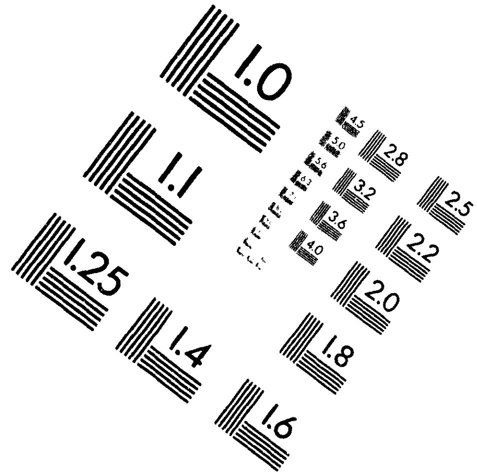
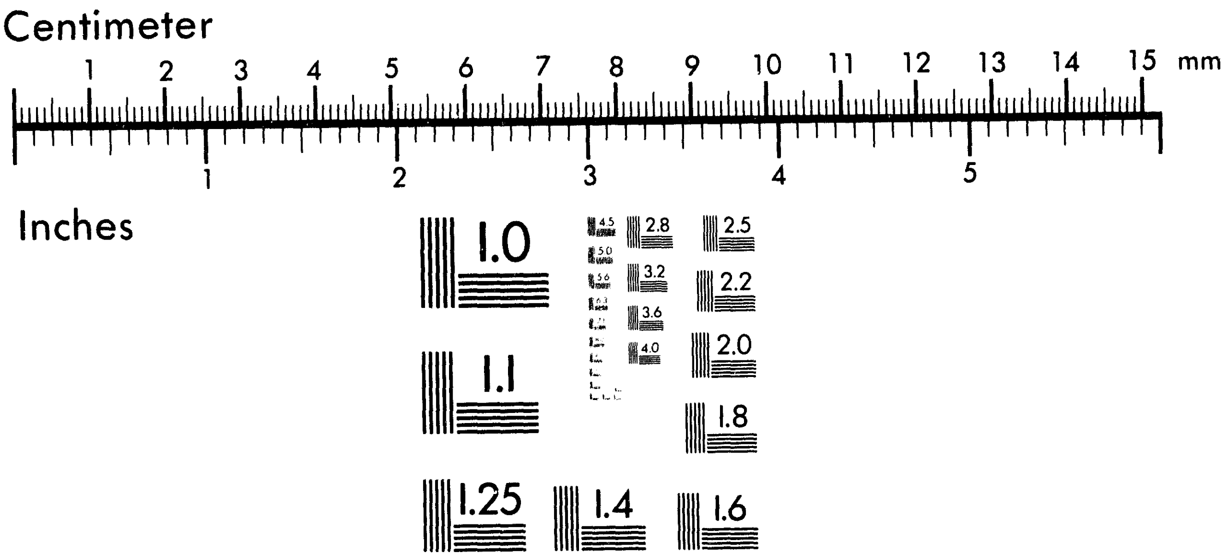
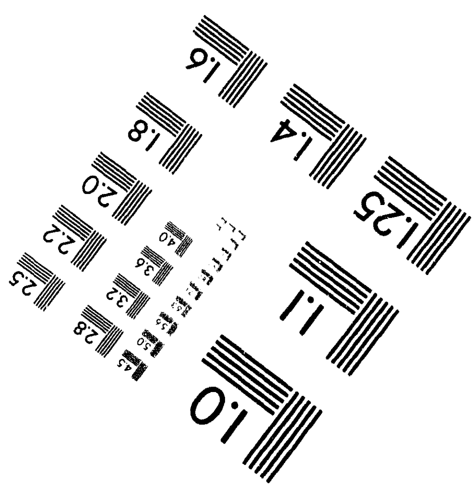


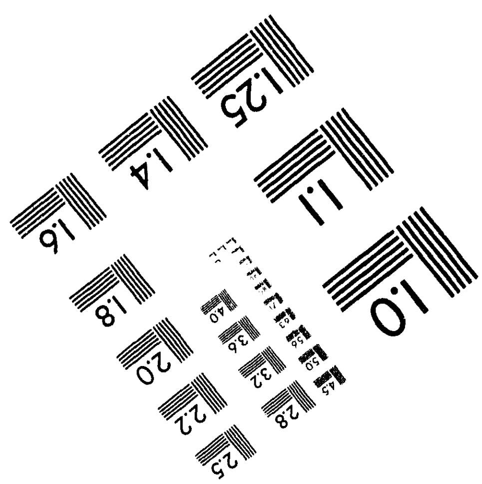


Association for Information and Image Management
1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910
301/587-8202









MANUFACTURED TO AIIM STANDARDS
BY APPLIED IMAGE, INC.

Conf-940507--36

UCRL-JC-117463
PREPRINT

Pauli-Blocking Effects in Neutron-Alpha Reactions

M. Avrigeanu
V. Avrigeanu
A.N. Antonov
M.B. Chadwick
P.E. Hodgson
M.V. Stoitsov

This paper was prepared for submittal to the
International Conference on Nuclear Data for Science and Technology
Gatlinburg, TN
May 9-13, 1994

June 1, 1994

Lawrence Livermore National Laboratory

PAULI-BLOCKING EFFECTS IN NEUTRON-ALPHA REACTIONS

M. Avrigeanu[1,4], V. Avrigeanu[1] A.N. Antonov[2,4],
M.B. Chadwick[3], P.E. Hodgson[4], and M.V. Stoitsov[2]

[1] *Institute of Physics and Nuclear Engineering, Bucharest 76900, Romania*
[2] *Institute of Nuclear Research and Nuclear Energy, Sofia 1784, Bulgaria*
[3] *University of California, Lawrence Livermore National Laboratory, Livermore, CA 94550, USA*
[4] *Nuclear Physics Laboratory, Department of Physics, University of Oxford, Oxford OX1 3RH, U.K.*

Abstract

We present a knockout model for direct (n, α) reactions in which the residual nucleus is left in a continuum excited state. The interaction of the neutron with a preformed alpha particle inside the nucleus is related to the free neutron–alpha scattering cross-section, with modifications to account for nuclear medium effects, including Fermi motion, Pauli-blocking, and barrier penetration. Phase space restrictions for the four nucleons of the alpha-particle after the knockout are imposed by a Pauli-blocking function. We apply this model, along with evaporation contributions, to analyze excitation functions of (n, α) reactions on ^{48}Ti, ^{51}V, ^{52}Cr, ^{54}Fe, ^{55}Mn, and ^{59}Co. Good agreement is obtained between our calculations and experimental measurements. Values for the local Fermi energy in the region from where knockout occurs indicate a surface reaction.

I. The Model

Nucleon-alpha reactions provide important infor mation on nuclear reaction mechanisms and on clustering in nuclei. There are a variety of competing mechanisms that contribute to the measured cross-sections: compound nucleus processes at low energies; and direct and preequilibrium processes at higher energies. At higher energies, reactions to the continuum are dominated by the knockout mechanism [1, 2], since the density of final states increases more rapidly than those corresponding to pick-up process.

Our model for (n, α) reactions has close similarities to quasi-free scattering models of nucleon and alpha particle emission [3, 4]. The interaction of the incident nucleon with the (preformed) alpha particle is related to the free nucleon-alpha scattering cross-section. Modifications are then applied to account for nuclear medium effects, notably the Fermi momentum of the struck alpha particle, the Pauli-blocking effects, and the influence of the residual nucleus nuclear and Coulomb barrier on the emitted alpha particle. Such an approach is also the basis of most intranuclear cascade models of nuclear reactions. In this work, however, we concentrate on the first-step "direct" part of the cascade, which is dominant for the energies we consider.

The influence of phase space restrictions in the nucleus can be expressed using a Pauli-blocking function, as in Chadwick *et al.*'s analysis of quasideuteron photoabsorption [5]. As in [5], it is supposed that the (n, α) cross-section is proportional to the available phase space, and Fermi-gas state densities are used. We require that the two protons and two neutrons of the preformed alpha-particle in the nucleus (with a preformation factor ϕ_α) after leaving the nucleus will all have energies greater than the Fermi-energy ϵ_F. The direct component of the α-particle emission cross-section can then be written as

$$\sigma_{DC} = \phi_\alpha \; \sigma^{\text{free}}_{(n,\alpha)}(\epsilon_{\text{inc}}) \; f(\epsilon_{\text{inc}}), \qquad (1)$$

where $f(\epsilon_{\text{inc}})$ is the Pauli-blocking function that depends on ϵ_{inc} (the energy of the incident neutron), $\sigma^{\text{free}}_{(n,\alpha)}$ is the free neutron-alpha cross-section, and ϕ_α is the preformation factor. Using a Fermi-gas momentum distribution for the alpha-part les,

$$f(\epsilon_{\text{inc}}) = \int_0^{\epsilon_F^\alpha} \rho_\alpha(\epsilon_\alpha) F(\epsilon_\alpha + \epsilon_{\text{inc}}) T(\epsilon_\alpha + \epsilon_{\text{inc}}) d\epsilon_\alpha, \qquad (2)$$

where ϵ_α is the energy of the preformed alpha-particle, relative to the bottom of the nuclear well, $\rho_\alpha(\epsilon_\alpha)$ is the alpha-particle state density, $F(\epsilon_\alpha + \epsilon_{\text{inc}})$ is the Pauli-blocking factor, and $T(\epsilon_\alpha + \epsilon_{\text{inc}})$

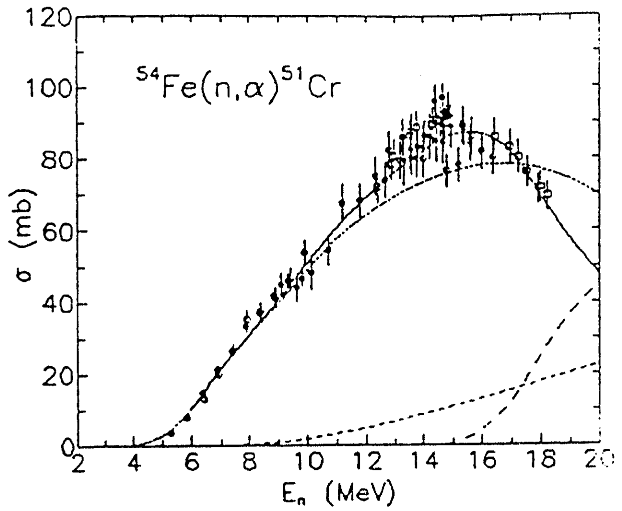


Figure 1: The excitation function of the ^{54}Fe(n,α)^{51}Cr reaction. We show the calculated contributions: σ_{DC}, (dashed line); σ_{HF} (dotted line); and $\sigma(n, \alpha n')$ (long-dashed line). The full calculation given by the solid line is $\sigma(n,\alpha)= \sigma_{DC} + \sigma_{HF} - \sigma(n, \alpha n')$. References to the works from which the experimental data are taken are given in the text.

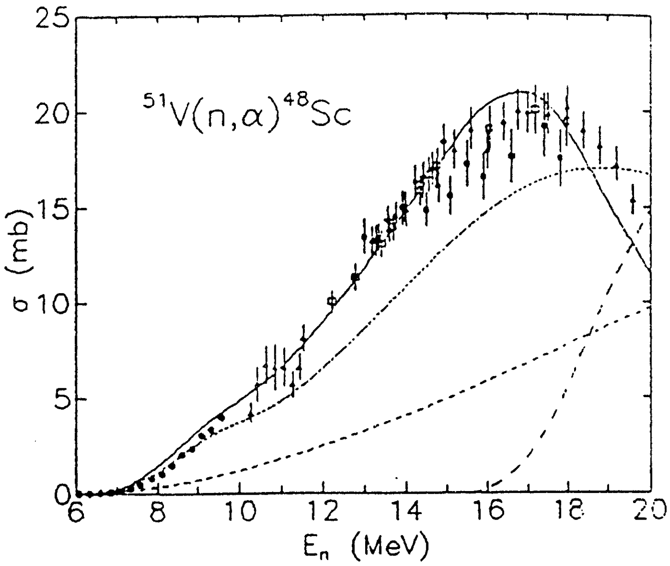


Figure 2: The same as in Fig.1 for the ^{51}V$(n, \alpha)^{48}$Sc reaction.

Table 1: Values of ϵ_F, the nucleon Fermi-energy (in MeV), for a preformation factor $\phi_\alpha = 0.30$. The low values of the Fermi energy indicate a nuclear surface reaction

	^{51}V	^{55}Mn	^{59}Co	^{48}Ti	^{52}Cr	^{54}Fe
ϵ_F	9.0	7.0	6.0	4.0	8.0	4.5

is the transmission coefficient for the excited alpha-particle to escape the nucleus (which we average for a range of angular momenta). We assume that the alpha-particle state density has a Fermi-gas model form, which is consistent with our use of a Pauli-blocking factor given by

$$F(E) = \frac{\rho^P(4p, E)}{\rho(4p, E)}, \quad (3)$$

defined as the ratio of the four-particle Fermi-gas state densities in which the Pauli blocking is included ($\rho^P(4p, E)$) and ignored ($\rho(4p, E)$) [5].

Results

We apply our model to analyze (n, α) excitation functions measured using activation techniques. To the direct contributions calculated with the above model, we add a compound nucleus contribution from the Hauser-Feshbach theory [6, 7]. If there is sufficient energy for subsequent particle decay following alpha emission, we isolate the (n, α) cross-section by subtracting such contributions. When calculating σ_{DC} with our model, the free elastic (n, α) cross-section was taken from Ref. [8], and the transmission coefficients from the optical potential in Ref. [9]. We have taken the value of the preformation factor as $\phi_\alpha = 0.30$ in accordance with Refs. [6, 10, 11].

The calculations of the (n,α) cross-section enable us to study the dependence of the results on the nucleon Fermi energy ϵ_F. This parameter is obtained by fitting the calculated excitation function to the experimental data. We have analyzed excitation functions of (n,α) reactions on ^{54}Fe, ^{51}V, ^{55}Mn, ^{59}Co, ^{48}Ti and ^{52}Cr. As an example of our calculations, we show in Fig. 1 the ^{54}Fe(n, α) reaction, in Fig. 2 the ^{51}V(n, α) reaction, and in Fig. 3 the ^{59}Co (n, α) reaction. Experimental measurements from Refs. [12, 13] are compared with our model calculation. Our calculation of the (n,α) cross-section (solid line) is the sum of Hauser-Feshbach (dotted line) and our direct component (dashed line), subtracting secondary alphas which follow primary neutron emission (long-dashed line). The calculations are seen to describe the measurements well.

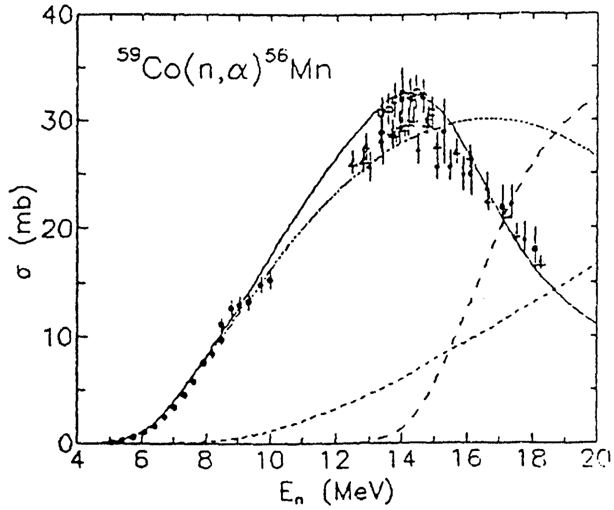


Figure 3: The same as in Fig.1 for the $^{59}Co(n,\alpha)^{56}Mn$ reaction.

The optimum values of the nucleon Fermi are given in Table 1. According to the local density approximation the values of ϵ_F from 9.0 to 4.0 MeV correspond to nuclear surface densities from $\rho = 0.106\rho_0$ to $\rho = 0.032\rho_0$ (when $\epsilon_F = 40$MeV at $\rho = \rho_0$) and agree with the range (4-8 MeV) found in the QFS-model [4] when applied to (nucleon,α) reactions. The sensitivity of the cross-section to variations of ϕ_α and ϵ_F was studied and it was found that the fit is essentially unaffected by correlated changes in these two parameters. Thus the parameter values (0.20, 7.0), (0.30, 9.0), and (0.40, 10.5) for $(\phi_\alpha, \epsilon_F)$ give the same cross-section for the ^{51}V (n,α)-reaction. For a particular value of ϕ_α, we estimate the uncertainty in ϵ_F to be about 0.5-1.0 MeV.

In summary, we have shown that our model accurately describes the direct components of the (n,α) cross-section (and the total excitation function after including statistical components). The values we obtain for the local Fermi-energy are consistent with results from other investigations, and indicate that alpha knockout occurs from the surface region. As a next step in this work, we plan to investigate the use of this model to calculate emission spectra of alpha particles.

This work was funded in part by the ECC (Contract No. ERB-CIPA-CT-92-2159), by the Bulgarian National Science Foundation (Contract No. Ph.-32) (A.N.A.), under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48 (M.B.C.), by the Royal Society (M.A.), and by the agreement of the Royal Society with the Bulgarian Academy of Sciences (A.N.A.).

References

[1] E. Gadioli and P.E. Hodgson, Rep. Prog. Phys. 52, 247 (1989); E. Gadioli and P.E. Hodgson, Pre-Equilibrium Nuclear Reactions, Clarendon Press, Oxford (1992).

[2] A. Ferrero, E. Gadioli, E. Gadioli Erba, I. Iori, N. Mohlo, L. Zetta, Z. Phys. A293, 123 (1979).

[3] A. Mignerey, M. Blann, W. Scobel, Nucl. Phys. A273, 125 (1976).

[4] W. Scobel, M. Blann, A. Mignerey, Nucl. Phys. A287, 301 (1977).

[5] M.B. Chadwick, P. Oblozinsky, P.E. Hodgson, G. Reffo, Phys. Rev. C44, 814 (1991).

[6] M. Avrigeanu, M. Ivascu and V. Avrigeanu, Z. Phys. A235, 299 (1990).

[7] M. Avrigeanu, V. Avrigeanu and P. E. Hodgson, in *Proc. of Int. Adv. Courses on Frontier Topics in Nuclear Physics*, Predeal, Romania, September 1993, Eds. W. Scheid, A. Sandulescu, Plenum, N.Y. (in press).

[8] JAERI-M 90-099 (JENDL-3); K. Shibata, J. of Nucl. Sci. and Technology 27[1], 81 (1990).

[9] V. Avrigeanu, P. E. Hodgson and M. Avrigeanu, Phys. Rev. C49, (1994) (in print).

[10] S.M. Qaim, M. Uhl, N.I. Molla, H. Liskien, Phys. Rev. C46, 1398 (1992).

[11] N. I. Molla, S. M. Qaim, M. Uhl, Phys. Rev. C42, 1540 (1990)

[12] V. Avrigeanu, "Calculations of Excitation Functions of (n,α) Reactions", IAEA Research Co-ordination Meeting on "Improvement of Measurements, Theoretical Computations and Evaluations of Neutron Induced Helium Production Cross Sections", Debrecen, Hungary, 17-19 November 1992 (and references therein).

[13] V. McLane, C.L. Dunford, P.E. Rose, Neutron Cross Sections, vol.2, Neutron Cross Section Curves, Academic Press, Inc., Boston, (1988).

DATE FILMED

9 /28 /94

END