Structure effects in the spectra of α particles from the interaction of 12 to 20 MeV neutrons with samarium isotopes

E. Gadioli and S. Mattioli
Dipartimento di Fisica, Universitá di Milano, Milano, Italy
and Istituto Nazionale di Fisica Nucleare, Sezione di Milano, Milano, Italy

W. Augustyniak, L. Głowacka, M. Jaskoła, and J. Turkiewicz
Soltan Institute for Nuclear Studies, Warsaw, Poland

A. Chiadli
Centre d'Etudes Nucleaires de Bordeaux-Gradignan, France
and Physics Department, Rabat University, Morocco
(Received 31 October 1990)

The spectra of α particles in (n,α) reactions induced on ^{144,147,149}Sm by neutrons with energy between ≈ 12 and 20 MeV are greatly affected by the shell structure of the target nucleus. Semimicroscopical calculations made in the framework of the pickup model, assuming dominance of transitions to neutron-hole states of the residual nuclei and the homology of high-energy states of ^{144,146}Nd excited in the reactions induced on the nonmagic ^{147,149}Sm isotopes with the low-energy states of ^{141}Nd excited in the reaction on the magic ^{144}Sm isotope, reproduce satisfactorily the data.

The study of reactions induced by neutrons with energy varying from ≈ 12 to ≈ 20 MeV is important for applied physics research e.g., for investigating the radiation damage caused by high fluxes of neutrons such as those produced by future fusion reactors. Though a large amount of work has been done to measure the cross section of these reactions, the experimental information is far from being exhaustive and an urgent demand exists for improving the accuracy of the theoretical predictions.

It has been found that, to obtain a fair reproduction of the emitted particle spectra in a given reaction, in many cases one must explicitly take into account the structure of the nuclei involved in the process. This is particularly evident for (n,α) reactions on magic and near-magic nuclei. The spectrum of the emitted α particles varies drastically for target nuclei differing only by one or two neutrons as found, for instance, in the case of Zr (^{90,91}Zr) and Nd (^{142,143,144}Nd) isotopes.[1,2] In the case of ^{90}Zr and ^{142}Nd which have a magic neutron shell, the yield of emitted α particles is concentrated at the highest energies, whereas for the near-magic nuclei ^{91}Zr and ^{143,144}Nd with one or two neutrons more, the yield of highest-energy α's is very small and the probability of emission reaches a maximum for residual nucleus excitation energies of the order of 4–5 MeV.

Despite these differences, in two previous papers[1,2] it was shown that once the spectrum of the α particles from the magic target nucleus is known, that of the α particles from a nucleus with one more neutron outside the magic shell may be evaluated by assuming that this nucleon acts as a spectator. Thus, the process occurring is essentially the same in the two cases, and to each state excited in the residue of the magic nucleus there corresponds a multiplet of states in the residue of the near-magic nucleus generated by the coupling of this state with the spectator nucleon. The state of the magic nucleus residue, that will be indicated hereafter as the *generator* state, is thus *homologous* to the states of the multiplet in the residue of the near-magic nucleus; still, its excitation energy is notably smaller than that of the states of the corresponding multiplet (typically by about 3 ± 1 MeV, approximately the sum of the width of the energy gap in the sequence of single-particle states at the filling of the magic shell and the average pairing energy of two neutrons of the magic shell).

The assumption that the cross section for population of the generator state is equal to the *total* cross section for populating the states of the multiplet allows one to satisfactorily reproduce the α-particle spectra from the near-magic target nuclei. In the case of a weak coupling between the generator state and the spectator nucleon, one also expects that the shape of the angular distributions and of the analyzing powers for transitions to homologous states is essentially the same and indeed this expectation is found to be fulfilled in the case of the (p,α) reaction (for which the same considerations apply) on the magic—near-magic pair ^{208}Pb and ^{209}Bi.[3]

The accurate reproduction of the α spectrum in an (n,α) reaction induced on a magic nucleus is far from being simple. Assuming the dominance of a pickup mechanism, the states excited in a one-step process may be either single neutron-hole states and one-neutron–two-proton-hole states. These last states, in most of the cases, may be described by a particle-vibration coupling scheme. Pickup of two protons from different orbits may also be important. In the most general case, one has to expect a mixing of the allowed configurations which contribute coherently to the transition amplitude. In a

 ©1991 The American Physical Society

semimicroscopic approach, the α spectrum may be evaluated once the single neutron and the diproton spectroscopic amplitudes are known.[4]

For nuclei in the rare-earth region, the only spectroscopic information experimentally available for the states which may be excited in a one-step pickup (n,α) reaction refers to the single neutron-hole component and in a previous work a calculation of the α-particle spectrum from ^{142}Nd was tentatively made by considering only the contribution of these states.[2] It was found that indeed a reasonable reproduction of both the α-spectrum shape at a given incident neutron energy and of the α yield varying the incident energy was possible, thus suggesting a predominance of transitions to single neutron-hole states.

A similar situation exists in the case of the (n,α) reactions induced on ^{144,147,149}Sm and we may test the previous conclusion by analyzing these α-particle spectra using the same optical-model parameters for the entrance and exit channels, the same geometrical parameters for the bound state of the transferred helion, and nearly the same factor normalizing the calculated cross sections to the experimental ones. The analyses of these data allows one to extend the calculation technique previously discussed for evaluating the spectrum of α particles from near-magic nuclei to nuclei with several neutrons outside the magic shell $50 < N \leq 82$. Obviously in the case of ^{147}Sm and ^{149}Sm the extra nucleons play an active role in the reaction and the cross section for their pickup may be evaluated, as we will show later. However, the spectroscopic information for the pickup of neutrons of the magic shell which excites states of ^{144}Nd and ^{146}Nd with several MeV of excitation energy is lacking and one may try to use that concerning the states of ^{141}Nd excited in the reaction on the magic isotope ^{144}Sm to estimate the yield of the α particles exciting these high-energy states.

The experimental arrangement and procedure were similar to those described in previous works.[5] Neutrons were produced by bombarding a thin titanium tritide target with a deuteron beam from the Van de Graaff accelerator at the Soltan Institute for Nuclear Studies. The beam current was 25 μA at 2-MeV deuteron energy. The desired neutron energy was selected by a suitable choice of the neutron emission angle with respect to the deuteron beam. The ^{3}H+Ti target, on a thick copper backing, had an average thickness of about 1 mg/cm^2. To minimize the target deterioration by the beam, the tritium target was continuously water cooled during bombardment.

The neutron energy spread (FWHM) was mainly due to the deuteron energy loss in the tritium target and to the geometrical conditions. It was estimated by a Monte Carlo calculation[6] to vary between 150 and 300 keV at the different neutron energies. The neutron flux was monitored by counting the protons recoiled from a polyethylene foil by means of a thin CsI(Tl) scintillator counter. The uncertainty in the absolute value of the neutron flux was estimated to be less than 6%. The targets investigated consisted of enriched samarium oxides deposited on thick aluminum backings. The isotopic composition of the Sm_2O_3 compounds used for target preparation is given in Table I. The average thickness of the targets was determined by weighing and was found to be about 4 mg/cm^2. The energy of the α particles was measured by means of surface-barrier-silicon detectors. The energy calibration was made using the known energies of the α particles from the ^{28}Si$(n,\alpha)^{25}$Mg reaction.

TABLE I. Isotopic composition of Sm_2O_3 compounds used for target preparation.

Isotope	^{144}Sm target (%)	^{147}Sm target (%)	^{149}Sm target (%)
^{144}Sm	91.2	0.1	0.1
^{147}Sm	2.8	96.4	0.2
^{148}Sm	1.3	2.2	0.8
^{149}Sm	1.3	0.5	96.9
^{150}Sm	0.5	0.2	1.4
^{152}Sm	1.7	0.4	0.4
^{154}Sm	1.2	0.2	0.2

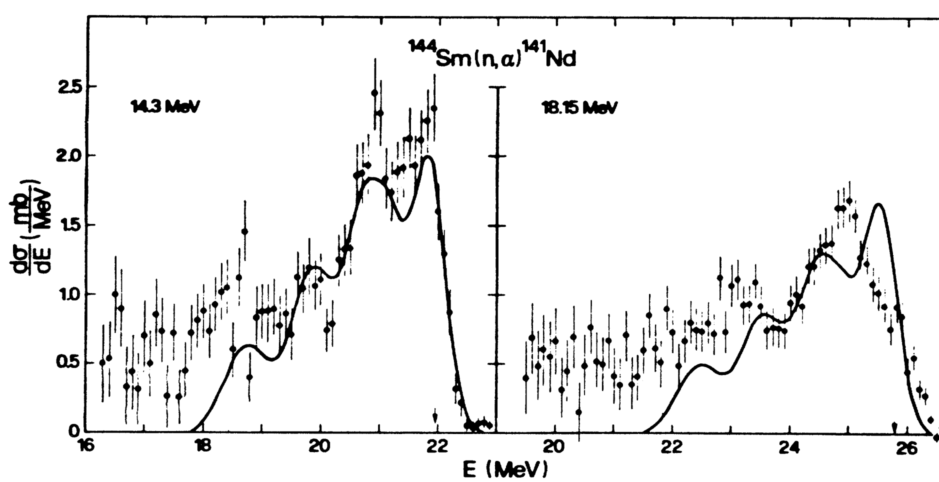

FIG. 1. Experimental (black points with error bars) and theoretical (full lines) angle-integrated spectra of α particles from the ^{144}Sm$(n,\alpha)^{141}$Nd reaction at 14.3 and 18.15 MeV.

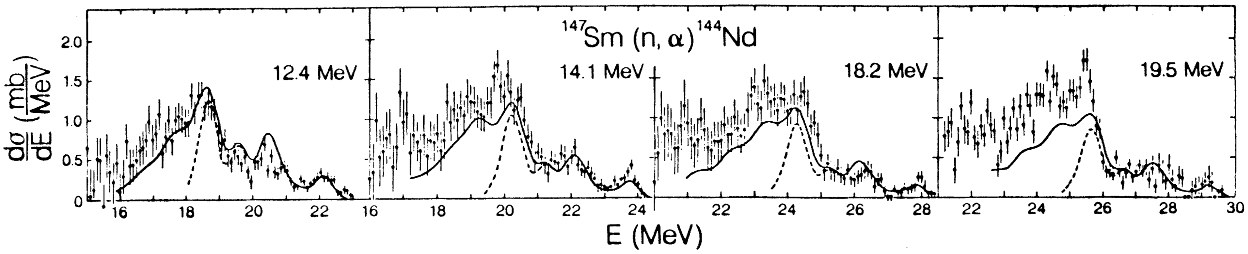

FIG. 2. Experimental (black points with error bars) and theoretical (full and dashed lines) angle-integrated spectra of α particles from the ^{147}Sm$(n,\alpha)^{144}$Nd reaction at 12.4, 14.1, 18.2, and 19.5 MeV.

The FWHM energy resolution (depending on solid-state detector resolution, target thickness, neutron energy spread, and geometrical conditions) was also estimated in this case by a Monte Carlo calculation and was found to vary between 480 and 700 keV. The overall accuracy in the absolute cross sections, resulting from target-thickness uncertainty and nonuniformity, neutron flux monitoring, and solid-angle uncertainty is of the order of 15%.

Angular distributions of α particles for states up to an excitation energy of about 5 MeV were measured at seven emission angles. The α-particle angular distributions display a forward peaking and decrease smoothly with increasing the observation angle. These distributions have been used to obtain the angle-integrated spectra shown in Figs. 1–3.

The theoretical spectra were calculated by finite-range distorted-wave Born approximation (DWBA) pickup theory in the framework of the semimicroscopic model,[4] as discussed in previous papers.[1,2]

In the case of an even-even target nucleus and in the hypothesis of dominance of transitions to single neutron-hole states β, the experimental cross section is related to the theoretical one by

$$\sigma^{\beta}_{\rm expt}(\theta)=[\mathcal{N}_{\rm PU}(A)\mathcal{A}^{LJ}_{\alpha_\beta J_\beta}]^2\sigma^{\beta}_{\rm PU,DW}(\theta) , \qquad (1)$$

where $\sigma^{\beta}_{\rm PU,DW}(\theta)$ is the angular distribution evaluated in DWBA theory (we use the code[7] TWOFNR in the finite-range option with a neutron-helion interaction potential of Gaussian form with variance $\sigma=\xi/\sqrt{2}=1.41$ fm). $\mathcal{A}^{LJ}_{\alpha_\beta J_\beta}$ is a spectroscopic amplitude given by

$$\mathcal{A}^{LJ}_{\alpha_\beta J_\beta}=\left[\frac{A}{A-3}\right]^{N+L/2}\times\left[\frac{A-2}{A}\right]^{\bar{N}+\bar{J}/2}G_{n\beta}(S^{NLJ}_{j_{n\beta},\bar{N},\bar{J}})^{1/2} , \qquad (2)$$

where α_β denotes the internal coordinates of the residual nucleus; N, L, and J are, respectively, the radial quantum number, the orbital momentum, and the total momentum of the transferred three-nucleus cluster, A is the target nucleus mass, $G_{n\beta}$ is the spectroscopic amplitude for the pickup of the neutron measured in single-neutron pickup reactions, $\bar{N}$ and $\bar{J}$ are the radial quantum number and the total angular momentum of the proton pair, and $(S^{NLJ}_{j_{n\beta},\bar{N},\bar{J}})^{1/2}$ is an algebraic factor,[4]

$$\mathcal{N}_{\rm PU}(A)=N(A)G_{\bar{N},\bar{J}} , \qquad (3)$$

where $G_{\bar{N},\bar{J}}$ is the spectroscopic amplitude for pickup of the two protons and $N(A)$ a normalizing factor. In the case of the (n,α) reactions induced by 12–20-MeV neutrons on Nd isotopes, it was found $\mathcal{N}_{\rm PU}(A)\approx 1.1\times 10^3$.

The first Sm isotope studied was ^{144}Sm having a magic neutron shell. The spectroscopic factors for exciting single-neutron-hole states of ^{141}Nd, $S_\beta\equiv G^2_{n\beta}$, are given by several authors.[8–13] The different estimates, obtained by analysis of (p,d), (d,t), and $(^3$He$,\alpha)$ reactions at several incident energies, often differ appreciably. The

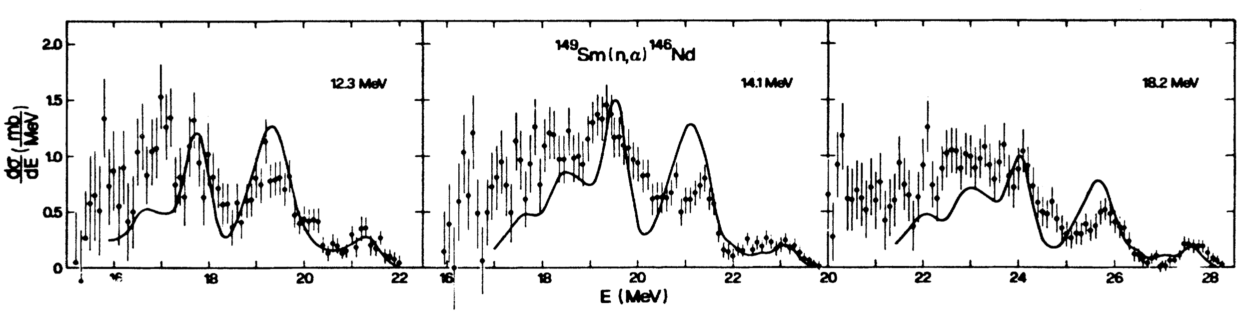

FIG. 3. Experimental (black points with error bars) and theoretical (full lines) angle-integrated spectra of α particles from the ^{149}Sm$(n,\alpha)^{146}$Nd reaction at 12.3, 14.1, and 18.2 MeV.

TABLE II. Optical-model parameters used for the evaluation of the elastic-scattering wave functions of the outgoing α particles and geometrical factors used for the helion bound state. The notation and potential forms are those adopted by Perey and Perey (Ref. 16).

V (MeV)	r (fm)	a (fm)	W (MeV)	r_W (fm)	a_W (fm)	r_c (fm)
$E_a \leq 21.5$ MeV						
189.6	1.450	0.486	12.75	1.450	0.486	1.3
$E_a > 21.5$ MeV						
192.0	1.435	0.523	19.92	1.435	0.523	1.3
Pickup						
h_{bs}	1.250	0.600				

discrepancies are, in part, of experimental and, in part, of theoretical origin. Here we use the values given by Van Rooden *et al.*[13] as a result of a high-resolution study of the (p,d) and (d,t) reactions on ^{142}Nd and a very detailed DWBA analysis of the angular distributions. These authors tried to estimate the spectroscopic factor uncertainty due to the combined uncertainty in the choice of the optical-model parameters for the entrance and exit channels and the bound-state geometry parameters. Their conclusion is that the uncertainty in estimating absolute S_β can easily exceed 50% especially in the case of the higher values of the transferred angular momentum l. In addition, relative spectroscopic factors also have uncertainties of about the same magnitude.

The calculation of the spectrum of the α particles strictly follows the procedure described by Gadioli *et al.*[1,2] so we will not repeat the discussion made there. The contribution of transitions to the single-neutron-hole states was calculated by means of relations (1)–(3) using, for the neutrons, the Wilmore and Hodgson[14] optical-model parameters and for the α's, the parameters used by Gadioli *et al.*[2] for the Nd isotopes which are reported in Table II. The calculated angle-integrated cross sections were finally spread with a Gaussian distribution of FWHM equal to the estimated energy resolution (≈ 600 keV).

The results of the calculations for the incident neutron energies of 14.3 and 18.15 MeV and a normalizing factor $\mathcal{N}_{\mathrm{PU}}(A) \approx 1.3\times10^3$ (20% higher than that used in the case of Nd isotopes) is shown in Fig. 1. The agreement with the experimental data is reasonably good (especially for the smaller energy considered) and the discrepancies found between the calculated and the experimental spectra are within the limits of the predicted accuracy of the calculation.

In the case of the reaction ^{147}Sm$(n,\alpha)^{144}$Nd, no spectroscopic information exists for the neutron-hole states of ^{144}Nd, so we used that referring to ^{146}Sm, the adjacent nucleus with two protons more, reported by Oelert *et al.*[15] who measured the spectroscopic factors for pickup of neutrons of the $2f_{7/2}$ and $3p_{3/2}$ orbitals above the $50<N\leq 82$ shell and of the $3s_{1/2}$ orbital of the magic shell. The results of such calculations made using the same optical-model parameters for neutrons and α's as in the previous case, a normalizing factor of 1.1×10^3 and a spreading width of 600 keV, are given by the dashed lines in Fig. 2.

To evaluate the contribution of the pickup of neutrons of deeper orbitals of the magic shell, we used, as discussed above, the spectroscopic information referring to ^{141}Nd,[13] equalizing the excitation energy of the $(3s_{1/2})^{-1}$ state to that of the centroid of the very fragmented $(3s_{1/2})^{-1}$ states of ^{146}Sm measured by Oelert *et al.*[15] To take into account that to each state of ^{141}Nd excited by the pickup of a neutron from the magic shell a multiplet of states now corresponds, due to the coupling of this state with the neutrons outside the shell, the FWHM of the Gaussian used to spread the contribution of these higher-energy states was increased to about 1 MeV.

The results of the calculations made using the Oelert *et al.*[15] and the Van Rooden *et al.*[13] spectroscopic factors are given by the full lines in Fig. 2.

It must be stressed that the very reasonable reproduction of the yield of the α's for transitions to both the g.s. and the higher excited states of ^{144}Nd represents a stringent test of the whole procedure we adopt. In fact, one could doubt that the need of normalizing the calculation to the experiment could mask the error due to neglecting important contributions of transitions to one-neutron–two-proton-hole configurations. On the other hand, a check of the correctness of the value of the normalizing factor we use is provided by the ability of the calculation to predict the strength of the transition to the g.s. of ^{144}Nd which certainly corresponds to the pickup of the least bound pair of protons and a $2f_{7/2}$ neutron from ^{147}Sm. The slight underestimate of the experimental spectra at the higher incident energies considered might be due to the inadequacy of some of the parameters we use, however, it is within the expected uncertainty of both the experimental data and the theoretical calculation.

The calculation of the α spectra for the reaction ^{149}Sm$(n,\alpha)^{146}$Nd was made using the spectroscopic information referring to ^{148}Sm for the pickup of neutrons from the $82<N\leq 126$ shell,[15] and that referring to ^{141}Nd for the pickup of neutrons from the $50<N\leq 82$ shell.[13] Also in this case, as shown in Fig. 3, the calculations reproduce reasonably well the experimental yield up to excitation energies of about 6 MeV. In this case, the normalizing factor used was 0.85×10^3, 20% smaller than the value used for the (n,α) reaction induced on Nd isotopes.

To conclude, we have shown that the calculation of the spectra of α particles emitted in (n,α) reactions on near-magic nuclei, based on the assumption of the homology of the residual nucleus states with excitation energy of ≈ 3–6 MeV with the low-energy states excited in the reaction induced on the adjacent magic nucleus may be generalized to the case of nuclei with several (three to five) nucleons outside the magic shell.

The values of the normalizing factors we have used in the analysis of the data concerning the three samarium isotopes, equal to $1.1\times10^3 \pm 20\%$, agree within the estimated uncertainty of both the experimental and the theoretical spectra and agree also with those used in the analysis of the reactions induced on the Nd isotopes. It must be stressed that one could use a slightly different normalizing factor in analyzing spectra measured at different energies for the same isotope, thus improving the agreement with the data, since the measure of the α-particle yield at a given incident energy is independent of the others and is affected by an estimated uncertainty of $\approx 15\%$.

The most intriguing conclusion of our analysis is the dominance of transitions to single-neutron-hole states in (n,α) reactions on rare-earth nuclei that appears much more pronounced than in the case of (p,α) reactions.[4,17] This conclusion is deserving of further investigation from both an experimental and a theoretical point of view.

[1]E. Gadioli, E. Gadioli Erba, L. Głowacka, M. Jaskoła, J. Turkiewicz, L. Zemło, J. Dalmas, and A. Chiadly, Phys. Rev. C **34**, 2065 (1986).

[2]E. Gadioli, E. Gadioli Erba, W. Augustyniak, L. Głowacka, M. Jaskoła, J. Turkiewicz, and J. Dalmas, Phys. Rev. C **38**, 1649 (1988).

[3]E. Gadioli, P. Guazzoni, S. Mattioli, L. Zetta, G. Graw, R. Hertenberger, D. Hofer, H. Kader, P. Schiemenz, R. Neu, H. Abele, and G. Staudt (unpublished).

[4]J. W. Smits and R. H. Siemssen, Nucl. Phys. **A261**, 385 (1976); J. W. Smits, Kernfysisch Versneller Instituut Report 140, 1977.

[5]W. Augustyniak, L. Głowacka, M. Jaskoła, J. Turkiewicz, L. Zemło, J. Dalmas, and A. Chiadli, Soltan Institute for Nuclear Studies Report SINS 2076/P-I/PL/A, 1989.

[6]L. Zemło, Institute for Nuclear Research Report INR 1464/I/Pl/B 1973.

[7]M. Igarashi, TWOFNR code, 1977, unpublished.

[8]A. Chameaux, G. Bruge, H. Faraggi, and J. Picard, Nucl. Phys. **A164**, 176 (1971).

[9]R. K. Jolly and E. Kashy, Phys. Rev. C **4**, 1398 (1971).

[10]J. L. Foster, Jr., O. Dietzsch, and D. Spalding, Nucl. Phys. **A169**, 187 (1971).

[11]G. Berrier, M. Vergnes, G. Rotbard, and J. Kalifa, J. Phys. (Paris) **37**, 311 (1976).

[12]S. El-Kazzaz, J. R. Lien, G. Lovhoiden, P. Kleinheinz, C. Ellegaard, J. Bjerregaard, P. Knudsen, and J. Rekstad, Nucl. Phys. **A280**, 1 (1977).

[13]C. D. Van Rooden, D. Spaargaren, H. P. Blok, and J. Blok, Nucl. Phys. **A430**, 125 (1984).

[14]D. Wilmore and P. E. Hodgson, Nucl. Phys. **55**, 673 (1964).

[15]W. Oelert, J. V. Maher, D. A. Sink, and M. J. Spisak, Phys. Rev. C **12**, 417 (1975).

[16]C. M. Perey and F. G. Perey, At. Data Nucl. Data Tables **17**, 1 (1976).

[17]E. Gadioli and P. E. Hodgson, Rep. Prog. Phys. **52**, 247 (1989).