# Alpha-particle emission from fast-neutron-induced reactions on neodymium isotopes

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Measurements of $\alpha$-particle spectra in $(n,\alpha)$ reactions induced on $^{142,143,144}$Nd by neutrons with energy between $\approx 12$ and 20 MeV are presented. The spectra are greatly affected by the shell structure of the target nucleus. A semi-microscopic calculation made in the framework of the pickup model, assuming dominance of transitions to neutron-hole states of the residual nucleus, provides a satisfactory reproduction of the data. Transitions to single neutron states through a knockout process have also been considered, but it is found that they may only slightly contribute to the measured $\alpha$-particle yield.

## I. INTRODUCTION

Pursuing a systematic study of $(n,\alpha)$ reactions on *magic* and *near magic* shell nuclei, the cross sections of the processes induced on $^{142}$Nd, $^{143}$Nd, and $^{144}$Nd, at energies varying from $\approx 12$ to $\approx 20$ MeV, have been measured.

The yield and the energy distributions of the emitted $\alpha$ particles are greatly affected by the structure of the target nucleus as shown by the comparison of the angle-integrated spectra for the three isotopes in Figs. 1–3. The spectrum of the $\alpha$ particles from $^{142}$Nd is concentrated at very low excitation energies reaching a maximum below 1 MeV and decreasing to approximately one quarter of the maximum value at $\approx 2.5$ MeV. In the case of the $^{143}$Nd$(n,\alpha)^{140}$Ce reaction, the levels of $^{140}$Ce are weakly excited below $\approx 3$ MeV; for energies between $\approx 3$ and $\approx 5.5$ MeV the emitted $\alpha$ particles have an energy distribution very similar to that of $\alpha$'s from $^{142}$Nd with energy in the interval 0–2.5 MeV. The spectrum of $\alpha$ particles from $^{144}$Nd is intermediate in character between the previous two.

The spectra of $\alpha$ particles from the $^{143}$Nd$(n,\alpha)^{140}$Ce reaction were measured some years ago and it was suggested[1,2] that the energy distribution of these $\alpha$ particles is indicative of the *spectator role* of the 83rd neutron of $^{143}$Nd in the $(n,\alpha)$ process. In this hypothesis, the lowest-energy states of $^{140}$Ce which may be excited with appreciable intensity have a neutron particle-hole character with $|\nu(2f_{7/2})(2d_{3/2})^{-1}\rangle$ and $|\nu(2f_{7/2})(3s_{1/2})^{-1}\rangle$ components. These states have been identified by means of the inelastic proton scattering on $^{140}$Ce proceeding through the 9.74 MeV $\frac{7}{2}^-$ resonance of $^{141}$Pr, the isobaric analog of the $\frac{7}{2}^-$ g.s. of $^{141}$Ce.[3] They have a centroid energy of $\approx 3.7$ MeV, in excellent agreement with the excitation energy of the first maximum one observes in the $\alpha$-particle spectrum.

Further, this effect was observable also in the $^{209}$Bi$(p,\alpha)^{206}$Pb (Ref. 2) and the $^{91}$Zr$(n,\alpha)^{88}$ Sr (Ref. 4) reactions, and it was shown that, in these cases, there are excited particle-hole states in the two residual nuclei which are *homologous* to the hole states excited in the residuals from the same reactions on, respectively, the magic nuclei $^{208}$Pb and $^{90}$Zr. These *homologous* states are excited with strength comparable to that of the hole states in the magic nucleus residual, so that the spectra of the $\alpha$ particles from the magic and the near magic target nuclei

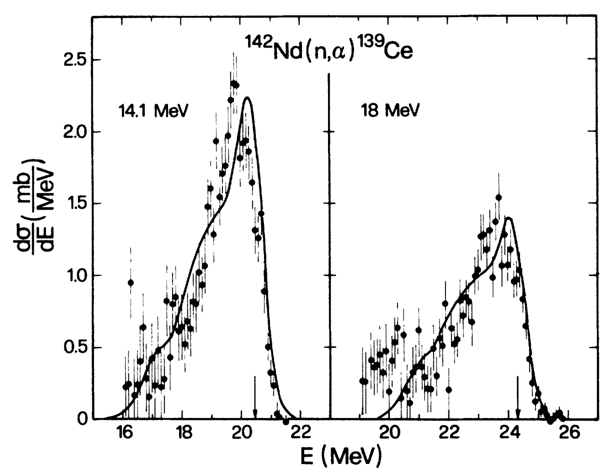


FIG. 1. Experimental (black points with error bars) and theoretical angle-integrated spectra of $\alpha$ particles from the $^{142}$Nd$(n,\alpha)^{139}$Ce reaction at $\approx 14.1$ and 18 MeV. The theoretical spectra have been calculated in the framework of pickup theory assuming dominance of transition to single neutron-hole states. The spectroscopic factors for neutron pickup are from Berrier *et al.* (Ref. 10). The arrows indicate the energy of the $\alpha$ particles feeding the g.s. of $^{139}$Ce.

 

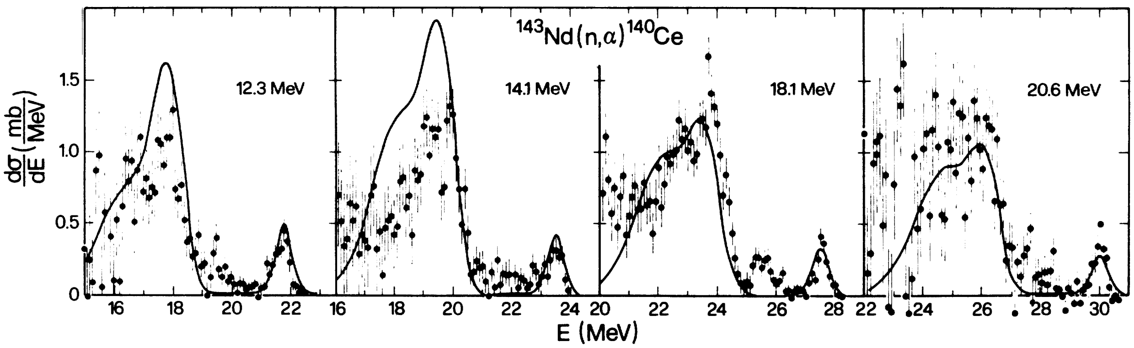


FIG. 2. Experimental (black points with error bars) and theoretical angle-integrated spectra of $\alpha$ particles from the $^{143}$Nd$(n,\alpha)^{140}$Ce reaction at $\approx 12.3$, 14.1, 18.1, and 20.6 MeV. The theoretical spectra have been calculated in the framework of pickup theory assuming dominance of transition to neutron particle-hole states homologous to the low-energy neutron-hole states excited in the $^{142}$Nd$(n,\alpha)^{139}$Ce reaction. The spectroscopic factors for neutron pickup are from Berrier *et al.* (Ref. 10).

may be superimposed as a function of the emitted $\alpha$-particle energy and found very similar, in spite of the very different $Q$ values. In the case of the $(n,\alpha)$ reaction induced on Zr isotopes it was shown that a theoretical analysis of these spectra proves very useful for understanding the reaction mechanism responsible for the process.[4]

These results prompted us to study, in addition to the $(n,\alpha)$ reaction on $^{143}$Nd, the same process on the *magic* $^{142}$Nd, and, to gain further information, on $^{144}$Nd.

In Sec. II the experimental procedure is presented and in Sec. III the analyses made in the framework of, respectively, pickup and knockout theories are discussed. Section IV is devoted to the conclusions. Preliminary discussion of part of these data has been reported in Ref. 5.

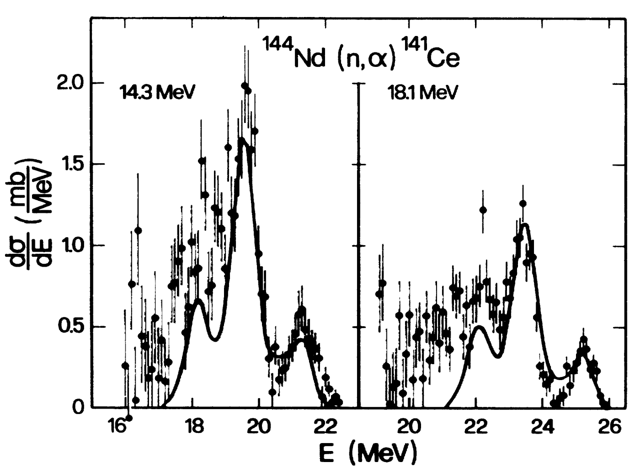


FIG. 3. Experimental (black points with error bars) and theoretical angle-integrated spectra of $\alpha$ particles from the $^{144}$Nd$(n,\alpha)^{141}$Ce reaction at $\approx 14.3$ and 18.2 MeV. The theoretical spectra have been calculated in the framework of pickup theory assuming dominance of transition to single neutron-hole states. The spectroscopic factors for neutron pickup are from Lien *et al.* (Ref. 12).

## II. EXPERIMENTAL RESULTS

The experimental arrangement and procedure were similar to those described in previous works from our group.[6] Fast neutrons were produced by the $^3$H$(d,n)^4$He reaction on a thin water-cooled titanium tritide target using 2–3 MeV deuterons from Van de Graaff accelerators. For neutron energies from $\approx 12$ to $\approx 18$ MeV, the measurements were made at the Institute for Nuclear Studies in Warsaw and at the higher energy of $\approx 20$ MeV, at the Centre d'Etudes Nucleaires de Bordeaux-Gradignan. The thicknesses of the titanium tritide targets varied from 0.8 to 1.2 mg/cm$^2$. The neutron energy spread (FWHM) due to the deuteron energy loss and geometrical conditions has been calculated by a Monte Carlo method and found to vary from $\approx 100$ to $\approx 200$ keV. The neutron flux was measured by counting the protons recoiling from a polyethylene foil with a thin CsI(Tl) scintillation counter. The accuracy in measuring neutron flux is estimated to be $\approx 6\%$.

The $^{142}$Nd, $^{143}$Nd, and $^{144}$Nd targets with thicknesses varying from $\approx 2.5$ to $\approx 3.6$ mg/cm$^2$ were prepared by sedimentation of the neodymium oxides onto thick aluminum backings. The isotopic composition of the $Nd_2O_3$ compounds used for target preparation is given in Table I.

The energies of the $\alpha$ particles were measured by sur-

TABLE I. Isotopic composition of $Nd_2O_3$ compounds used for target preparation.

| Isotope | $^{142}$Nd target (%) | $^{143}$Nd target (%) | $^{144}$Nd target (%) |
|---|---|---|---|
| $^{142}$Nd | 95.70 | 1.58 | 0.29 |
| $^{143}$Nd | 3.10 | 88.40 | 0.33 |
| $^{144}$Nd | 0.76 | 9.14 | 97.40 |
| $^{145}$Nd | 0.15 | 0.37 | 1.43 |
| $^{146}$Nd | 0.19 | 0.40 | 0.47 |
| $^{148}$Nd | 0.05 | 0.06 | 0.05 |
| $^{150}$Nd | 0.05 | 0.05 | 0.03 |

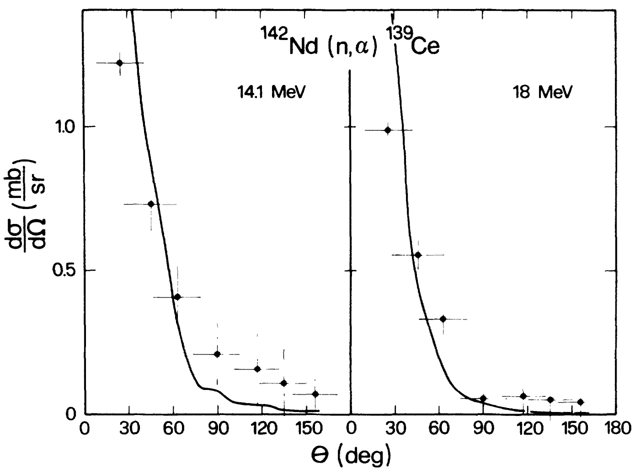


FIG. 4. Experimental and theoretical angular distributions of $\alpha$ particles from the $^{142}$Nd$(n,\alpha)^{139}$Ce reaction at $\approx 14.1$ and 18 MeV incident energy, corresponding to the 0–3 meV excitation energy interval in the residual nucleus. The theoretical angular distributions have been calculated in the framework of pickup theory.

face barrier silicon detectors at seven emission angles between 25° and 156° with an angular resolution $\approx 16°$. Due to the negative $Q$ values for $(n,\alpha)$ reactions on $^{16}$O, $^{27}$Al, and $^{28}$Si, $\alpha$ particles from the oxide part of the target, the backing, and the detector were prevented from contributing to the background up to an excitation energy $\approx 4-5$ MeV in the cases of $^{139}$Ce and $^{141}$Ce and $\approx 7$ MeV in the case of $^{140}$Ce. The well-resolved peaks of the $\alpha$ particles of smaller energy, produced in the detector by $(n,\alpha)$ reactions, were used for the energy calibration. The energy resolution due to the neutron energy spread, the $\alpha$-energy loss, the geometrical conditions, and the counter energy resolution was estimated to vary from $\approx 360$ to $\approx 500$ keV.

The angle-integrated spectra for the three targets and the different incident energies are shown in Figs. 1–3. The $\alpha$-particle angular distributions display a forward peaking and decrease smoothly with increasing observation angle. As a typical example, the angular distributions of $\alpha$ particles from the $^{142}$Nd$(n,\alpha)^{139}$Ce reaction are reported in Fig. 4.

## III. THEORETICAL INTERPRETATION

The cross sections for the transitions to the residual nucleus states are calculated using the distorted wave Born approximation (DWBA) assuming a definite reaction mechanism (pickup or knockout) with spectroscopic amplitudes calculated as described in the following. The calculated cross sections are properly normalized, and after having been folded with Gaussian distributions to simulate the low energy resolution, are added to obtain the theoretical spectra that are compared with the measured ones.

Most of the known low-lying states of $^{139}$Ce have been observed in $(p,d)$ (Refs. 7–9) and $(d,t)$ and $(^3\text{He},\alpha)$ (Ref. 10) reactions which feed their single neutron-hole components. Only for these components has the spectroscopic factor been measured. A similar situation exists for $^{141}$Ce. The only spectroscopic information which is experimentally known for states which may be excited in a one-step pickup $(n,\alpha)$ reaction refers to the single neutron-hole component.[11,12] For this reason, in pickup calculations the only contribution that has been considered is that of transitions to single neutron-hole states.

Though previous calculations of the cross section of the $(n,\alpha)$ reaction on Zr isotopes showed that this is really the dominant contribution for transitions to low-energy states,[4] and $(p,\alpha)$ reaction systematics shows that transitions to the single proton-hole states are greatly favored, this is a rather drastic assumption whose approximate validity may only be checked *a posteriori*. In fact, the large fractionation of states with a single neutron-hole component (especially of $2d_{5/2}^{-1}$ and $1g_{7/2}^{-1}$ types) in $^{139}$Ce and $^{141}$Ce suggests that most of the single neutron-hole components assumed to be populated in the $(n,\alpha)$ reaction are mixed with configurations that may be described by a particle-vibration coupling scheme.[10,13] It is well known that, in the case of $(p,\alpha)$ reactions on medium-heavy and heavy nuclei, to get a good reproduction of the experimental relative spectroscopic factors one has to explicitly consider also the contribution of these last components to the spectroscopic amplitudes.[14] Residual nucleus configurations reached by picking up two protons from different orbits may also be important.[4]

The contribution of transitions to single neutron states by a knockout process has also been evaluated. In the case of $^{139}$Ce, the experimental information concerning these states is not known, so their energies and spectroscopic factors have been assumed approximately equal to the energies and spectroscopic factors measured in the $^{136}$Ba$(d,p)^{137}$Ba reaction.[15] In the case of $^{141}$Ce the single neutron states have been studied by the $(d,p)$ reaction.[16,17]

In the case of both pickup and knockout, the cross section for production of $^{140}$Ce in the $^{143}$Nd$(n,\alpha)^{140}$Ce reaction has been calculated by assuming that the states excited in this nucleus are *homologous* to those of $^{139}$Ce populated in the $^{142}$Nd$(n,\alpha)^{139}$Ce reaction.

### A. Pickup calculations

In the absence of coherent contributions from different configurations, within the *semi-microscopic* model,[14] the following relation holds for an even-even target nucleus like $^{142}$Nd or $^{144}$Nd:

$$\sigma_{\exp}(\theta)=(A^{LJ}_{\alpha_\beta J_\beta})^2\sigma_{\text{PU,DW}}(\theta)\ , \qquad (1)$$

where $\sigma_{\exp}(\theta)$ is the measured angular distribution, $A^{LJ}_{\alpha_\beta J_\beta}$ a spectroscopic amplitude, and $\sigma_{\text{PU,DW}}(\theta)$ the angular distribution evaluated in DWBA. In this work, this cross section was calculated in the finite range approximation using the TWOFNR code.[18] The optical model elastic scattering wave functions of the incident neutron have been calculated with the optical model parameters suggested by Wilmore and Hodgson,[19] and those for the outgoing $\alpha$ particles with the parameters reported in Table II, obtained by a best fit analysis of elastic scattering data on $^{140}$Ce.[20] In this table are also reported the geometrical parameters used to calculate the helion bound state wave functions. These are equal to those used in Ref. 21 for evaluating the triton bound state in the $^{144}$Nd$(p,\alpha)^{141}$Pr reaction at 25 MeV. The neutron-helion interaction potential was assumed to be of Gaussian form

$$V(r_{\rm NH})=V_0\exp\left[-\left[\frac{r_{\rm NH}}{\xi}\right]^2\right], \quad (2)$$

with $\xi=2$ fm and $V_0=40$ MeV.

The spectroscopic amplitude $A^{LJ}_{\alpha_\beta J_\beta}$ for the excitation of a given state is given by

$$A^{LJ}_{\alpha_\beta J_\beta}=N(A)_{\rm PU}\left[\frac{A}{A-3}\right]^{N+(L/2)}\left[\frac{A-2}{A}\right]^{\bar{N}+(\bar{J}/2)} \times G_n G_{\bar{N},\bar{J}}[S^{NLJ}_{j_n,\bar{N},\bar{J}}]^{1/2}. \quad (3)$$

$\alpha_\beta$ 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-nucleon cluster; $A$ is the target nucleus mass and $N(A)_{\rm PU}$ a mass-dependent normalization factor; $G_n$ and $G_{\bar{N},\bar{J}}$ are the spectroscopic amplitudes for, respectively, the pickup of the neutron and the two protons; $\bar{N}$ and $\bar{J}$ are the radial quantum number and the total angular momentum of the proton pair. In the hypothesis of dominance of transitions to single neutron-hole states, if one is interested only in relative yields, $G_{\bar{N},\bar{J}}$ does not need to be evaluated, so one may simply assume

$$\sigma_{\rm exp}(\theta)=(\mathcal{N}_{\rm PU}(A)\mathcal{A}^{LJ}_{\alpha_\beta J_\beta})^2\sigma_{\rm PU,DW}(\theta), \quad (4)$$

where now the mass-dependent normalization factor is

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

and the reduced spectroscopic amplitude is

$$\mathcal{A}^{LJ}_{\alpha_\beta J_\beta}=A^{JL}_{\alpha_\beta J_\beta}/N(A)_{\rm PU}G_{\bar{N},\bar{J}}.$$

The algebraic factors $[S^{NLJ}_{j_n,\bar{N},\bar{J}}]^{1/2}$ are tabulated by Smits.[23] The neutron spectroscopic amplitudes are those measured in neutron pickup reactions.

### *1. The $^{142}$Nd$(n,\alpha)^{139}$Ce reaction*

The excitation energies and the spectroscopic factors of $^{139}$Ce states with a single neutron-hole component have been measured with the $(p,d)$ reaction at incident energies $\approx 25$ MeV,[8] 35 MeV,[9] and 55 MeV,[7] the $(d,t)$ reaction at $\approx 26$ MeV,[10] and the ($^3$He,$\alpha$) reaction at 25 MeV.[10] In all these experiments only states with energy less than $\approx 3.7$ MeV are observed.

When one compares the data from the different authors one finds quite appreciable discrepancies in the identification of some of these states and in the estimated spectroscopic factors. These discrepancies are of different origins: (i) experimental uncertainties due to the presence of impurities, insufficient energy resolution, and difficulty in observing weakly excited states above the background; (ii) the theoretical difficulty of differentiating angular distributions corresponding to $L=4$ and $L=5$ transfers leading, respectively, to $g^{-1}_{7/2}$ and $h^{-1}_{11/2}$ states; (iii) theoretical uncertainties in estimating spectroscopic factors from DWBA calculations due to finite range and nonlocality effects and to the fact that the calculations are very sensitive to the optical model parameters and details of the form factor in the nuclear interior.

In Table III are compared the centroids of single neutron-hole state energies and the sum of the corresponding spectroscopic factors reported by these authors.

In Fig. 5 are compared $(n,\alpha)$ spectra calculated using single neutron-hole energies and spectroscopic factors from these different authors. There is good agreement between calculations made using the Jolly and Kashy[9]

TABLE II. Optical model parameters used for the evaluation of the elastic scattering wave functions of the outgoing $\alpha$ particles and geometrical factors used for the helion bound state in pickup calculations and for the neutron and $\alpha$ bound states in knockout calculations. The notation and potential forms are those adopted by Perey and Perey (Ref. 22).

| $V$ (MeV) | $r$ (fm) | $a$ (fm) | $W$ (MeV) | $r_W$ (fm) | $a_W$ (fm) | $r_c$ (fm) |
|---|---|---|---|---|---|---|
| $E_\alpha \le 21.5$ MeV | | | | | | |
| 189.6 | 1.450 | 0.486 | 12.75 | 1.450 | 0.486 | 1.3 |
| $E_\alpha > 21.5$ MeV | | | | | | |
| 192.0 | 1.435 | 0.523 | 19.92 | 1.435 | 0.523 | 1.3 |
| Pickup | | | | | | |
| $h_{bs}$ | 1.250 | 0.600 | | | | |
| Knockout | | | | | | |
| $\alpha_{bs}$ | 1.520 | 0.610 | | | | |
| $n_{bs}$ | 1.300 | 0.750 | | | | |

TABLE III. Energies of the centroids of single neutron-hole states in $^{139}$Ce and total spectroscopic factors for their excitation in neutron pickup reactions.

| | $\bar{E}_{Nlj}$ (MeV) | | | | $(\sum_i S_i)_{Nlj}$ | | | |
|---|---|---|---|---|---|---|---|---|
| $Nlj$ | Ref. 7 | Ref. 8 | Ref. 9 | Ref. 10 | Ref. 7 | Ref. 8 | Ref. 9 | Ref. 10 |
| $2d_{3/2}$ | 0.00 | 0.00 | 0.00 | 0.00 | 4.00 | 4.00 | 4.00 | 4.00 |
| $3s_{1/2}$ | 0.25 | 0.25 | 0.33 | 0.57 | 2.00 | 1.60 | 1.45 | 1.80 |
| $1h_{11/2}$ | 0.75 | 0.75 | 1.07 | 1.27 | 10.20 | 9.10 | 8.70 | 8.64 |
| $2d_{5/2}$ | 1.58 | 1.58 | 1.72 | 1.97 | 4.98 | 3.16 | 5.60 | 5.70 |
| $1g_{7/2}$ | 2.81 | 2.76 | 2.90 | 2.62 | 7.44 | 1.40 | 7.10 | 3.92 |

and Berrier *et al.*[10] results, while calculations based on the Chameaux *et al.*[8] and Yagi *et al.*[7] results predict substantially smaller cross sections for excitation energies between 1 and 4 MeV. In Fig. 1 the comparison between the experimental angle-integrated spectra and the calculations based on Berrier *et al.*[10] data is shown. The normalizing factor $\mathcal{N}_{\rm PU}(A)$ resulted as 33.5

For completeness of information Table IV gives the excitation energies, configurations, and squares of the reduced spectroscopic amplitudes of the states that have been considered for evaluating the $\alpha$ spectra and the DWBA cross sections multiplied by $\mathcal{N}^2_{\rm PU}(A)$.

The overall reproduction of the $\alpha$ spectra at both energies is quite good, although some systematic discrepancies are apparent. In both cases the yield of $\alpha$ particles feeding the g.s. $2d_{3/2}^{-1}$ and the 0.25 MeV $3s_{1/2}^{-1}$ states of $^{139}$Ce is slightly overestimated, and that of the $\alpha$ particles feeding the 0.75 MeV $1h_{11/2}^{-1}$ state is slightly underestimated. In the case of the $1h_{11/2}^{-1}$ state, the discrepancy does not exceed the uncertainty affecting the estimated

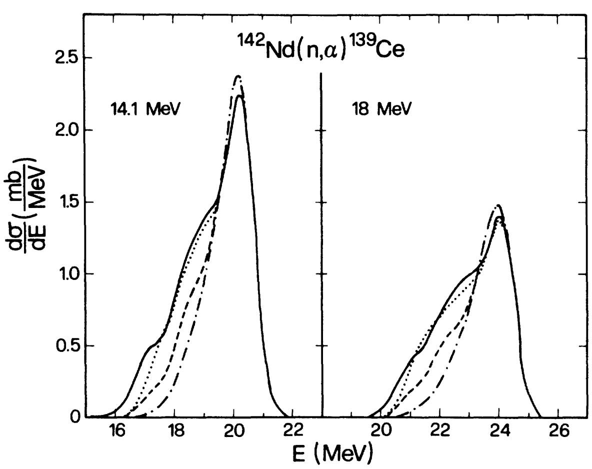


FIG. 5. Theoretical spectra of $\alpha$ particles from neutron bombardment of $^{142}$Nd at 14.1 and 18 MeV calculated, in the framework of pickup theory, using spectroscopic information on single neutron-hole states from Berrier *et al.* (Ref. 10) (full line), Jolly and Kashy (Ref. 9) (dotted line), Yagi *et al.* (Ref. 7) (dashed line), and Chameaux *et al.* (Ref. 8) (dash and dot line).

TABLE IV. Excitation energies, configurations, and squares of the reduced spectroscopic amplitudes of the neutron-hole states considered for evaluating the $\alpha$ spectra in the $^{142}$Nd$(n,\alpha)^{139}$Ce reaction and the normalized angle-integrated DWBA cross sections for transitions to these states.

| $E_{\rm exc}$ (MeV) | Configuration | $(\mathcal{A}^{LJ}_{\alpha\beta J_\beta})^2$ | $\sigma_{14.1}$ (mb) | $\sigma_{18}$ (mb) |
|---|---|---|---|---|
| 0.00 | $2d_{3/2}^{-1}$ | 0.2275 | 5.52 | 3.57 |
| 0.25 | $3s_{1/2}^{-1}$ | 0.1193 | 7.09 | 3.90 |
| 0.75 | $1h_{11/2}^{-1}$ | 0.0872 | 8.57 | 6.07 |
| 1.32 | $2d_{5/2}^{-1}$ | 0.1421 | 5.10 | 3.38 |
| 1.35 | $1g_{7/2}^{-1}$ | 0.0301 | 2.64 | 2.76 |
| 1.60 | $2d_{5/2}^{-1}$ | 0.0244 | 5.10 | 3.38 |
| 1.63 | $2d_{5/2}^{-1}$ | 0.0045 | 5.10 | 3.38 |
| 1.82 | $2d_{5/2}^{-1}$ | 0.0057 | 5.10 | 3.38 |
| 1.89 | $3s_{1/2}^{-1}$ | 0.0183 | 7.09 | 3.90 |
| 1.91 | $2d_{5/2}^{-1}$ | 0.0419 | 5.20 | 3.51 |
| 2.10 | $2d_{5/2}^{-1}$ | 0.0335 | 5.20 | 3.51 |
| 2.14 | $2d_{5/2}^{-1}$ | 0.0130 | 5.20 | 3.51 |
| 2.25 | $1g_{7/2}^{-1}$ | 0.0077 | 2.64 | 2.75 |
| 2.29 | $1h_{11/2}^{-1}$ | 0.0227 | 6.83 | 6.26 |
| 2.36 | $1g_{7/2}^{-1}$ | 0.0140 | 2.64 | 2.75 |
| 2.43 | $2d_{5/2}^{-1}$ | 0.0062 | 5.20 | 3.51 |
| 2.45 | $1g_{7/2}^{-1}$ | 0.0086 | 2.64 | 2.75 |
| 2.55 | $1g_{7/2}^{-1}$ | 0.0140 | 2.64 | 2.75 |
| 2.80 | $1g_{7/2}^{-1}$ | 0.0088 | 2.64 | 2.75 |
| 2.82 | $1h_{11/2}^{-1}$ | 0.0126 | 6.83 | 6.26 |
| 2.91 | $2d_{5/2}^{-1}$ | 0.0057 | 5.20 | 3.51 |
| 2.91 | $1g_{7/2}^{-1}$ | 0.0086 | 2.64 | 2.75 |
| 2.96 | $2d_{5/2}^{-1}$ | 0.0034 | 5.20 | 3.51 |
| 3.08 | $1g_{7/2}^{-1}$ | 0.0043 | 2.64 | 2.75 |
| 3.14 | $3s_{1/2}^{-1}$ | 0.0023 | 7.09 | 3.90 |
| 3.17 | $2d_{5/2}^{-1}$ | 0.0040 | 5.20 | 3.51 |
| 3.20 | $1g_{7/2}^{-1}$ | 0.0176 | 2.64 | 2.75 |
| 3.28 | $1g_{7/2}^{-1}$ | 0.0148 | 2.64 | 2.75 |
| 3.30 | $3s_{1/2}^{-1}$ | 0.0016 | 7.09 | 3.90 |
| 3.33 | $2d_{5/2}^{-1}$ | 0.0040 | 5.20 | 3.51 |
| 3.33 | $1g_{7/2}^{-1}$ | 0.0054 | 2.64 | 2.75 |
| 3.35 | $2d_{5/2}^{-1}$ | 0.0108 | 5.20 | 3.51 |
| 3.35 | $1g_{7/2}^{-1}$ | 0.0064 | 2.64 | 2.75 |
| 3.41 | $3s_{1/2}^{-1}$ | 0.0013 | 7.09 | 3.90 |
| 3.54 | $2d_{5/2}^{-1}$ | 0.0045 | 5.20 | 3.51 |
| 3.59 | $2d_{5/2}^{-1}$ | 0.0051 | 5.20 | 3.51 |
| 3.66 | $2d_{5/2}^{-1}$ | 0.0068 | 5.20 | 3.51 |
| 3.85 | $2d_{5/2}^{-1}$ | 0.0068 | 5.20 | 3.51 |
| 4.26 | $2d_{5/2}^{-1}$ | 0.0045 | 5.20 | 3.51 |

single neutron-hole state spectroscopic factor in the neutron pickup reaction.

The decrease of the calculated $\alpha$-particle yield going from 14.1 to 18 MeV, which satisfactorily reproduces that observed experimentally, is mainly due to the use of a different set of $\alpha$-particle optical model parameters, obtained from an independent fitting of elastic scattering data,[20] for $E_\alpha \leq 21.5$ MeV and $E_\alpha > 21.5$ MeV. The $\alpha$ spectra from the $^{144}$Nd$(n,\alpha)^{141}$Ce reaction, reported in Fig. 3, show the same energy dependence, satisfactorily reproduced by the calculations, while a drop in the measured $\alpha$-particle yield with an increase of the neutron energy is not discernible in the case of the $^{143}$Nd$(n,\alpha)^{140}$Ce reaction (Fig. 2).

The measured and the calculated angular distributions of the $\alpha$ particles feeding states up to an excitation energy of $\approx 3$ MeV in $^{139}$Ce are compared in Fig. 4. Similar results are obtained also in the case of the other target nuclei investigated in this work.

### 2. The $^{143}$Nd$(n,\alpha)^{140}$Ce reaction

As previously mentioned, in this case we expect that most of the cross section is accounted for by transitions to neutron particle-hole states corresponding to the coupling of the $2f_{7/2}$ neutron outside the magic $N=82$ shell with neutron-hole states in $^{139}$Ce. These particle-hole states are homologous to the low-lying states of $^{139}$Ce excited in the previous reaction and are expected to be populated with comparable intensity.

The centroid energy of the first multiplet of states of this type, $2f_{7/2}2d_{3/2}^{-1}$, is estimated to be $\approx 3.7$ MeV from the results of the $(p,p')$ resonant inelastic scattering experiment by Wurm *et al.*,[3] previously quoted. The centroid energy of the other neutron particle-hole multiplets of states is estimated by adding the excitation energy of the neutron-hole states in $^{139}$Ce to the centroid energy of the $2f_{7/2}2d_{3/2}^{-1}$ states. To further simplify the calculation, instead of considering each fragmented neutron-hole state in $^{139}$Ce, the centroid energy of each group has been considered, using the values reported by Berrier *et al.*[10] To evaluate the reduced spectroscopic amplitudes, a spectroscopic factor for neutron pickup equal to the sum of the spectroscopic factors corresponding to each fragmented state was attributed to each group. This procedure is simply a first approximation that does not take accurately into account the pairing energy effects.

In addition to these homologous states, states populated via pickup of the $2f_{7/2}$ neutron are also expected to be excited. These states include the ground state of $^{140}$Ce and, presumably, the two-proton-hole states of $^{140}$Ce observed via the $^{141}$Pr$(d,^3$He$)^{140}$Ce reaction,[24] with excitation energies between 1.6 and $\approx 3$ MeV, that are excited with moderate intensity in the $(n,\alpha)$ reaction as shown in Fig. 2. Of all these possible transitions, only that to the $^{140}$Ce g.s. has been considered in the present calculations.

The energy of the centroids of the multiplets of states of $^{140}$Ce assumed to be strongly excited in addition to the g.s., the corresponding configurations, the squares of the reduced amplitudes, and the normalized DWBA cross sections are shown in Table V. In Fig. 2 the calculated cross sections are compared to the measured ones (in folding the calculated cross sections with Gaussian distributions we also took into account the estimated width of each neutron particle-hole multiplet). The energy distribution of the emitted $\alpha$ particles is rather satisfactorily reproduced at all energies. The $\alpha$-particle yield is estimated rather correctly using the same normalization factor used in the case of the $^{142}$Nd$(n,\alpha)^{139}$Ce reaction, even if the rather pronounced decrease in the calculated yield, going from 14.1 to 18.1 MeV neutrons, is not confirmed by the experimental data. However, these discrepancies are consistent with the uncertainties affecting the theoretical calculations as well as the experimental absolute cross sections.

It has to be explicitly noted that the reproduction of the absolute value of the cross section for the g.s. transition provides an independent check of the normalization factor.

### 3. The $^{144}$Nd$(n,\alpha)^{141}$Ce reaction

The excitation energies and the spectroscopic factors of $^{141}$Ce states with a single neutron-hole component have been measured by $(d,t)$ and $(^3$He$,\alpha)$ reactions on $^{142}$Ce (Ref. 12) at 17 MeV and 24 MeV, respectively.

In Fig. 3, the measured angle-integrated $(n,\alpha)$ spectra

TABLE V. Excitation energies and configurations of the g.s. and of the centroids of the neutron particle-hole states of $^{140}$Ce used for evaluating the $\alpha$ spectra in the $^{143}$Nd$(n,\alpha)^{140}$Ce reaction, together with the squares of the reduced spectroscopic amplitudes and the normalized angle-integrated DWBA cross sections.

| $\bar{E}_{exc}$ (MeV) | Configuration | $(\mathcal{A}^{LJ}_{\alpha_\beta J_\beta})^2$ | $\sigma_{12.3}$ (mb) | $\sigma_{14.1}$ (mb) | $\sigma_{18.1}$ (mb) | $\sigma_{20.6}$ (mb) |
|---|---|---|---|---|---|---|
| 0.00 | Closed shell | 0.0364 | 9.65 | 8.79 | 6.66 | 5.58 |
| 3.69 | $2d_{3/2}^{-1}2f_{7/2}$ | 0.2275 | 4.49 | 5.22 | 3.40 | 2.94 |
| 4.26 | $3s_{1/2}^{-1}2f_{7/2}$ | 0.1432 | 6.11 | 6.77 | 3.94 | 3.24 |
| 4.96 | $1h_{11/2}^{-1}2f_{7/2}$ | 0.1091 | 4.51 | 7.44 | 5.85 | 5.43 |
| 5.66 | $2d_{5/2}^{-1}2f_{7/2}$ | 0.3236 | 3.15 | 5.03 | 3.74 | 3.30 |
| 6.29 | $1g_{7/2}^{-1}2f_{7/2}$ | 0.0842 | 0.55 | 1.94 | 2.60 | 2.66 |

are compared to the calculated ones [$\mathcal{N}_{\rm PU}(A)$ is the same used in the case of the other two isotopes].

At both energies the general features of the spectral shape are correctly reproduced; however the $\alpha$-particle yield is somewhat underestimated at excitation energies between 2 and 3.5 MeV. This discrepancy may be partly ascribed to the fact that a small fraction of the single neutron-hole strength has been observed for the $1h_{11/2}^{-1}$, the $1g_{7/2}^{-1}$, and the $2d_{3/2}^{-1}$ states in the neutron pickup reaction.[12] Nonetheless it seems that one may conclude that also in this case, assuming a pickup process, the transitions to single neutron-hole states constitute the dominant contributions, up to about 3.5 MeV of excitation energy. The excitation energies, the configurations, the squares of the reduced spectroscopic amplitudes for the transitions considered, and the normalized DWBA cross sections are given in Table VI.

TABLE VI. Excitation energies, configurations, and squares of the reduced spectroscopic amplitudes of the neutron-hole states considered for evaluating the $\alpha$ spectra in the $^{141}$Nd$(n,\alpha)^{141}$Ce reaction and normalized angle-integrated DWBA cross sections.

| $E_{\rm exc}$ (MeV) | Configuration | $(\mathcal{A}_{\alpha_\beta J_\beta}^{LJ})^2$ | $\sigma_{14.3}$ (mb) | $\sigma_{18.2}$ (mb) |
|---|---|---|---|---|
| 0.00 | $2f_{7/2}^{-1}$ | 0.0332 | 9.01 | 7.35 |
| 0.66 | $3p_{3/2}^{-1}$ | 0.0104 | 17.99 | 9.53 |
| 1.14 | $3p_{1/2}^{-1}$ | 0.0035 | 19.07 | 10.21 |
| 1.37 | $1i_{13/2}^{-1}$ | 0.0014 | 16.47 | 12.02 |
| 1.38 | $1h_{11/2}^{-1}$ | 0.0048 | 7.28 | 5.35 |
| 1.50 | $2f_{5/2}^{-1}$ | 0.0040 | 14.04 | 8.68 |
| 1.63 | $2d_{3/2}^{-1}$ | 0.1251 | 4.41 | 3.20 |
| 1.74 | $2f_{7/2}^{-1}$ | 0.0007 | 13.32 | 8.27 |
| 1.78 | $3s_{1/2}^{-1}$ | 0.0796 | 5.63 | 3.57 |
| 1.91 | $1h_{11/2}^{-1}$ | 0.0109 | 6.84 | 5.43 |
| 1.94 | $3s_{1/2}^{-1}$ | 0.0062 | 5.66 | 3.62 |
| 2.04 | $1h_{11/2}^{-1}$ | 0.0058 | 6.73 | 5.44 |
| 2.17 | $1h_{11/2}^{-1}$ | 0.0265 | 6.63 | 5.47 |
| 2.20 | $1g_{7/2}^{-1}$ | 0.0090 | 2.59 | 2.33 |
| 2.24 | $1g_{7/2}^{-1}$ | 0.0014 | 2.58 | 2.34 |
| 2.32 | $2f_{7/2}^{-1}$ | 0.0012 | 13.25 | 8.57 |
| 2.40 | $2d_{(3/2)-(5/2)}^{-1}$ | 0.0014 | 4.42 | 3.40 |
| 2.46 | $2d_{(3/2)-(5/2)}^{-1}$ | 0.0077 | 4.43 | 3.40 |
| 2.53 | $1h_{11/2}^{-1}$ | 0.0008 | 6.33 | 5.51 |
| 2.65 | $2d_{(3/2)-(5/2)}^{-1}$ | 0.0014 | 4.43 | 3.40 |
| 2.84 | $3s_{1/2}^{-1}$ | 0.0011 | 5.85 | 3.90 |
| 2.89 | $2d_{(3/2)-(5/2)}^{-1}$ | 0.0043 | 4.44 | 3.40 |
| 2.99 | $3s_{1/2}^{-1}$ | 0.0215 | 5.88 | 3.95 |
| 3.06 | $2d_{(3/2)-(5/2)}^{-1}$ | 0.0256 | 4.45 | 3.48 |
| 3.07 | $2d_{(3/2)-(5/2)}^{-1}$ | 0.0122 | 4.45 | 3.48 |
| 3.11 | $1h_{11/2}^{-1}$ | 0.0095 | 5.85 | 5.60 |
| 3.21 | $2d_{(3/2)-(5/2)}^{-1}$ | 0.0020 | 4.45 | 3.48 |
| 3.33 | $2f_{5/2}^{-1}$ | 0.0109 | 12.34 | 8.68 |
| 3.41 | $3s_{1/2}^{-1}$ | 0.0037 | 5.60 | 4.08 |
| 3.41 | $1h_{11/2}^{-1}$ | 0.0023 | 5.97 | 5.64 |
| 3.61 | $1g_{7/2}^{-1}$ | 0.0101 | 2.19 | 2.43 |
| 3.66 | $2d_{(3/2)-(5/2)}^{-1}$ | 0.0017 | 4.47 | 3.48 |

### B. Knockout calculations

The $\alpha$-particle spectra resulting from population of single neutron states in a knockout process have also been calculated. Knockout may also populate neutron-hole states; however, calculations of the cross sections of $(p,\alpha)$ reactions on $^{144}$Nd indicated that knockout contributions to one-hole state transitions are small in comparison with pickup.[21] For this reason, taking also into account the difficulty of giving reliable estimates of relative spectroscopic factors for processes involving knockout of neutron pairs on different orbits, the knockout contribution to neutron-hole states has not been evaluated.

Within the cluster approximation, in the absence of configuration mixing, in the case of an even-even target nucleus, and considering only single neutron final states, the cross sections for transitions to the residual nucleus levels are simply given by[18]

$$\sigma_{\rm exp}(\theta)=\mathcal{N}_{\rm KO}^2(A)S_n\sigma_{\rm KO,DW}(\theta)\ , \quad (5)$$

where $\sigma_{\rm KO,DW}(\theta)$ is the DWBA cross section calculated, also in this case, with the TWOFNR code,[18] $S_n$ is the spectroscopic factor, measured in a stripping reaction, for the transition to the considered single-neutron state of the residual nucleus, and $\mathcal{N}_{\rm KO}^2(A)$ is a normalizing factor including the $\alpha$-particle spectroscopic factor.

To evaluate $\sigma_{\rm KO,DW}(\theta)$, the elastic scattering wave functions for the incident neutron and the outgoing $\alpha$ particle have been calculated with the optical model parameters reported in Table II together with the geometrical parameters used to calculate the neutron and the $\alpha$-particle bound state wave functions. They are equal to those used for evaluating the proton and the $\alpha$-particle bound states in the calculation of the knockout contribution to the cross sections of transitions to low-lying $^{141}$Pr states in the $^{144}$Nd$(p,\alpha)^{141}$Pr reaction at 25 MeV.[21] The neutron–alpha-particle interaction potential was assumed to be of the Woods-Saxon type,

$$V(r_{n\alpha})=V_0\left[1+\exp\left[\frac{r_{n\alpha}-R_{\rm WS}}{a_{\rm WS}}\right]\right]^{-1}\ , \quad (6)$$

with $R_{\rm WS}=1.3$ fm, $a_{\rm WS}=0.2$ fm, and $V_0=70$ MeV.[21]

#### *1. The $^{142}$Nd$(n,\alpha)^{139}$Ce reaction*

On the average, the energies of single neutron states of $^{139}$Ce that are assumed to be approximately equal to those of the single neutron states of $^{137}$Ba observed in the $^{136}$Ba$(d,p)^{137}$Ba stripping reaction[15] are higher than the single neutron-hole state energies. Thus, as shown in Fig. 6, the calculated knockout spectrum, folded to simulate the experimental energy resolution, displays a maximum at an excitation energy of about 2.2 MeV, substantially higher than that of the maximum of the measured spectrum. Then, one may conclude that knockout processes populating single neutron states of $^{139}$Ce only provide a minor contribution to the measured $\alpha$ spectrum. The same conclusion is reached in the case of the $^{143}$Nd$(n,\alpha)^{140}$Ce reaction.

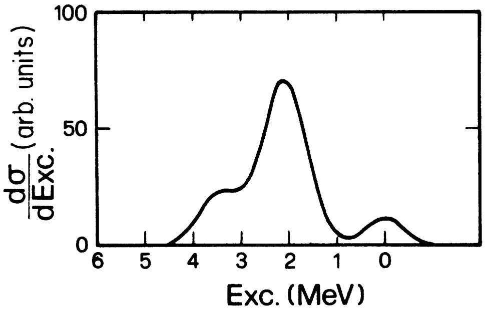


FIG. 6. Predicted angle-integrated knockout spectrum for the $^{142}Nd(n,\alpha)^{139}Ce$ reaction at 14.1 MeV. The neutron spectroscopic factors are from Ref. 15.

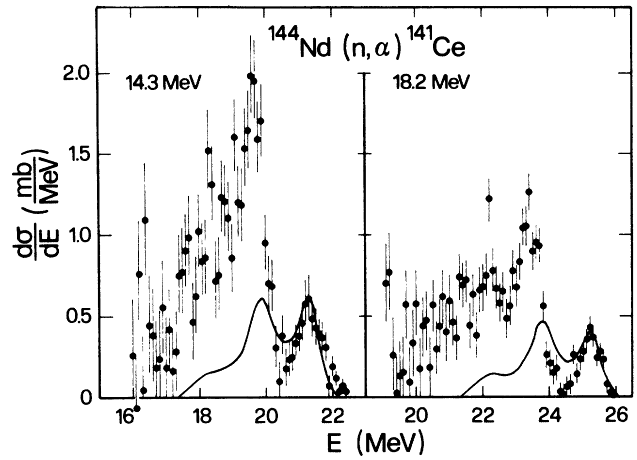


FIG. 7. The full lines represent an upper limit for the knockout contribution to the angle-integrated spectra for the $^{144}Nd(n,\alpha)^{141}Ce$ reaction at 14.3 and 18.2 MeV, obtained by normalizing the calculated cross section for the g.s. transition to the experimental value. The neutron spectroscopic factors are from Ref. 16.

### 2. The $^{144}Nd(n,\alpha)^{141}Ce$ reaction

The excitation energies and the spectroscopic factors of single neutron states of $^{141}Ce$ have been measured by $(d,p)$ reactions on $^{140}Ce$.[16,17] To evaluate the $\alpha$-particle spectra we used the results of Booth *et al.*[16]

The normalization of the calculated knockout cross section to the experimental value for the transition to the g.s. of $^{141}Ce$ provides an upper limit for the contributions of knockout transitions to single neutron states (Fig. 7, full lines). As shown by the figure, even in this extreme case, this process predicts a too low $\alpha$-particle yield at excitation energies greater than $\approx 1.3$ MeV.

The reproduction of the measured spectrum as an incoherent sum of pickup and knockout (in the case considered here this is a reasonable approximation since a calculation considering explicitly both pickup and knockout contributions to the transition amplitude shows that even in the case of the g.s. transition pickup and knockout cross sections add almost incoherently) shows that knockout transitions to single neutron states may give only a minor contribution to the total cross section.

## IV. CONCLUSIONS

A semi-microscopic analysis of the $\alpha$-particle spectra from $(n,\alpha)$ reactions induced on $^{142,143,144}Nd$ isotopes by $\approx 12-20$ MeV neutrons has been presented.

Both pickup and knockout contributions have been considered. Pickup calculations, assuming dominance of transitions to single neutron-hole states, provide a satisfactory reproduction of all the data considered using as a free parameter only one factor which normalizes the calculated to the experimental absolute cross sections. The value we found for this normalizing factor $\mathcal{N}^2(A \approx 143) \approx 33.5^2 \approx 1122$ is about half the value $\mathcal{N}^2(A \approx 90) \approx 2203$ that was used to reproduce, by pickup theory, the yield of $\alpha$ particles emitted in $(n,\alpha)$ reactions on $^{90,91}Zr$ isotopes at $\approx 14$ and 18 MeV.[4] However, considering the experimental uncertainties affecting the estimates of the absolute cross sections, and the well-known sensitivity of these calculations to the optical model parameters used for evaluating the outgoing $\alpha$ particle and the helion bound state wave functions, one cannot conclude that this result indicates a decrease of $\mathcal{N}(A)$ with increasing mass. It might be also compatible with an $\mathcal{N}(A)$ almost independent of the mass.

Knockout processes leading to single neutron states of the residual nucleus may only provide a minor contribution to the measured spectra at such low excitation energies.

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