PHYSICAL REVIEW C VOLUME 24, NUMBER 5 NOVEMBER 1981

Influence of the shell structure of the target nucleus on α emission in (nucleon, α) reactions

E. Gadioli and E. Gadioli Erba
Istituto di Fisica dell'Università and I N F N, Sezione di Milano, Milano, Italia

L. Głowacka, M. Jaskoła, J. Turkiewicz, and L. Zemło
Institute of Nuclear Research, Warsaw, Poland

(Received 23 July 1981)

The unusual energy distribution of α particles emitted in the reaction ^{143}Nd(n,α) ^{140}Ce at incident energies 12–18 MeV, is explained as being due to the shell structure of ^{143}Nd in the hypothesis that the mechanism responsible for α emission is the knockon by the incident neutron of α particles preformed in the target nucleus. The same interpretation is offered to describe the spectrum of α particles in the reaction ^{209}Bi(p,α) ^{206}Pb.

[NUCLEAR REACTIONS ^{143}Nd(n,α) ^{140}Ce, $E=12-18$ MeV; measured $\sigma(E_\alpha,E_n)$ and $\sigma(E_\alpha,\theta)$. Discussed influence of shell structure of ^{143}Nd on the measured spectrum.]

In the course of a series of measurements of spectra of α particles emitted in (n,α) reactions induced by 12–18 MeV neutrons on rare earth nuclei, the reactions ^{143}Nd(n,α) ^{140}Ce and ^{147,149}Sm(n,α) ^{144,146}Nd have been investigated. The spectra of the α particles emitted in the bombardment of Sm targets conform to the general trend observed in previous experiments on $A\sim150-170$ nuclei.[1] The energy distribution of these α's shows a well defined structure but its average energy dependence is reasonably well reproduced by a smooth distribution which, as it is shown in Fig. 1, is the one expected on the basis of exciton model calculations discussed in literature.[2]

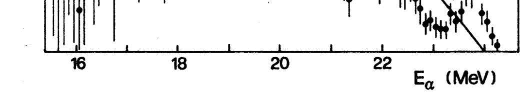

FIG. 1. Comparison between measured (black points with error bars) and calculated (full line) angle integrated spectrum of α particles from the ^{147}Sm(n,α) ^{144}Nd reaction. The theoretical curve is calculated according to the theory discussed in Ref. 2. The relevant parameters are: α particle and nucleon Fermi energies equal, respectively, to 80 and 20 MeV; $R=\phi_\alpha/g_\alpha=(1.20/A)$ MeV, for a Fermi gas model distribution of preformed α's.

On the contrary, as shown in Fig. 2(a), the energy distribution of α particles emitted in the ^{143}Nd(n,α) ^{140}Ce reaction markedly differs from the ones corresponding to neighboring nuclei: (a) final nucleus states of energy smaller than ~2.5 MeV are very weakly populated, and (b) starting from an excitation energy ~2.5 MeV, the yield of emitted α's steeply increases, reaching a maximum at approximately 4 MeV of excitation energy, and

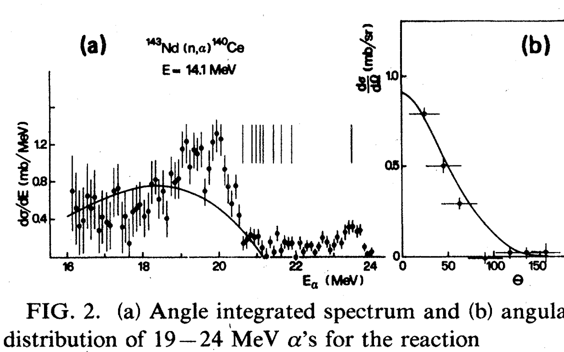

FIG. 2. (a) Angle integrated spectrum and (b) angular distribution of 19–24 MeV α's for the reaction ^{143}Nd$(n,\alpha)^{140}$Ce. The full lines represent the theoretical predictions. In (b) the calculated angular distribution corresponds to 20.5 MeV α's. The bars in the right side of part (a) indicate the lowest energy levels of residual nucleus.

thereafter it decreases quite rapidly.

This unusual behavior is easily explained as being due to the shell structure of ^{143}Nd, in the hypothesis that the mechanism responsible for α emission is the knockon of α particles preformed in the target nucleus by the incident neutron.[2] The explanation is the same as that offered to explain why, in the α decay of odd-even nuclei, excited levels of the daughter nucleus often are preferentially populated in comparison to the ground state, notwithstanding the smaller energy of emitted α's.[3]

The odd-even ^{143}Nd nucleus contains 83 neutrons and 60 protons. The 83rd neutron is expected to be in a state of energy notably greater (a few MeV) than the one of neutrons filling the major shell closing at $N=82$. One may reasonably assume that when the α particle forms in the ^{143}Nd nucleus, it is not likely to incorporate the odd 83rd neutron, but will probably consist of protons and neutrons which are already paired.[3] If this assumption is true, a residual nucleus, resulting from the knockon of a preformed α by the incident neutron, should be in an excited state of energy equal, at least, to Δ_s, the difference between the energy of the first state above the $N=82$ shell and the energy of states at the closure of the shell, whose exact value depends on the deformation of ^{143}Nd, but certainly is of the order of a few MeV. The fact that the yield is concentrated at excitation energies one or two MeV greater than Δ_s, is also easily explained if one takes into account that the dynamics of the nucleon-α interaction greatly favors the ejection of preformed α particles with energy, before emission, near the maximum allowed.

When high energy α particle is ejected, the incident neutron is captured in a low energy neutron hole state and the total excitation energy of the residual nucleus is not greatly different from Δ_s. Higher energy states will be excited when the incident neutron will be captured in states outside the $N=82$ shell, but due to the energy gap at the closure of the shell these states will be excited to an energy greater than approximately $2\Delta_s$. The energy of the corresponding α particles, in the incident neutron energy range considered, will not differ greatly from the height of the Coulomb barrier and the probability of such events will be correspondingly reduced.

The interpretation offered is substantiated by the observation that, as shown in Fig. 3, the energy distribution of the α particles emitted in the reaction ^{209}Bi(p,α) ^{206}Pb at an incident proton energy of $\sim$20 MeV, measured by Milazzo Colli *et al.*,[4]

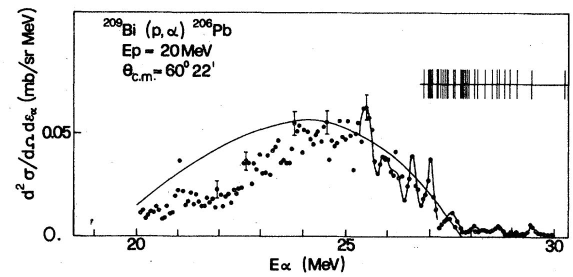

FIG. 3. Double differential cross section of α particles from the ^{209}Bi(p,α) ^{206}Pb reaction at $\Theta_{c.m.}=60°22'$. The full line represents the theoretical prediction. The bars in the upper right part of the figure indicate the lowest energy levels of residual ^{206}Pb.

also displays the same feature discussed above. The ^{209}Bi nucleus contains 126 neutrons and 83 protons, one outside the $Z=82$ major shell, and the same interpretation holds. Also, in this case, the yield of emitted α's starts to increase above Δ_s and the value of this quantity is the same as in the case of the ^{143}Nd(n,α) ^{140}Ce reaction, an indication that the gap in the sequence of neutron and proton states at the filling of the 82 nucleon magic shell should be nearly the same. Milazzo Colli *et al.* have also measured the spectra of α particles from lead isotopes. In all the cases, the α spectra extend up to nearly the ground state of residual nucleus, thus showing that the effect so clearly present in the Bi case is now absent, in agreement with the interpretation we have suggested. These authors[4] (see also Ref. 5) have also suggested that the preequilibrium emission of preformed α particles in (nucleon, α) reactions is affected by shell effects. The effect they consider is different from the one discussed here. According to these authors, the probability for the incident nucleon interacting with a preformed α is strongly reduced for magic nuclei, thus indicating a smaller *formation factor* for the α, in qualitative agreement with calculations by Mang[6] and spectroscopic factors from $(d,^6\text{Li})$ reactions as deduced by Becchetti *et al.*[7]

Present data, as well as the data of Ref. 4, in our opinion, do not indicate a reduced yield of preequilibrium α emission in nucleon bombardment of magic nuclei. In Figs. 2(a) and 3, the measured α spectra are compared to the ones calculated according to the theory discussed in Ref. 2. The theoretical calculation cannot reproduce in detail the measured spectra, since it does not take into account the disuniformities in level density of residual nuclei due to their shell structure; however, the absolute yield of emitted α's is quite reasonably estimated using approximately the same parameters which hold for nonmagic nuclei. The calculation is made using, in both cases, an effective binding energy for the α equal to $B_\alpha + \Delta_s = B_\alpha + 2.5$ MeV, according to the previous discussion. The Fermi energies of nucleons and α's have been taken to be equal to 20 and 80 MeV, respectively, and the momentum distribution of preformed α's has been assumed to be the one predicted by the Fermi gas model. The ratio R between the density of preformed α's, ϕ_α, and the single α state density g_α, was $\approx(1.81/A)$ MeV for Nd and $\approx(1.98/A)$ MeV for Bi, values $\approx 20\%$ and 30% greater than the one [$\approx(1.51/A)$ MeV] suggested in Ref. 2. This variation can be easily explained since the value of g_α for magic nuclei should be notably smaller than the one expected for nonmagic systems.

In fact, in the case of Bi, the value of R is the one expected if one assumes a percentage reduction of g_α for the near magic ^{210}Po, at $E_{\text{exc}} \approx 25$ MeV, equal to the one expected for the corresponding single nucleon state density g.[8]

Also, the comparison of α spectra from (p,α) reactions on ^{27}Al, ^{59}Co, ^{90}Zr, ^{197}Au, ^{208}Pb, and ^{232}Th at 72 MeV (Ref. 9) does not indicate a reduced yield of pre-equilibrium α's from the doubly magic ^{208}Pb. In fact, the same reaction mechanism is indicated in all the cases, since the energy and the angular distributions of the emitted α's is the same for all the nuclei, and the yield of α's from the doubly magic ^{208}Pb is greater than the one corresponding to the other nuclei considered.

[1]L. Głowacka, M. Jaskoła, J. Turkiewicz, L. Zemło, M. Kozłowski, and W. Osakiewicz, Nucl. Phys. A244, 117 (1975).

[2]E. Gadioli, E. Gadioli Erba, I. Iori, and L. Zetta, J. Phys. G 6, 1391 (1980).

[3]M. A. Preston, *Physics of the Nucleus* (Addison-Wesley, Reading, Mass., 1962), Chap. 14.

[4]L. Milazzo Colli, M. G. Braga Marcazzan, and M. Milazzo, Nuovo Cimento A30, 632 (1975).

[5]R. Bonetti, L. Milazzo Colli, and G. D. Sassi, J. Phys. G 3, 1111 (1977).

[6]H. J. Mang, Annu. Rev. Nucl. Sci. 14, 1 (1964).

[7]F. D. Becchetti, L. T. Chua, J. Janecke, and A. M. Van der Molen, Phys. Rev. Lett. 34, 225 (1975).

[8]E. Gadioli, I. Iori, N. Molho, and L. Zetta, Nucl. Phys. A138, 321 (1969).

[9]Z. Lewandowski, E. Loeffler, R. Wagner, H. H. Mueller, W. Reichart, P. Schober, E. Gadioli, and E. Gadioli Erba, Lett. Nuovo Cimento 28, 15 (1980).