(n, α) REACTIONS ON HEAVY NUCLEI INDUCED BY 14.2 MeV NEUTRONS

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The energy spectra of alpha particles from (n, α) reactions on ^{122}Te, ^{139}La, ^{159}Tb, ^{160}Dy, ^{161}Dy, ^{163}Dy, ^{164}Dy, ^{166}Er, ^{168}Er and ^{169}Tm induced by 14.2 MeV neutrons have been measured using the semiconductor detector technique. The analysis of the energy spectra leads to results which imply that the evaporation theory is inadequate to describe the investigated reactions. The shapes of the experimental spectra suggest the presence of strong direct effects.

Introduction

The spectrometry of charged particles emitted in neutron induced reactions is one of the more difficult problems in experimental nuclear physics. Especially large difficulties are connected with alpha particle spectra measurements in (n, α) reactions induced by fast neutrons in heavy nuclei. Difficulties are mainly due to the relatively low cross-sections of these reactions, the impossibility of getting alphas out of thick targets and serious background problems, typical of fast neutron experiments. For these reasons the experimental data gathered up to now are scarce and suffer rather large errors.

The application of semiconductor detectors gave a possibility of studying energy spectra of alpha particles with more precission than that obtained with the methods used in earlier works. Some years ago, we initiated investigations of the (n, α) reactions induced by 14 MeV neutrons in heavy nuclei ($A > 120$). The present paper gives a brief summary of our results. The energy distributions of alpha particles from 14 MeV (n, α) reactions in ^{122}Te, ^{139}La, ^{159}Tb, ^{160}Dy, ^{161}Dy, ^{163}Dy, ^{164}Dy, ^{166}Er, ^{168}Er and ^{169}Tm have been measured. The analysis of these spectra seem to indicate that the evaporation theory is inadequate for describing all of the investigated reactions and that direct effects with strong excitation of the single neutron levels in the residual nucleus are present. The (n, α) reactions were also used as a tool for investigating the cluster structure of the nuclear surface [1, 2].

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Experimental method

The neutrons of energy about 14.2 MeV were produced in the $^{3}H(d, n)^{4}He$ reaction with deuterons accelerated up to 500 keV in the "LECH" Van de Graaff accelerator [3]. The neutron energy spread due to the deuteron energy loss in the T–Ti target and geometrical conditions was about ± 150 keV. The neutron flux incident to the investigated targets was monitored by counting the recoil protons from a thin polyethylene foil. Recoil protons were registered by a CsI(Tl) scintillator followed by a photomultiplier and standard electronics. The accuracy of neutron monitoring was better than 2%.

A sample od ^{122}Te was obtained by evaporation in a nitrogen atmoshpere on thick aluminium backing. The other targets were made of oxides and deposited on the thick carbon backings by means of sedimentation from suspensions in isopropyl alcohol which had been slowly evaporated under an infrared lamp.

A description of the investigated targets is given in Table I.

TABLE I

Target mass	Isotopic abundance	Chemical compound	Backing	Thickness (mg/cm^2)
^{122}Ta	80.4	Ta	aluminium	4.0
^{139}La	99.91	La_2O_3	carbon	5.4
^{159}Tb	100	Tb_4O_7	carbon	5.2
^{160}Dy	77.6	Dy_2O_3	carbon	3.9
^{161}Dy	94.2	Dy_2O_3	carbon	4.4
^{163}Dy	92.8	Dy_2O_3	carbon	4.2
^{164}Dy	97.8	Dy_2O_3	carbon	4.9
^{166}Er	95.8	Er_2O_3	aluminium	3.1
^{168}Er	95.6	Er_2O_3	aluminium	6.2
^{169}Tm	100	Tm_2O_3	aluminium	8.8

The alpha particles were detected by n-type surface barrier silicon detectors of 15 mm diameter.

The experimental arrangement used in this work is shown in Fig. 1. The distance between the neutron source and the target was 10–20 cm, and that between the target and detector was 1 cm. The targets were set a $\theta = 90°$ relative to the incident deuteron beam. In order to reduce the time of measurements four spectrometers working simultaneously with alternate changes of targets were used. The detectors and investigated targets were housed in a vacuum chamber lined with graphite. This ensured a reduction of the background due to reactions produced in the walls of the chamber. The background pulses in the investigated energy region (15–22 MeV) were mainly due to the pile-up of pulses caused in the silicon detector by incident neutrons. The charged particles from the (n, p), (n, d), (n, t) and (n, α) reactions in the silicon isotopes give a background of up to about 14 MeV, but due to pile-up effects there are background pulses in the higher energy region. In order to keep this background at a reasonable low level the neutron flux was limited to about 5×10^{8} neutrons sec^{-1} sr^{-1}.

The background was measured by replacing the investigated target by its backing.

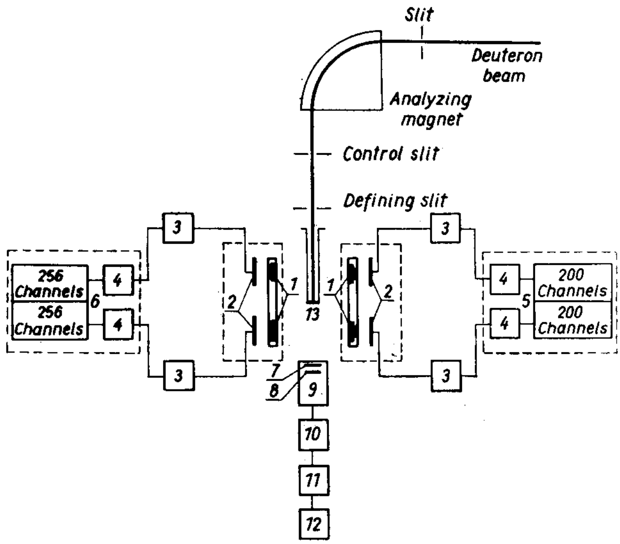

Fig. 1. Schematic diagram of the experimental arrangement. *1* — investigated target, *2* — silicon detector, *3* — charge sensitive preamplifier, *4* — linear amplifier, *5* — "SA 40B — Intertechnique" multichannel analyser, *6* — multichannel analyser, *7* — polyethylene target, *8* — thin csI(Tl) scintillator, *9* — photomultiplier, *10* — linear amplifier, *11* — discriminator, *12* — scaler, *13* — tritium target T–Ti

The pulses from the detectors were amplified by charge sensitive preamplifiers, followed by linear amplifiers and then analysed by multichannel analysers. The energy scale calibrations for each spectrometer were performed with employment of alphas from ThC (6.05 MeV), ThC′ (8.78 MeV) and from the reactions $^{28}Si(n, \alpha)$ ^{25}Mg and $^{29}Si(n, \alpha_0)^{26}Mg$ produced in the detectors by incident neutrons.

During the measurements the energy scale was continuously checked with alpha-particles from $^{29}Si(n, \alpha_0)^{26}Mg$ reaction. The long time stabilities of the spectrometers were better than 2%.

Results and discussion

The results of the alpha-particle spectra measurements are shown in Figs 2 and 3. All spectra were measured for forward angles ($0° \pm 60°$). The error bars in the figures refer to statistical errors only. Corrections accounting for the energy loss in the target were calculated on the basis of tables given by Williamson *et al.* [4].

A characteristic feature of the observed spectra is, similarly as in those obtained for other (n, α) reactions [5–9], the sharp initial rise and the broad maximum corresponding to the transitions to the excited states of the residual nuclei. For all investigated reactions the analysis based on statistical theory have been performed by applying the Weisskopf-Ewing formula. The values used for inverse cross-sections were taken from the calculations of Huizenga and Igo [10]. The energy dependence of the level density was taken in the familiar form, $\varrho(U) \propto U^{-2} \exp(2\sqrt{aU})$, with the level density parameter "a" taken from Erba *et al.* [11]. The a-values obtained from the statistical analysis of the investigated reactions

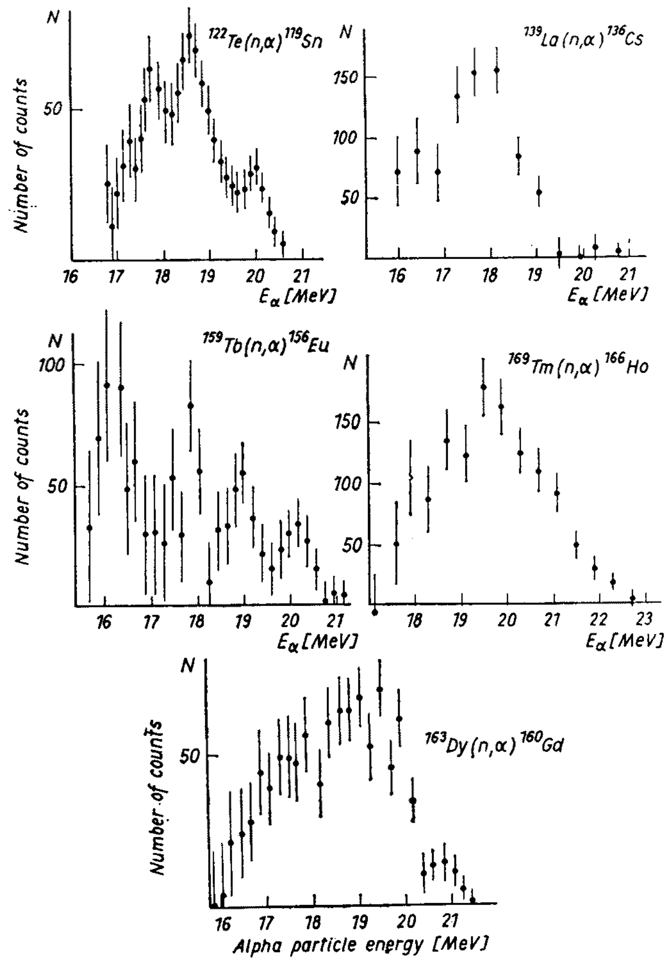

Fig. 2. The experimental alpha particle spectra from the ^{122}Te(n, α) ^{119}Sn, ^{139}La(n, α) ^{136}Cs, ^{159}Tb(n, α) ^{156}Eu, ^{169}Tm(n, α) ^{166}Ho and ^{163}Dy(n, α) ^{160}Gd reactions

are much smaller than those given by Erba *et al.* [11]. A comparison of these a-values is given in Table II.

In addition, the experimental spectra are shifted considerably (about 5 MeV) towards higher energies in comparison with the predictions of the statistical theory. Both these facts suggest the presence of strong direct processes in the investigated reactions. Similar conclusions concerning the direct mechanism governing the (n, α) reactions on heavy nuclei have been drawn is several studies made by different authors [5–9].

If the direct interaction mechanism, with alpha particles emitted mainly in a knock-out process, dominates in the investigated reactions, it seems reasonable to expect the single neutron levels in the odd-neutron final nucleus to be preferentially excited. To interpret the observed alpha particle spectrum from the ^{159}Tb$(n, \alpha)^{156}$Eu reaction, a strong excitation of such levels was assumed [12].

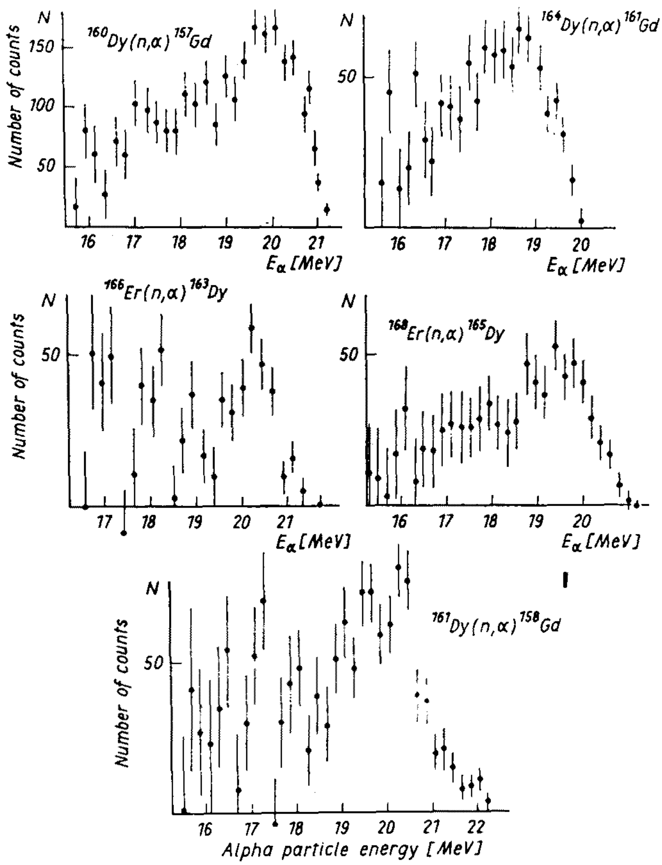

Fig. 3. The experimental alpha particle spectra from the $^{160}Dy(n,\alpha)$ ^{157}Gd, $^{164}Dy(n,\alpha)$ ^{161}Gd, $^{166}Er(n,\alpha)^{163}Dy$, $^{168}Er(n,\alpha)$ ^{165}Dy and $^{161}Dy(n,\alpha)$ ^{158}Gd reactions

TABLE II

Nucleus	Level density parameter "a" (MeV^{-1})	
	present work	Erba *et al.*
^{119}Sn	5.41	19.65
^{136}Cs	3.25	16.36
^{156}Eu	7.68	24.48
^{157}Gd	4.93	20.17
^{158}Gd	6.25	23.49
^{160}Gd	5.71	22.50
^{161}Gd	4.97	22.83
^{163}Dy	3.97	20.20
^{165}Dy	5.28	20.20
^{166}Ho	6.45	20.18

A similar enhancement of single particle excitations has been observed in other (n, α) reactions [8], [13], [14], [15] and in several (n, p) reactions [16], [17]. Bloch *et al.* [18] have also shown that in certain reactions induced by charged particles the relatively simple states of the residual nucleus are strongly excited. These states are successfully described by the shell model.

The strong excitation of single-neutron levels suggests that in the investigated reactions the knock-out process of alpha substructures from the nuclear surface plays an important role. The pick-up mechanism of ^{3}He substructures would not lead to the especially strong excitations of single-neutron levels.

This conclusion supports the validity of the assumption made in the investigation of the nuclear surface by means of (n, α) reactions [1] where the knock-out mechanism of alpha substructures was assumed to be dominant.

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