Absolute cross sections and isomeric cross-section ratios for the ^{148}Nd(d,2n), ^{148}Nd(p,n), and ^{146}Nd(α,pn) reactions producing the isomeric pair ^{148}Pm^{m,g}

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Excitation functions and isomeric cross-section ratios were determined for the ^{148}Nd(d,2n), ^{148}Nd(p,n), and ^{146}Nd(α,pn) reactions producing the isomeric pair ^{148}Pm^{m,g}. The experimental isomer ratios of 41.3-day ^{148}Pm^{m} (6−) and 5.37-day ^{148}Pm^{g} (1−) were compared with statistical model calculations wherein spin cutoff parameters σ were obtained assuming that σ is either independent or varying with excitation energy. The spin cutoff parameters and the effective moments of inertia deduced from these calculations were $\sigma = 4.2$ and $\theta = 0.70\theta_r$, respectively, for the reaction ^{148}Nd(p,n) ^{148}Pm^{m,g}, and $\sigma = 3.9$ and $\theta = 0.65\theta_r$, respectively, for the reaction ^{148}Nd(d,2n) ^{148}Pm^{m,g}.

[NUCLEAR REACTIONS ^{148}Nd(p,n), (d,2n), ^{146}Nd(α,pn), E_p = 9–45 MeV, E_d = 6.5–52 MeV, E_α = 29–59 MeV; measured $\sigma(E)$, isomer ratio; deduced spin cutoff parameter, moment of inertia.]

I. INTRODUCTION

In the past several years numerous isomeric cross-section ratios σ_h/σ_l, where σ_h and σ_l are the cross sections for the production of the high-spin and low-spin isomers of the residual nucleus, respectively, have been determined. A number of authors have compared their experimental results with theoretical calculations of isomer ratios by means of the formalism of Huizenga and Vandenbosch,[1,2] which is based on the statistical model. This formalism gives a qualitative description of the final population of the isomeric and the ground state. It was applied to (n,γ) reactions,[3-6] (n,2n) reactions,[7-17] and charged particle induced reactions.[18-32] The same formalism for calculating isomer ratios for nuclear reactions in which the initial angular momentum distribution is known has also been applied to extract information about the intrinsic angular momenta of primary fission fragments.[33] These calculations require the knowledge of the value of the spin cutoff parameter σ which characterizes the angular momentum dependence of the nuclear level density of the fragments in addition to the number of neutrons and γ rays emitted by the fragments. We have measured the isomer ratio of ^{148}Pm for thermal neutron induced fission of ^{233}U and ^{235}U and for fission of ^{232}Th by ^{4}He ions.[34] To obtain a reliable value of the spin cutoff parameter for the calculations of the average intrinsic angular momentum of the primary fission fragments on the basis of the isomer ratio ^{148}Pm^{m}(6−)/^{148}Pm^{g}(1−) in the fission reactions we decided to undertake also a study of the same isomer ratio from the ^{148}Nd(p,n) and ^{148}Nd(d,2n) reactions. The fission product nuclei ^{148}Pm^{m} and ^{148}Pm^{g} are formed by neutron and/or γ-ray emission of the primary fragments ^{148}Pm, ^{149}Pm, and ^{150}Pm. The same nuclei with similar excitation energies can be produced through the reactions ^{148}Nd(p,n), ^{148}Pm^{m,g}, and ^{148}Nd(d,2n)^{148}Pm^{m,g}. In the first reaction the compound nucleus ^{149}Pm is formed; in the second one, the compound nucleus ^{150}Pm. The initial spin distribution of these nuclei can be calculated when they are formed through these reactions. The root-mean-square angular momentum $(\overline{J^2})^{1/2}$ of the compound nucleus ^{149}Pm formed through proton bombardment of ^{148}Nd increases from 2.1 to 4.5$\hbar$ for proton energies of 8–20 MeV. The compound nuclei ^{150}Pm which are formed through deuteron bombardment of ^{148}Nd have a root-mean-square angular momentum in the range of 3–9$\hbar$ for deuterons of 8–20 MeV. The average spin of the ^{149}Pm and ^{150}Pm nuclei are therefore of the same magnitude as the one of primary fission fragments in thermal neutron induced fission of ^{235}U which have been determined to be about 4–10$\hbar$.[34]

The deexcitation process of the ^{150}Pm and ^{149}Pm nuclei as fission fragments by emission of neutrons and γ rays yielding the ^{148}Pm^{m,g} isomeric pair can therefore be compared with the deexcitation process of the same nuclei produced by proton and deuteron bombardment of ^{148}Nd. In this way one should obtain a reliable spin cutoff parameter for the fission calculations giving results which are less subject to the particular assumption made in the statistical model calculations.

In the present paper we report the experimental results on absolute cross sections and isomeric cross-section ratios for the reaction ^{148}Nd(p,n)-^{148}Pm^{m,g} for E_p=9.0–44.9 MeV, the reaction ^{148}Nd($d,2n$)^{148}Pm^{m,g} for E_d=6.5–51.9 MeV, and the reaction ^{146}Nd(α,pn)^{148}Pm^{m,g} for E_α=28.6–59.1 MeV. With the assumption that the reactions proceed primarily by compound-nucleus formation, at least at low excitation energies for which the contribution of direct interactions could be neglected, the isomer ratios ^{148}Pm^m(6–)/^{148}Pm^g(1–) for the ^{148}Nd(p,n) and ^{148}Nd($d,2n$) reactions were calculated on the basis of the Huizenga-Vandenbosch formalism.[1,2] In these calculations the spin cutoff parameter was either assumed to be independent of excitation energy or it was allowed to vary as a function of excitation energy. The calculated isomeric cross sections were compared with the experimental ones to determine the spin cutoff parameter.

II. EXPERIMENTAL PROCEDURE

Targets of isotopically enriched ^{148}Nd and ^{146}Nd were prepared by electrodeposition from isopropanol solution.[35] Deposits of 250–450 μg/cm^2 were made upon 0.012-mm thick aluminium. The isotopic purity of the targets was 95.44% ^{148}Nd and 97.46% ^{146}Nd as given by the Isotopes Division of Oak Ridge National Laboratory, where the isotopes were purchased. The Nd layers were protected against loss by covering them with another 0.012-mm thick aluminium foil. Four or five targets were placed between aluminium degrading foils of known thickness. The foil stack was placed in a water-cooled target holder which served as a Faraday cup to measure the current of the charged particles on the targets so that absolute cross sections could be determined. The energy of the incident charged particles was calculated for each target layer by means of the range-energy tables of Williamson, Boujot, and J. Picard.[36] Typical beam currents were about 2–3 μA, and targets were irradiated for a length of time of from 6 to 10 h.

The irradiations with protons were performed at the Jülich isochronous cyclotron, the irradiations with deuterons and ^{4}He ions at the Karlsruhe isochronous cyclotron. Two deuteron irradiations at low energies (<16 MeV) were carried out at the Munich MP tandem accelerator.

The amounts of ^{148}Pm^m and ^{148}Pm^g produced in the reactions were determined without any chemical purification after a cooling time of 4–5 days by γ spectroscopy with a 25-cm^3 Ge(Li) detector in conjunction with a Nuclear Data 4000 multichannel analyzer. The detector resolution was 2.3 keV for the 1.33-MeV γ ray of ^{60}Co. The absolute photopeak efficiency of the detector was determined using a set of IAEA standard sources.

The nuclear data used to calculate the abundance of the radionuclides are given in Table I. In these calculations one must take into account that 4.6% of the ^{148}Pm^m nuclei decay by isomeric transition.[38]

For calculating the absolute cross sections the exact amount of Nd on the targets has to be known. Because the conditions of the electrodeposition procedure cannot be reproduced unambiguously, the amount of Nd on the targets was determined by neutron activation analysis after the charged particle irradiation and measurement of the Pm isomers. The neutron irradiations were carried out in the Munich research reactor. The amount of ^{148}Nd was determined by evaluating the 114.6 keV photopeak of 1.73-h ^{149}Nd. For the determination of ^{146}Nd the 531 keV γ line of 10.98-h ^{147}Nd was measured. Solutions of known Nd content were used as comparator samples.

III. EXPERIMENTAL RESULTS

The observed activities were converted to cross sections by the usual equations. The absolute cross sections and isomer ratios measured in the present work are plotted in Figs. 1–7. In Figs. 1, 2, and 3, the lines drawn through the data are to guide the eye. The excitation functions are given as functions of $E_{\text{proj}} - E_{\text{thres}}$, where E_{proj} is the kinetic energy of the projectile in the laboratory system and E_{thres} is the threshold energy. Thus the influence of the threshold energy on the position of the excitation functions is canceled and one should begin approximately at zero energy. Besides, a direct comparison with systematics of excitation functions[40] will be possible. The threshold energies for the three reactions are: 1.3 MeV for ^{148}Nd(p,n), 3.5 MeV for ^{148}Nd($d,2n$), and 17.5 MeV for ^{146}Nd(α,pn).

TABLE I. Nuclear data used in the analysis of experimental data.

Nuclide	Spin-parity	Half-life	γ-ray energy (keV)	Absolute intensity
^{148}Pm^m	6–	41.3±0.1 day [a]	629.9 [b]	89.8±1.7 [b]
			725.6	32.5±0.7
^{148}Pm^g	1–	5.37±0.009 day [c]	1465.1 [b]	24.3±2.5 [b]

[a] Reference 37. [b] Reference 38. [c] Reference 39.

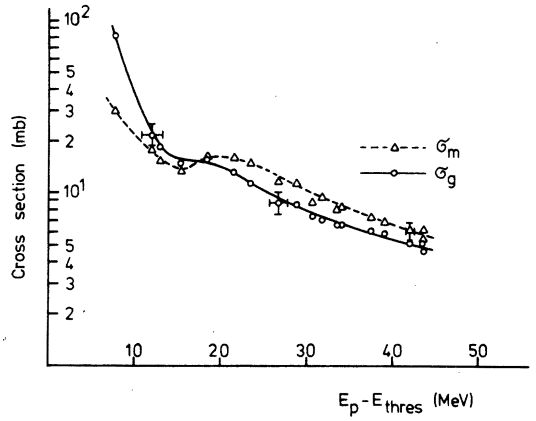

FIG. 1. Absolute cross sections of the reaction ^{148}Nd$(p,n)^{148}$Pm^{m,g}. The lines drawn through the data are to guide the eye.

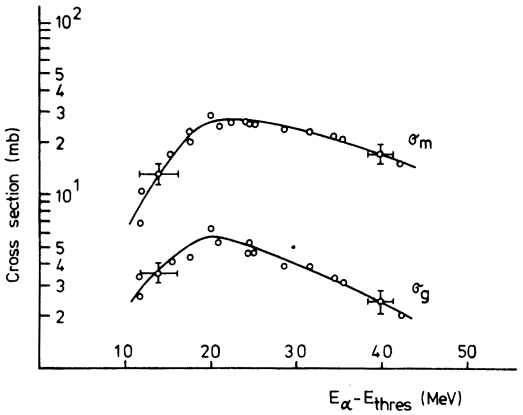

FIG. 3. Absolute cross sections of the reaction ^{146}Nd$(\alpha,pn)^{148}$Pm^{m,g}. The lines drawn through the data are to guide the eye.

The experimental errors shown in the figures were obtained by compounding the estimated errors of all measured quantities. The uncertainty in the absolute value of the cross sections is less than 15%. The uncertainty in the projectile energy depends on the position of the target layer in the foil stack. It varies between 1 and 10%.

IV. STATISTICAL MODEL CALCULATIONS

The figures show that as the projectile energy and thus the angular momentum in the compound nucleus is increased, the relative yield of the high spin isomer increases. This results in a displacement of the excitation functions for the reaction leading to ^{148}Pm^m relative to the one leading to ^{148}Pm^g, which is especially obvious in Fig. 2. The breaks in the steady increase of the isomer ratio for the ^{148}Nd(p,n) reaction at proton energies

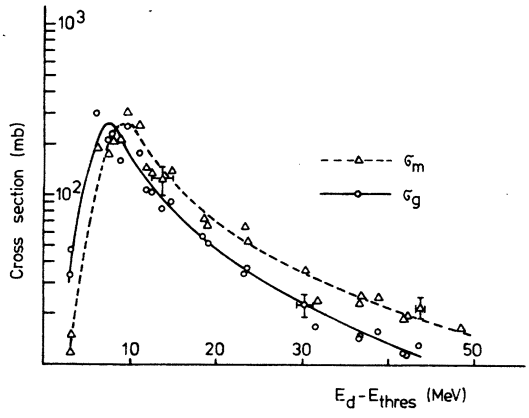

FIG. 2. Absolute cross sections of the reaction ^{148}Nd$(d,2n)^{148}$Pm^{m,g}. The lines drawn through the data are to guide the eye.

above 25 MeV and for the ^{148}Nd$(d,2n)$ reaction at deuteron energies above 15 MeV indicate that only above 25 and 15 MeV, respectively, the contribution of direct reaction mechanisms in which the angular momentum transfer to the residual nucleus is much less than in compound nucleus reactions cannot be neglected.

Verdieck and Miller[41] have shown that for the ^{142}Ce$(p,n)^{142}$Pr reaction the cross sections calculated according to the compound-nucleus mechanism are in agreement with the experimental results except in the high-energy tail above 18 MeV. Pement and Wolke[42] conclude from their comparison of excitation functions for $(d,2n)$ reactions with the predictions of the compound-statistical theory that all $(d,2n)$ reactions above $A=47$ up to 15 or 20 MeV proceed predominantly if not entirely by compound-nucleus formation followed by the statistical evaporation of two neutrons. We conclude therefore that compound-nucleus formation predominates in the low energy regions of the ^{148}Nd(p,n) and ^{148}Nd$(d,2n)$ reactions, and that direct interaction mechanisms can be neglected.

According to the method proposed by Huizenga and Vandenbosch,[1,2] spin cutoff parameters σ were deduced from the experimental isomeric cross-section ratios. The method is based on the statistical theory and has been described extensively elsewhere.[1-3,13,18,20,43] Therefore only a brief outline of the single steps of the procedure is given here, together with a discussion of the parameters used in the calculations. The calculations were performed with the computer program of Hafner, Huizenga, and Vandenbosch.[43] The effects of competition on spin distribution and isomer ratio due to deexcitation modes other than the one of interest have been neglected.

The spin dependence of the nuclear level density

$\rho(E,J)$ is assumed to be given by

$$\rho(J,E)=\rho(0,E)(2J+1)\exp[-J(J+1)/2\sigma^2] ,$$

where $\rho(0,E)$ is the density of levels of zero angular momentum and at excitation energy E. The spin cutoff parameter characterizes the distribution function. Quantitative information about the parameter σ can be obtained[1,2] from a calculation of the isomeric cross-section ratio under the assumption that the reaction can be described as a statistical process and takes place through three independent steps: Compound-nucleus formation, neutron evaporation, and γ-ray deexcitation of the final nucleus which populates either the isomeric or the ground state. The well-known calculations[1,2,43] give at each step of the reaction the spin distribution of the system and the relative population of the two final states is then calculated. The values of several parameters have to be known to carry out the calculations:

Transmission coefficients. The barrier transmission coefficients for the incoming projectile have been taken from the optical model calculations of Melkanoff, Sawado, and Cindra[44] for deuterons and of Mani, Melkanoff, and Iori[45] for protons. The transmission coefficients for the outgoing neutrons were taken from the optical model values calculated by Lindner.[46]

Energy of the emitted neutrons. The excitation energy of the compound nucleus E_c was obtained from the relation

$$E_c=E_{c.m.}+Q ,$$

where $E_{c.m.}$ is the kinetic energy of the projectile in the center-of-mass system and Q is the Q value for the formation of the compound nucleus. The latter were taken from Ref. 47. The average kinetic energy of the emitted neutrons E_n was assumed to be twice the nuclear temperature T (Ref. 18):

$$\overline{E_n}=2T ,$$

where T is the nuclear temperature of the residual nucleus which is linked with the excitation energy[48]

$$E-\delta=aT^2-4T ,$$

δ represents the pairing correction which was taken from Ref. 49. A value of $a=21.3$ MeV^{-1} was used for the level density parameter for all Pm nuclei under consideration as reported by Baba.[50]

The average energy of the residual nucleus E_r is given by

$$E_r=E_c-\overline{E_n}-B_n .$$

The binding energy of the outgoing neutrons were taken from Ref. 47.

Number, energy, and multipolarity of the emitted γ rays. After neutron emission is energetically forbidden γ-ray emission occurs. It was assumed that the average number and the energy of the γ rays depend on the residual excitation energy following neutron emission. The energies of the γ rays were obtained by successively applying the relation[51]

$$E_\gamma=4\left(\frac{E}{a}-\frac{5}{a^2}\right)^{1/2} ,$$

where E is the excitation energy after the last emission of a neutron or a γ ray. The excitation energy at which the final isomer-deciding γ ray is emitted was chosen by the prescription of Ref. 51 using a cutoff interval of 2.0–1.0 MeV.

In most of the statistical-model calculations of isomer ratios only deexcitations by dipole-radiation cascades were assumed. There are at present no decisive experimental results which give the relative contribution of dipole and quadrupole radiation to the γ cascade. The inclusion of quadrupole transitions may improve the agreement considerably between experimental and calculated isomer ratios.[27,52-55] It seemed to us therefore reasonable to assume that quadrupole transitions play an important role in the deexcitation process. The analysis showed that a quadrupole admixture of 10% is required for the optimum interpretation of our experimental isomeric cross-section ratios for the ^{148}Nd(p,n) and ^{148}Nd$(d,2n)$ reactions.

Spin cutoff parameter. In the present work the spin cutoff parameter σ was left as free parameter which was varied so as to determine the value for which best agreement between the experimental results and the statistical-model calculations exists. Two kind of calculations were made; one in which σ is considered constant and independent of excitation energy. A number of investigators have assumed constant values of σ and have obtained values for σ ranging from 2 through 5. In another calculation σ was allowed to vary as a function of excitation energy. The spin cutoff parameter is related to the nuclear moment of inertia θ[56] and the thermodynamic temperature by

$$\sigma^2=\theta t/\hbar^2 .$$

The energy dependence of σ is introduced by t, which for the shifted Fermi gas model is linked to the excitation energy E by the relation[19,48,51]

$$E-\delta=at^2-t .$$

A nuclear moment of inertia, however, which corresponds to a fraction of the rigid body θ_r is normally required to fit the calculated isomer ratios to the ones observed experimentally.[19,21,23,25,32,51] Therefore, the moment of inertia was arbitrarily reduced to the value which gives the best agreement with the experimental results.

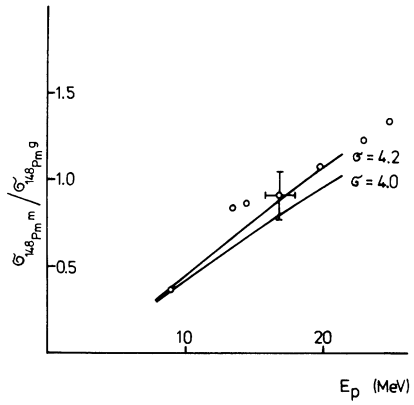

FIG. 4. Comparison of experimental (open circles) and calculated isomeric cross-section ratios $\sigma_{^{148}Pm^m}/\sigma_{^{148}Pm^g}$ for the $^{148}Nd(p,n)$ reaction. The solid line curves were calculated for two values of the spin cutoff parameter σ assuming that σ is independent of excitation energy.

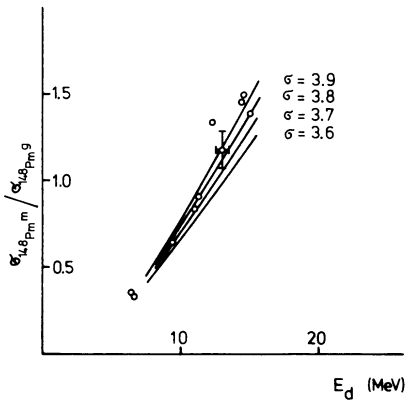

FIG. 6. Comparison of experimental (open circles) and calculated isomeric cross-section ratios $\sigma_{^{148}Pm^m}/\sigma_{^{148}Pm^g}$ for the $^{148}Nd(d,2n)$ reaction. The solid line curves were calculated for different values of the spin cutoff parameter σ, assuming that σ is independent of excitation energy.

V. COMPARISON OF EXPERIMENTAL RESULTS WITH CALCULATIONS

The results calculated on the basis of the shifted Fermi gas model with the various parameters as discussed in the preceding sections are compared with experimental values for the two reactions $^{148}Nd(p,n)^{148}Pm^{m,g}$ and $^{148}Nd(d,2n)^{148}Pm^{m,g}$ in Figs. 4–7. The calculations were restricted to a projectile bombardment energy region of 8–20 MeV for protons and 8–15 MeV for deuterons. In this energy region the influence of direct reaction mechanisms can still be neglected. Besides this range of excitation energy of the compound nuclei ^{149}Pm and ^{150}Pm agrees with that of the primary fission fragments ^{149}Pm and ^{150}Pm.

Figure 4 shows the results for the $^{148}Nd(p,n)$ $^{148}Pm^{m,g}$ reaction by using a constant spin cutoff parameter independent of excitation energy. A value of $\sigma = 4.2$ gives the best fit to the experimental data. The isomer ratios calculated with an energy dependent spin cutoff parameter are shown in Fig. 5 for the same reaction. Results with values of θ_r, $0.7\theta_r$, and $0.5\theta_r$ for the nuclear moment of inertia are shown. Best agreement was obtained with a value of $\theta = 0.7\theta_r$. The calculations with an energy independent spin cutoff parameter for the $^{148}Nd(d,2n)$ $^{148}Pm^{m,g}$ reaction are shown in Fig. 6 with values for σ of 3.6 to 3.9. A value of $\sigma = 3.9$ is required to produce agreement between

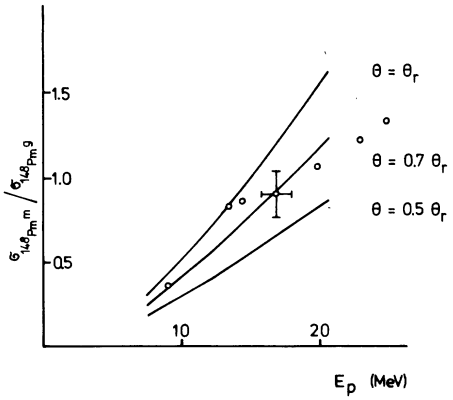

FIG. 5. Comparison of experimental (open circles) and calculated isomeric cross-section ratios $\sigma_{^{148}Pm^m}/\sigma_{^{148}Pm^g}$ for the $^{148}Nd(p,n)$ reaction. The solid line curves were calculated for three values of the nuclear moment of inertia $-\theta$.

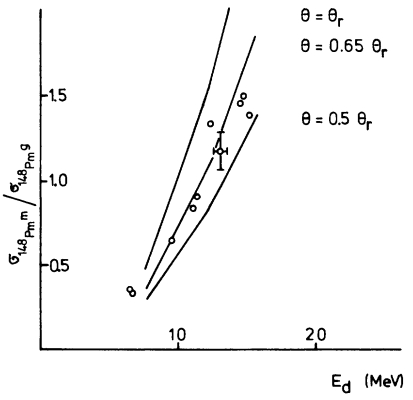

FIG. 7. Comparison of experimental (open circles) and calculated isomeric cross-section ratios $\sigma_{^{148}Pm^m}/\sigma_{^{148}Pm^g}$ for the $^{148}Nd(d,2n)$ reaction. The solid line curves were calculated for three values of the nuclear moment of inertia $-\theta$.

the calculated and experimental isomer ratios. A reduction of the nuclear moment of inertia to $\theta = 0.65\,\theta_r$ is required to fit the experimental isomer ratios in the calculations for the ^{148}Nd$(d,2n)$-^{148}Pm^{m,g} reaction using an energy dependent σ (Fig. 7). The results of the statistical-model analysis for the low energy region of the ^{148}Nd-$(p,n)^{148}$Pm^{m,g} and ^{148}Nd$(d,2n)^{148}$Pm^{m,g} reactions are summarized in Table II.

TABLE II. Spin cutoff parameters and effective moment of inertia from statistical-model calculations for the reactions ^{148}Nd$(p,n)^{148}$Pm^{m,g} and ^{148}Nd$(d,2n)^{148}$Pm^{m,g}.

Reaction	Compound nucleus	σ = const	$\sigma = f(E)$
^{148}Nd$(p,n)^{148}$Pm^{m,g}	^{149}Pm	4.2	$\theta = 0.70\theta_r$
^{148}Nd$(d,2n)^{148}$Pm^{m,g}	^{150}Pm	3.9	$\theta = 0.65\theta_r$

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