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Карнаухов В.А. **E7 - 10834**

О поляризационных эффектах в реакциях с тяжелыми ионами

Рассматривается распад поляризованного составного ядра с высоким угловым моментом. Используются известные результаты о форме вращающегося составного ядра. Рассчитывается высота кулоновского барьера для заряженной частицы, вылетающей в направлении осей динамической деформации. Оценивается степень поляризации испаряющихся нейтронов. В качестве способа получения поляризованных вращающихся ядер рассматриваются реакции передачи (частичное слияние) с регистрацией фрагмента с бомбардирующего иона.

Работа выполнена в Лаборатории ядерных реакций ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1977

Karnaukhov V.A. **E7 - 10834**

On Polarization Effects in the Reactions Induced by Heavy Ions

The decay of a polarized compound nucleus with a high angular momentum is considered. The calculations have been performed for the Coulomb potential on the surface of the dynamically deformed rotating nucleus with sharp edge . The known results on the shape of the rotating nucleus obtained in the framework of the liquid-drop model have been used. The polarization degree is estimated for neutrons evaporated by the polarized nucleus with a high angular momentum. The multinucleon transfer reactions (partial fusion) with light fragment detection are considered as a tool for the production of a high spin polarized nuclei.

The investigation has been performed at the Laboratory of Nuclear Reactions, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna 1977

INTRODUCTION

Heavy ion induced reactions give unique possibilities for investigating the properties of excited nuclei with a high angular momentum. Compound nuclei formed by the complete fusion of interacting nuclei have the angular momentum distributed over a wide range from 0 to some I_{max} with zero projection to the beam direction. Angular momentum projections to the axis perpendicular to the beam direction range from $-I_{max}$ to $+I_{max}$. This leads to averaging and, consequently, to decreasing all the effects connected with the rotation of the compound nucleus.

As has been noted in ref. [1], the new experimental possibilities in the studies of the decay of rotating compound nuclei appear if one uses partial fusion reactions (multinucleon transfer)*.

$$^{A_p}Z_p + {}^{A}Z \to {}^{A_c}Z_c^* + {}^{A_1}Z_1 , \qquad (1)$$

*A comprehensive review of experimental data on the multinucleon transfer reactions has been given by V.Volkov in ref. [2] and J.Galin in ref. [3] .

where $Z_c = Z + Z_2$, $A_c = A + A_2$, $Z_2 = Z_p - Z_1$, and $A_2 = A_p - A_1$.

The registration of the projectile fragment ($^{A_1}Z_1$) defines the reaction plane. It can be concluded from a classical consideration, that the angular momentum of the residual compound nucleus ($^{A_c}Z^*_c$) should be directed perpendicularly to the reaction plane. This means that it is a tool to produce polarized rotating excited nuclei. It should be expected that the dispersion of the spin values of compound nuclei ($^{A_c}Z^*_c$) will be rather small for the given energy and the emission angle of the $^{A_1}Z_1$-fragment. The reasons for that are as follows: i) the reactions of type (1) take place in the peripheral collisions of interacting nuclei and the range of impact parameters is relatively small, ii) the nucleon Fermi-motion of the captured fragment ($^{A_2}Z_2$) is significantly averaged, providing that $A_2 \gg 1$. As an estimate of the spin value of the $^{A_c}Z^*_c$-compound nucleus, the maximum angular momentum produced in the complete fusion of the $^{A_2}Z_2$ and ^{A}Z nuclei can be taken.

Recently F.Pougheon et al.[4,5] have obtained a direct experimental evidence for the strong polarization of $^{20}Ne^*$ produced by the $^{16}O(^{16}O, ^{12}C)$ $^{20}Ne^*$ reaction. The reaction plane was defined by registering the ^{12}C - fragment. The decay of the following $^{20}Ne^*$ states was investigated: 3^-(7.17 MeV), 5^-(8.45 MeV), 6^+(8.79 MeV), and 5^-(10.25 MeV). These states decay through α-particle emission: $^{20}Ne^* \to {}^{16}O + \alpha$. The angular distributions of ^{16}O were measured in the reaction plane and in the plane perpendicular to the reaction one including the recoil direction. The correlation functions obtained are close to the expected ones according to the classical model with the mixture of trajectories, corresponding to the positive and negative θ-deflection angles of ^{12}C. The main contribution belongs to the positive deflection angle. It has been found for $\theta = 20.5°$ that the weight factor for the maximum negative projection of the $^{20}Ne^*$-spin on the quantization axis (which is perpendicular to the reaction plane) is about 90% for all levels investigated. These data are in strict contradiction with DWBA calculations, which predict isotropical spin distribution in the plane perpendicular to the recoil direction.

Obviously, the semi-classical approximation is even more adequate for the reactions with the transfer of heavier fragments than α-particle.

The investigation of the decay of the polarized compound nuclei with a high spin value promises new information of a different kind. First of all, it concerns the dynamic deformation of rotating nuclei. In the next section we consider the Coulomb potentials on the surface of the rotating nucleus and the possibilities of obtaining the experimental data on the deformation of the compound nucleus by measuring the spectra of the evaporated charged particles. Then the polarization of neutrons evaporated from the compound nucleus with a high angular momentum is estimated.

COULOMB POTENTIAL ON THE SURFACE OF THE ROTATING NUCLEUS

The equilibrium shapes of the rotating nuclei have been analysed by Cohen, Plasil and Swiatecki[6]) by means of the liquid drop model. In this work two dimensionless parameters have been used: $x = E_c^{(o)}/2E_s^{(o)}$ is a fissility parameter, and $y = E_R^{(o)}/E_s^{(o)}$ is a rotational parameter, where $E_c^{(o)}$, $E_s^{(o)}$ and $E_R^{(o)}$ are electrostatic, surface and rotational energies of spherical configuration. For small amounts of rotation the originally spherical drop is flattened by the centrifugal force into an oblate spheroid. With increasing the value of y the equilibrium shapes are no longer exact spheroids but rather close to it (pseudospheroids). This equilibrium configuration continues to flatten with increasing the value of y until a certain critical value of y_1. At this point a qualitative change takes place: the flat pseudospheroid becomes unstable towards conversion into a three-axial pseudoellipsoid, which rotates about its shortest axis. Two other axes are almost equal at $y \gtrsim y_1$. Later, with increasing rotation, one of them becomes rapidly longer and the other tends to approximate equality with the shortest axis. The elongation of this equilibrium configuration continues until the second critical value of $y = y_2$ is reached. At this point the nucleus is unstable towards a symmetric disintegration. The values of y_1 and y_2 are functions of x. They are equal for x-values exceeding a certain critical value of $x_c \simeq 0.81$.

Figure 1 shows the principal axes of the equilibrium configurations as a function of the rotation parameter y for some values of the fissility parameter x. This plot was drawn on the basis of the calculation performed in ref. [6]. The splitting of the major axis (a) into a major and a median (b) ones takes place at the critical point y_1.

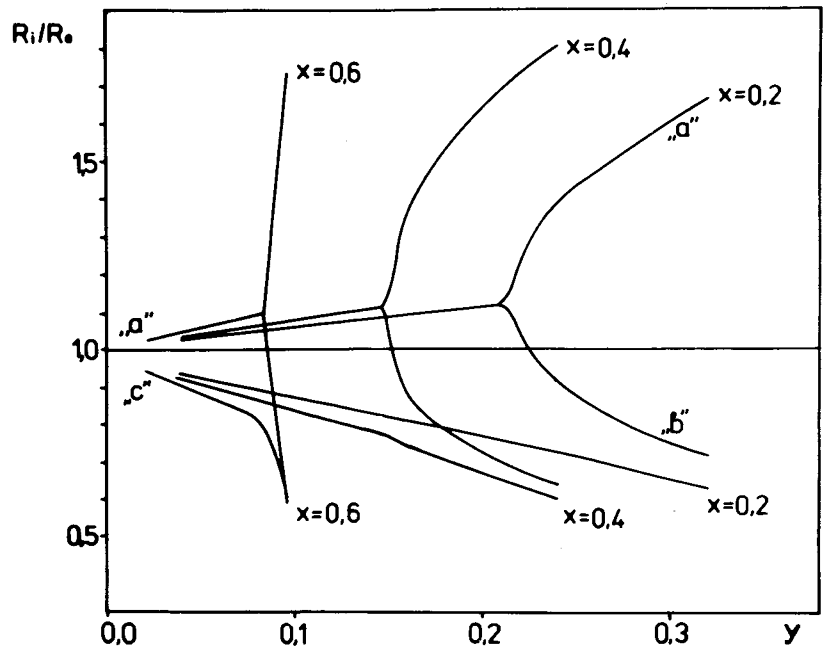

Fig. 1. The principal axes of the equilibrium configurations of the rotating nucleus as a function of the rotation parameter y for some values of the fissility parameter x (labelled in the Fig.). The major (a), median (b) and minor (c) axes are given in the units of the radius of the sphere with the same volume. The plot has been made on the basis of ref. [6].

The value of $I(y_1)$ angular momentum corresponding to the critical value of the rotational parameter y_1 depends somewhat on the values of Z and A for a given value of the fissility parameter x. Figure 2 shows the value of $I(y_1)$ as a function of x calculated

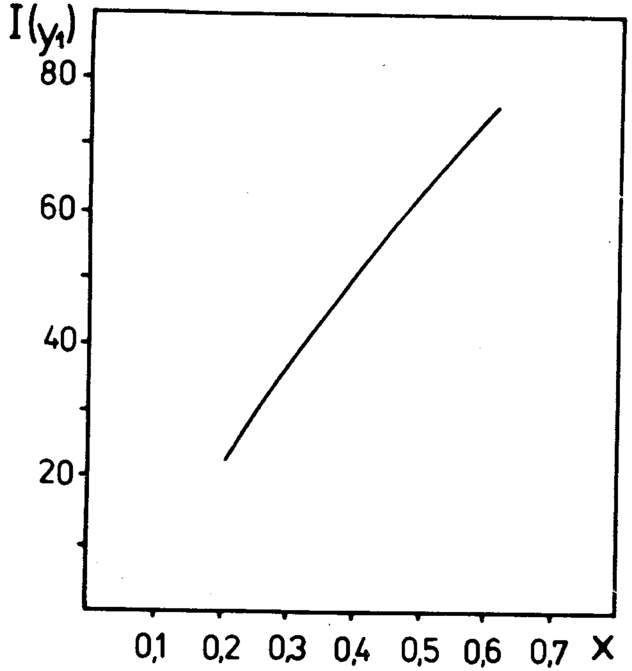

Fig. 2. The angular momentum as a function of the fissility parameter x for the critical rotation energy, above which the equilibrium configuration is a three-axial ellipsoid.

for the most neutron deficient compound nuclei formed by the ^{20}Ne -capture.

To calculate Coulomb potentials at the surface of the rotating nucleus we assume that the nucleus has a shape of an oblate spheroid until a critical value of y_1 and after that equilibrium configuration is converted into a triaxial ellipsoid. The nucleus is assumed to be uniformly charged with the sharp edge.

A number of theoretical studies have been made on the problem of ellipsoid potentials during the last two centuries. For our pur-

poses we shall use the book by R.Muratov [7], devoted to this problem. Denote the Coulomb potentials on the nucleus surface by V_a, V_b , V_c for the major (a), median (b) and minor (c) axes, respectively. According to ref. [7], the Coulomb potential on the ellipsoid surface is equal to:

$$V(\vec{r}) = 2\pi\rho_o(M_o - M_a x^2 - M_b y^2 - M_c z^2)\,^{*} \tag{2}$$

where ρ_o is a volume charge density; M_o, M_a , M_b , M_c are intrinsic potential factors of the ellipsoid [7] for which the following relation is valid:

$$M_o = a^2 M_a + b^2 M_b + c^2 M_c . \tag{3}$$

Equations (2) and (3) lead to:

$$\begin{aligned} V_a &= \frac{3}{2} V_o \left(\frac{b^2}{R_o^2} M_b + \frac{c^2}{R_o^2} M_c\right), \\ V_b &= \frac{3}{2} V_o \left(\frac{a^2}{R_o^2} M_a + \frac{c^2}{R_o^2} M_c\right), \\ V_c &= \frac{3}{2} V_o \left(\frac{a^2}{R_o^2} M_a + \frac{b^2}{R_o^2} M_b\right), \end{aligned} \tag{4}$$

where V_o is the Coulomb potential on the nuclear surface for the spherical configuration with the radius equal to R_o The intrinsic

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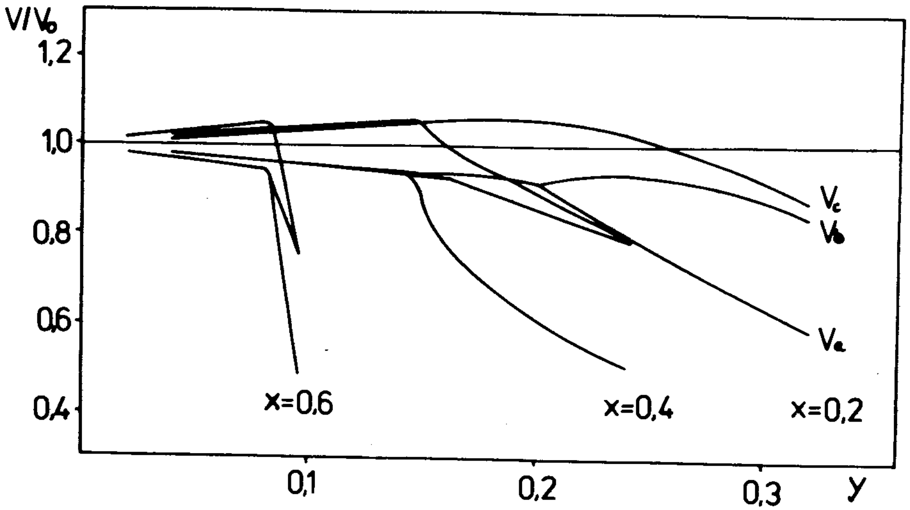
*In this formula x , y , z are Descartes coordinates.



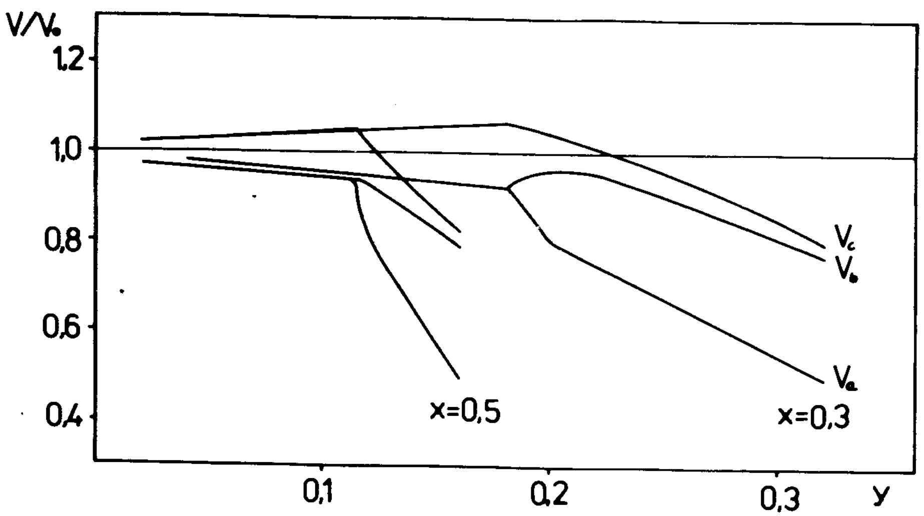


Fig. 3,4. The Coulomb potentials on the nuclear surface at the principal axes given in the units of the spherical nucleus potential: V_a, V_b, V_c - Coulomb potentials at major, median and minor axes, respectively.

potential factors are unambiguously determined by eccentricity values b/a and c/a. They are tabulated in ref.[7] in the eccentricity range from 0.005 to 1.0.

Figures 3 and 4 show the calculation results for the Coulomb potentials V_a, V_b and V_c as functions of y for some values of the fissility parameter x. The change of the potentials with y is qualitatively the same for all the values of x. The potential at the minor axis is growing up with increasing rotation, while the potential at the major axis is falling down with approximately the same rate of changing. But the picture is changed after the critical point y_1: the potential V_c starts to fall down while the decrease of the potential V_a becomes faster. The median potential V_b tends from V_a to V_c while the median axis b is approaching the shortest axis c. At the critical point y_1 the value $(V_c - V_a)/V_0$ is equal to 10-15% for the range of the fissility parameter $0.6 \geq x \geq 0.2$.

The data on the Coulomb potential on the surface of the rotating nucleus can be obtained by measuring the energy spectra of evaporated charged particles. These data should give information on the centrifugal deformation of the compound nucleus. Consider the reaction of type (1) with the detection of a projectile fragment. The energy spectra of charged particles evaporated by the polarized compound nucleus $^{A_c}Z_c^*$ should be different in the reaction plane and perpendicular to it*. For the particles, evaporated along the angular momentum of the compound nucleus, the maximum position of the spectrum is determined by the potential V_c. The situation is more complicated for the spectra of particles directed in the reaction plane. The maximum position is determined by the potential V_a until the critical point y_1 and after that by some intermediate values between V_b and V_c depending upon nuclear temperature.

As an example, let us give some numbers for the compound nucleus ^{118}Xe $(x = 0.49)$, which can be investigated in the reaction $^{96}Ru(^{40}Ar, ^{18}O)\ ^{118}Xe^*$.

a) The angular momentum $I(y_1) = 61\hbar$ corresponds to the first critical rotational energy y_1. For that value of the angular momentum we obtain the following estimates for the proton and α-particle Coulomb barriers: $(V_c^p - V_o^p) \simeq -(V_a^p - V_o^p) \simeq 0.6$ MeV; $(V_c^\alpha - V_o^\alpha) \simeq -(V_a^\alpha - V_o^\alpha) \simeq 1.0$ MeV. b) For the angular momentum $I = 71\hbar$ $(y = 0.15)$ the changes of the Coulomb barriers for proton and α-particle emission are completely different: $(V_c^p - V_o^p) \simeq -1.5$ MeV, $(V_c^\alpha - V_o^\alpha) \simeq -2.5$ MeV, $(V_a^p + V_b^p)/2 - V_o^p \simeq -3.3$ MeV, $(V_a^\alpha + V_b^\alpha)/2 - V_o^\alpha \simeq -5.5$ MeV.

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*It is obvious that one should compare the spectra in the center-of-mass system for the $^{A_c}Z_c$ -nucleus although very demonstrative should be the comparison of the experimental spectra measured in both cases for the particles evaporated perpendicularly to the recoil direction when the effect of the center-of-mass velocity is the same.

It is known that the compound nucleus cannot be formed with an angular momentum exceeding a certain critical value I_{cr}; At present there is no comprehensive experimental data on the values of I_{cr} as a function of ^{A}Z, $^{A_p}Z_p$ and E. Nevertheless, on the basis of what is known now [8,9] one should expect that: $I(y_1) < I_{cr}$.

NEUTRON POLARIZATION

Consider the evaporation of the neutron carrying away the energy ϵ from the polarized compound nucleus with the excitation energy E^* and the angular momentum I_o. According to the statistical theory of the compound nuclear decay one can write the following expressions for the probabilities of neutron emission with the spin directed along the nuclear angular momentum $W(E^*, \epsilon, I_o, s\uparrow)$ and against it $W(E^*, \epsilon, I_o, s\downarrow)$:

$$W(E^*, \epsilon, I_o, s\uparrow) = \frac{1}{\hbar\rho(E^*, I_o)} \sum_\ell \sum_{m=-\ell}^{m=\ell} T_{\ell,s}^{I_f} \cdot \rho(E^* - \epsilon, I_o - 1/2 - m)$$

$$W(E^*, \epsilon, I_o, s\downarrow) = \frac{1}{\hbar\rho(E^*, I_o)} \sum_\ell \sum_{m=-\ell}^{\ell} T_{\ell,s}^{I_f} \cdot \rho(E^* - \epsilon, I_o + 1/2 - m). \tag{5}$$

Here $\rho(E^*, I)$ is the level density for the nucleus with the excitation energy equal to E^* and with the angular momentum I; ℓ - is the neutron orbital angular momentum, $T_{\ell,s}^{I_f}$ is the neutron transmission coefficient; I_f is the angular momentum of the residual (after neutron emission) nucleus. The polarization coefficient P is equal to

$$P = \frac{W(s\uparrow)-W(s\downarrow)}{W(s\uparrow)+W(s\downarrow)} = \left(\frac{W(s\uparrow)}{W(s\downarrow)} - 1\right)\left(\frac{W(s\uparrow)}{W(s\downarrow)} + 1\right)^{-1}. \qquad (6)$$

Assume that the transmission coefficients depend only upon the ℓ-values. Apparently, this is a good approximation for highly excited nuclei. If one restricts oneself to only the partial wave with $\ell = \langle\ell\rangle$ and $m = \langle\ell\rangle$, the expression for $W(s\uparrow)/W(s\downarrow)$ is written in a very simple form:

$$\frac{W(s\uparrow)}{W(s\downarrow)} = \frac{\rho(E^*-\epsilon, I_0 - \tfrac{1}{2} - \langle\ell\rangle)}{\rho(E^*-\epsilon, I_0 + \tfrac{1}{2} - \langle\ell\rangle)}. \qquad (7)$$

In what follows we shall use this equation because taking into account all the partial waves alters the P-value not larger than 10% of its magnitude. For the level density we shall take the expression given by the model with equidistant single particle states (valid for the large rotational energy E_R)[10]:

$$\rho(E^*, I) = \frac{1}{24\sqrt{2}}\left(\frac{1}{a}\right)^{1/4} \cdot \frac{1}{\sigma^3}\,\frac{2I+1}{(E^*)^{5/4}} \cdot \exp 2\sqrt{a\left(E^* - (I+\tfrac{1}{2})^2\frac{\hbar^2}{2J}\right)}. \qquad (8)$$

Equations (7) and (8) lead to:

$$\frac{W(s\uparrow)}{W(s\downarrow)} \simeq \frac{I_0 - \langle\ell\rangle}{I_0 - \langle\ell\rangle + 1} \exp 2\sqrt{a}\,\frac{\hbar^2 (I_0 - \langle\ell\rangle)/2J}{\sqrt{(E^*-\epsilon) - (I_0 - \langle\ell\rangle)^2\hbar^2/2J}}. \qquad (9)$$

Here $a = A/7{,}5$ is the level density parameter[10], J is the moment of inertia, which has been taken as a rigid-body one and depending on nuclear deformation[6].

Note, that in the limit of $E_R \ll E^*$ expression (9) tends to the one obtained in ref.[1].

The calculations of neutron polarization have been performed for the polarized compound nuclei $^{55}Co^*$, $^{83}Y^*$, $^{127}La^*$ formed in the reaction of type (1). As the targets ^{39}K, ^{63}Cu, and ^{107}Ag were taken. As the captured fragments ^{16}O in the first case and ^{20}Ne in other cases were used. The value of I_0 was taken to be equal to $\frac{3}{2}\langle I\rangle$, where $\langle I\rangle$ is the mean angular momentum for the complete fusion of the target and captured fragment considered as a projectile[11]. For all the cases $\langle\ell\rangle$ was taken to be equal to 2[12]. Note that the results are slightly sensitive to the $\langle\ell\rangle$-value.

The calculation results are shown in Fig. 5. The degree of polarization reaches a significantly large value for rather a modest range of the angular momentum. The polarization degree reaches its maximum value in the vicinity of the critical point $I(y_1)$ and falls down after that as a result of the drastic increase of the moment of inertia. Until the critical point the polarization degree decreases for a given I_0 value with increasing the mass number of the compound nucleus due to the decrease of rotational energy.

We should stress, that the estimates of neutron polarization have been made on the basis of the statistical model of the decay of the polarized compound nucleus, assuming the independence of the Fermi-level position on the spin of the single particle state. The exact theory should take into account the possible spin polarization of single particle states of the rotating nucleus, which can be significant especially for low nuclear temperature, as has been shown by Pick-Pichak[12].

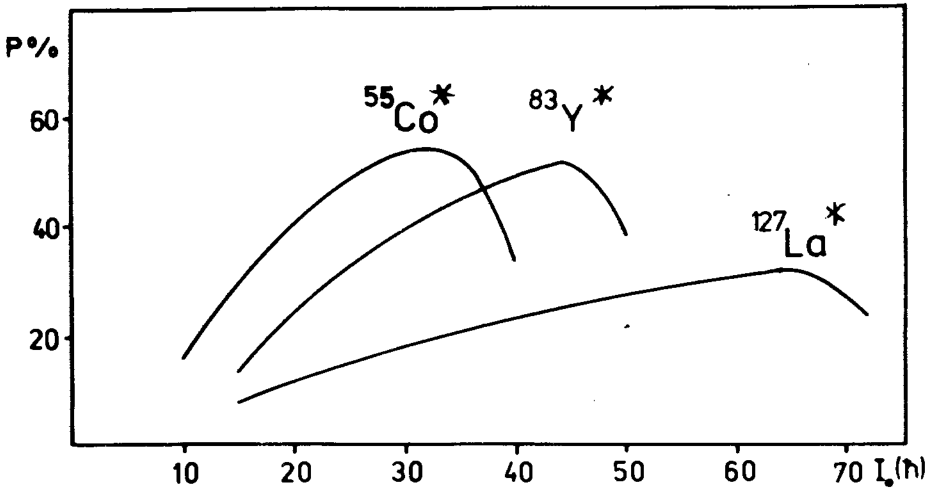

Fig. 5. The polarization (in per cent) for neutrons evaporated by the polarized compound nucleus as a function of its angular momentum. The calculations have been made for compound nuclei ^{55}Co*, ^{83}Y*, and ^{127}La*. As the targets ^{39}K, ^{63}Cu, and ^{107}Ag have been taken, the nuclei ^{16}O in the first case and ^{20}Ne, in others have been considered as the captured fragments.

CONCLUDING REMARKS

The correlation experiments give a possibility of investigating the decay of polarized compound nuclei with a high angular momentum in the reactions of the partial fusion of heavy ions (multinucleon transfer reactions). The measurements of the energy spectra of the charged particles evaporated over the nuclear angular momentum and perpendicular to it can provide data on the centrifugal deformation of nuclei.

The measurement of neutron polarization is a more difficult task because of a low polarimeter efficiency. For such experiments the use of direct current accelerators seems to be more reasonable. The experimental data on neutron polarization may illuminate a complete new problem of the spin-orbital coupling in nuclei with a very high angular momentum.

To interpret correlation experiments suggested in this paper it is important to know the value of the angular momentum of the polarized nucleus. Besides the estimates on the basis of the reaction kinematics, one can use the measurements of the γ-ray multiplicity as it has been made, for example, in refs. /14,15/. The angular momentum removed by a γ-ray cascade is close to the initial compound nuclear spin, because the angular momentum lost during the nucleon evaporation stage is rather small /12/. From the last statement one can conclude that the depolarization of the compound nucleus during the evaporation stage should be insignificant. It means that averaging over the evaporating cascade slightly changes the effects calculated above.

In the present paper we have not considered the possible γ-ray polarization following the nucleon evaporation. One should expect significant circular γ-ray polarization because initial compound nucleus polarization survives during a nucleon evaporation stage. But this question should be the subject of a special study.

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