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Yield of low-lying high-spin states at optimal charge-particle reactions

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Abstract. Isomeric cross-section ratios (ICSR) σ_g/σ_m for the ^{4,6,8}He-induced reactions of Sr isotopes giving rise to ^{89mg}Zr isomeric pair ($J^\pi = 9/2^+$, $T_{1/2}^{(g)} = 3.27$ d; $J^\pi = 1/2^-$, $T_{1/2}^{(m)} = 4.18$ min) are calculated using a statistical model approach. ICSR of the reactions ^{86}Sr$(\alpha,\mathrm{n})^{89mg}$Zr and ^{87}Sr$(\alpha,2\mathrm{n})^{89mg}$Zr measured by us earlier in the energy range $E = 17$–29 MeV are used as a test. Calculations and analysis of ICSR of reactions produced by unstable projectiles are performed for the first time. The dependence of obtained values on the projectile neutron number is discussed.

PACS. 25.60.-t Reactions induced by unstable nuclei

At the moment the development of investigations of nuclear isomers (NI) is expected in the context of the use of unstable nuclear beams. In the present paper we discuss the probability of low-lying high-spin states production in the reactions with light neutron-rich (halo) projectiles.

The ratio of cross-sections of a certain pair of isomeric states (high-spin and low-spin respectively) in one and the same nucleus allows to obtain an information on angular momentum dynamics of a preceding reaction and spin dependence of nuclear level density. This dynamics depends on the properties of a target, projectile, and emitted particles. It is important to find out optimal reaction parameters to populate high-spin isomer. In the present work we investigate the dependence of its yield on the projectile neutron number and the bombarding energy.

Measurements of isomeric cross-section ratios in the reactions ^{86}Sr$(\alpha,\mathrm{n})^{89mg}$Zr and ^{87}Sr$(\alpha,2\mathrm{n})^{89mg}$Zr in the energy range 17–29 MeV were carried out by us earlier using off-beam measurements of induced activity of the isomeric pair [1]. The activation method is a reliable tool for identification of reaction products. Here we present for the first time our results improved through the handling of the activation data with the use of the optimal extraction formula from [2].

Calculations of ICSR for the indicated reactions are performed using the upgraded program EMPIRE-II-18 [3]. This code is based on Hauser-Feshbach version of the statistical theory of nuclear reactions [4]. The field of application of the model is placed over the area of 10–50 MeV excitation energy of a compound nucleus, where the widths of resonances are greater than the distances between them.

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Table 1. Values of the cross-section of population σ^p in the reaction ^{86}Sr$(\alpha,\mathrm{n})^{89}$Zr at $E_\alpha = 25.0$ MeV.

E (MeV)	J^π	σ^p (mb)
0.0	$9/2^+$	7.245
0.59	$1/2^-$	0.184
1.09	$3/2^+$	0.292
1.45	$5/2^-$	0.45
1.51	$9/2^+$	1.25
1.62	$5/2^+$	0.34
1.71	$3/2^+$	0.127
1.83	$5/2^+$	0.259
1.86	$3/2^+$	0.107
1.94	$13/2^+$	4.761
2.01	$9/2^+$	0.557
2.10	$5/2^-$	0.184
2.10	$7/2^+$	0.318
2.12	$13/2^-$	3.513

Properties of nuclei involved in the discussed reactions are taken from the table [5].

ICSR is calculated using the formula: $\sigma_g/\sigma_m = \sigma_t/\sigma_m - 1$, where σ_t is the total cross-section of the reaction, $\sigma_m = \sum_p \sigma_m^p$ - the sum of partial cross-sections of the processes which result in population of the levels corresponding the condition $J \leq 5/2$. According to [5] γ-transitions to low-spin member $J^\pi = 1/2^-$ of the pair of ^{89}Zr nucleus dominate for such levels. De-excitation of other levels results mainly in the high-spin state $J^\pi = 9/2^+$ population.

Let us exemplify typical σ^p values. For lower levels of the ^{89}Zr nucleus populated in the reaction ^{86}Sr$(\alpha,\mathrm{n})^{89}$Zr

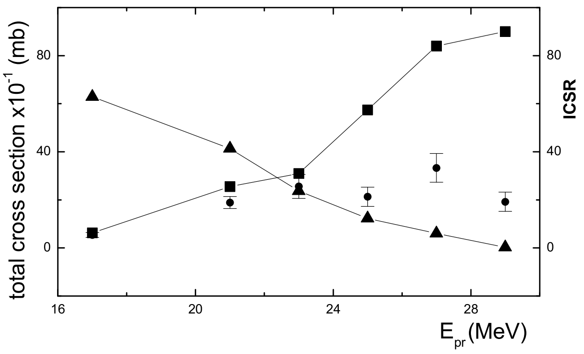

Fig. 1. The excitation function (triangles-line) and isomeric cross-section ratios (squares-line: the calculation, circles: the experiment) for the reaction ^{86}Sr$(\alpha, \mathrm{n})^{89mg}$Zr.

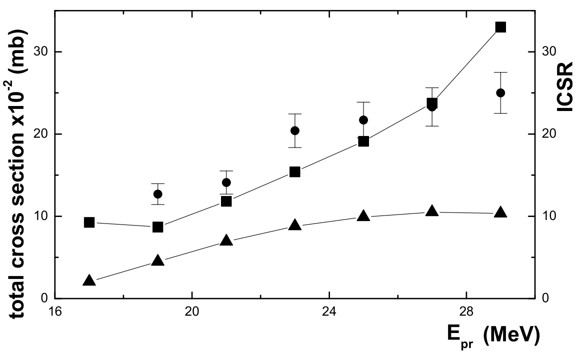

Fig. 2. The excitation function (triangles-line) and isomeric cross-section ratios (squares-line: the calculation, circles: the experiment) for the reaction ^{87}Sr$(\alpha, 2\mathrm{n})^{89mg}$Zr.

at $E_\alpha = 25.0$ MeV they are given in table 1, which is the fragment of population data produced by the EMPIRE code. In fact the list of the levels contributing the σ_m value is exhausted by this fragment. The list of high-spin levels contributing σ_g is very broad and extends far beyond table 1. As it is seen from table 1 the values of partial cross-sections for these levels are essentially larger than for presented low-spin ones. For high-spin levels which are not presented in table 1 that is also true. That is why ICSR are so large in the reaction.

The experimental data and the results of calculations are represented in figs. 1 and 2 together with the excitation functions $\sigma_t(E)$. As is shown on fig. 1 for the reaction ^{86}Sr$(\alpha, \mathrm{n})^{89mg}$Zr experimental values of ICSR up to energy $E_{pr} = 23$ MeV are in agreement with calculated ones with an accuracy of 20–30%.

At higher energy of α-particles calculated isomeric ratios exceed experimental ones, this is evidence of mechanisms of (α, n)-reactions other than statistical ones (pre-equilibrium, direct). For the reaction ^{87}Sr$(\alpha, 2\mathrm{n})^{89mg}$Zr a good agreement of the experimental and calculated values of ICSR is observed in the energy range of α-particles $E_{pr} = 19$–27 MeV (fig. 2).

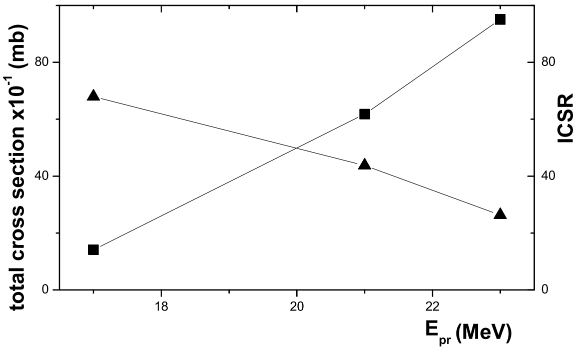

Fig. 3. The excitation function (triangles-line) and calculated isomeric cross-section ratios (squares-line) for the reaction ^{84}Sr$(^6\mathrm{He}, \mathrm{n})^{89mg}$Zr.

Calculations of isomeric ratios produced by the reactions ^{84}Sr$(^6\mathrm{He}, \mathrm{n})^{89mg}$Zr and ^{84}Sr$(^8\mathrm{He}, 3\mathrm{n})^{89mg}$Zr are carried out by us for the first time. As is shown in fig. 3, the value of the total cross-section of the reaction $(^6\mathrm{He}, \mathrm{n})$ falls down as the projectile energy increases. Isomeric ratios increase with the growth of the energy of ^{6}He-particles. Comparing ICSR values of the (α, n)- and $(^6\mathrm{He}, \mathrm{n})$-reaction (figs. 1 and 3) calculated in the statistical model in the energy region $E = 17$–23 MeV (where the theoretical results are in agreement with measured ones for the (α, n)-reaction) one can conclude that the greater angular momentum contributing by ^{6}He is strongly reflected in ICSR. Is this tendency realized in the planning experiment with the ^{6}He beam? This depends on the contrbution of the competing reaction mechanisms there. ICSR calculated for the reaction with ^{8}He (another compound nucleus) is approximately fixed at the value $\sigma_g/\sigma_m \simeq 12$ in the energy region $E = 25$–29 MeV (we omit the respective figure for brevity).

Thus experimental investigation of ICSR produced by halo projectiles such as $^{6(8)}$He seems to be very interesting because these values are sensitive to the relative contribution of direct and compound mechanisms as it was demonstrated above for ^{4}He-induced reactions. For heavier helium projectiles probability of a halo neutron to be ejected in a direct reaction is expected to be much higher.

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