Isomeric cross section ratios data as a test for codes descriptive of nuclear reactions

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Abstract. Investigations of isomeric cross-section ratios of the reactions $^{187}$Re($\alpha$,n)$^{190}$mgIr, $^{194}$Pt($\alpha$,n)$^{197}$mgHg and $^{41}$K($\alpha$,n)$^{44}$mgSc in the energy range 18 – 32 MeV are carried out using off-beam measurements of induced activity of members of the isomeric pair. Analysis of the obtained ICSR data is performed using the codes EMPIRE-3 and TALYS. The reliability of these advanced data-containing codes is analyzed. The results of the measurements of the isomeric cross section ratios are proved to be a promising test of the codes and their capability to reproduce angular momentum dynamics of the discussed and related reactions.

1. Introduction. ICSR as a tool for nuclear reaction studies

Energy dependences of isomeric cross-section ratios (ICSR) studied experimentally by means of off-beam measurements of the induced activity of members of the isomeric pair are the data, very convenient to disclose reaction mechanisms. They are significantly more sensitive to details of the mechanisms compared to the total excitation functions of nuclear reactions. Measurements of ICSR allow one to obtain 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.

Alpha-particle induced reactions are popular because usually the maximal relative yield of high-spin state in ~ 20 – 50 MeV region of compound nucleus energy can be achieved by application of $\alpha$-projectiles. The values of ICSR obtained in typical $\alpha$-induced nuclear reactions such as ($\alpha$,n), ($\alpha$,2n), etc. are presented in many papers, see, for example Refs. [1–14]. The calculations of the total excitation functions performed by use of modern computer codes demonstrate the similarity of the resulting curves and a reasonable agreement of the computed absolute values with the measured data. Various experimental and theoretical results reliably indicate that at least for near-barrier energies of the incident $\alpha$-particle the compound nucleus mechanisms are dominating. In contrast to that the behaviour of the ICSR curves is very different in accordance with spin characteristics of the initial, the intermediate and the final states. In many cases it turns out to be impossible to reproduce the ICSR in calculations if even a broad variety of starting assumptions is exploited. Thus some properties of the angular momentum dynamics in these reactions and spin dependence of nuclear level density are not disclosed yet.
Off-beam measurement of reaction product radiation is a popular method in studies of ICSR of various nuclear reactions. Distinctive features of this method are high efficiency and reliable recognition of radioactive residues. Experiments of such a type are rather convenient and labour-saving. At the same time analysis of the isomeric cross section ratios allows one to reveal reaction mechanisms of a residue production and properties of the intermediate states involved in the cascade. Indeed, as a rule the yield of the products strongly depends on the density of these states, particle capture and emission strength functions, discrete spectra of a nucleus under study, etc.

The value of ICSR which characterizes the relative yield of high- and low-spin isomers of one and the same isotope is determined to a large measure on spin distributions of the intermediate products of the reaction as well as on the properties of gamma-cascade in a final residue. Thus the results of the measurements of the ICSR indicate the dynamics of distribution of angular momentum over the reaction products. In particular, one can expect that ICSR observed in alpha-particle-induced reactions reveal the spin dependence of the alpha-cluster strength in the energy area under study.

Recently the analysis of the excitation functions and the ICSR is based on large-scale data-containing codes, for example, EMPIRE [15] and TALYS [16]. Codes of such a type allow one to take into account various reaction mechanisms as well as a large number of characteristics of nuclear reactions and nuclei involved in them. Thus the codes turn out to be beneficial in search for various associations of these characteristics with the results of the discussed measurements.

2. Results and conclusions

Experiments performed by the group from Kiev [7] and by our group [8,9] demonstrate that maximal values of isomeric cross-section ratios (up to 30) are obtained in α-particle induced reactions. For some isomeric pairs anomalous maxima in behavior of ICSR are detected. In some cases these anomalies are hard for the description by the statistical and pre-equilibrium models.

The experimental investigations and calculations of isomeric cross-section ratios of the reactions $^{187}$Re($\alpha,n$)$^{190}$Ir, $^{194}$Pt($\alpha,n$)$^{197}$Hg and $^{41}$K($\alpha,n$)$^{44}$Sc in the energy range 18 – 32 MeV are carried out.

The results of the measurements and the calculations of ICSR in the framework of, EMPIRE-3 and TALYS codes are presented in Figs. 1, 2 and 3.

![Figure 1](image-url)  
**Figure 1.** Values of the ICSR for the reaction $^{187}$Re($\alpha,n$)$^{190}$Ir ($J_m=11^+, J_g=4^+$): D – calculated by TALYS, E – calculated by EMPIRE-3.1, B – experiment.
These figures demonstrate both similarity and distinctions in behaviour of ICSR of the respective reactions.

For the reaction $^{187}$Re($\alpha$,n)$^{190}$Ir experimental values of ICSR up to energy $E_{pr} = 21\ \text{MeV}$ are in agreement with calculated by EMPIRE-3 ones with an accuracy of $20 – 30\%$. At higher energy of $\alpha$-particles calculated isomeric ratios exceed experimental ones, this behaviour is an evidence indicating that mechanisms of $\alpha$-reactions other than statistical ones (pre-equilibrium, direct) become dominant. As for the data calculated by TALYS a good agreement with experimental results takes place.

![Figure 2](image-url)

**Figure 2.** The same as in Fig. 1 for the reaction $^{194}$Pt($\alpha$,n)$^{197}$Hg ($J_m = 13/2^+$, $J_g = 1/2^-$).

For the reaction $^{194}$Pt($\alpha$,n)$^{197}$Hg a satisfactory agreement of the experimental and calculated values of ICSR occur in the $\alpha$-particle energy range $E_{pr} = 14 – 18\ \text{MeV}$ for both EMPIRE-3 and TALYS codes. These values are obtained with rather large error bars in fact upper limits of them are measured. Because of that they are not shown in Fig. 2. At higher energies of $\alpha$-particles calculated isomeric ratios strongly exceed experimental ones and this difference turns out to be more significant for EMPIRE-3 code than for TALYS.

The discrepancies of the measured and the calculated results revealed in the framework of the analysis are of the same order as the ones revealed in the framework of the analysis of ICSR of well-studied reaction $^{41}$K($\alpha$,n)$^{44}$Sc. Indeed, a large body of ICSR measurements of the ICSR of this reaction were performed. Our own results which are in a good agreement with the other ones are presented in Fig. 3. The figure demonstrates a well-expressed maximum at the energy $\sim 26\ \text{MeV}$. In spite of many calculations an interpretation of the maximum is an open question up to now. Perhaps some $\alpha$-clustering effect in compound nucleus $^{45}$Sc takes place.

In conclusion it should be emphasize that codes under discussion are constructed as a synthesis of more or less standard theoretical models and a broad spectrum of nuclear data. Nevertheless delicate properties of nuclear structure including, as one may expect, properties of high-spin alpha-cluster states turn out to be lost in the input of these codes.
Figure 3. The same as in Fig. 1 for the reaction $^{41}\text{K}(\alpha,n)^{44}\text{Sc}$ ($J_u=6^+$, $J_g=2^+$).

The measurements of the isomeric cross-section ratios and comparison of the results with the ones obtained in the calculations seem to be a good test of the capability of nuclear reaction codes and a tool to demonstrate a manifestation on unusual properties of highly-excited states including, probably, their clustering.

References
[1] Brenquindj C L et al. 1979 J. Inorg. Nucl. Chem. 41 617
[2] Grent I S, M. Rathle M 1979 J. Phys. G; Nucl. Phys. 5 1741
[3] Newton G W A , Robinson V J, Shaw E M 1981 J. Inorg. Nucl. Chem. 43 2227
[4] Avchukhov V D et al. 1980 Izv. AN SSSR; ser. fiz. 44 155
[5] Baskova K A et al. 1984 Izv. AN SSSR; ser. fiz. 48 38
[6] Baskova K A et al. 1984 Sov. J. Nucl. Phys. USSR 39 538
[7] Vishnevsky I N et al. 1984 Sov. J. Nucl. Phys. USSR 41 1435
[8] Chuvilskaya T V et al. 1989 Izv. AN SSSR; ser. fiz. 53 2262
[9] Glebov N K et al. 1991 Izv. AN SSSR; ser. fiz. 55 141
[10] Tulinov A F et al. 1993 Izv. RAN; ser. fiz. 57 135
[11] Nagame Y et al. 1990 Phys. Rev. C 41 889
[12] Sudar S, Qaim S M 2006 Phys. Rev. C 73 034613
[13] Chuvilskaya T V 2015 JPS of Japan, Conference Proceedings 6 030083
[14] Chuvilskaya T V. Journal of Physics: Conf. Ser. 863 012040
[15] Herman M, Marcinkowski A, Stanekwitz K 1984 Comp. Phys. Comm. 33 373; https://nddx4.bnl.gov/gf/project/empire/
[16] Koning A J, Hilaire S and Duijvestijn M 2009 Talys-1.2. A nuclear reaction program, User manual. December 22