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# Isomer Ratios for íhe Reactions $\alpha+^{70}Ge$

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**Abstract** Isomer ratios for $^{73}Se^{m,g}$, produced in the reaction $a+^{70}Ge$, with incident laboratory energy ranging from 8 to 28 MeV, have been deduced using off-line $\gamma$-ray spectroscopy. Relative cross-section for isomeric and ground states formation were obtained with $^{nat}Ge$ targets. Compound nucleus statistical analyses were performed with the codes ALICE and JULIAN, and a good agreement was obtained between predictions of JULIAN and the experimental results. Angular momentum populations for isomer formation have been determined in the $^{70}Ge(\alpha,n)^{73}Se$ reaction.

## 1. INTRODUCTION

Isomer ratios have been largely used[1-3] in the last few decades to get some insight into nuclear states formed at very high energies and angular momenta. Huizenga and Vandenbosh[1] have studied isomer ratios for a large variety of target and projectile combinations and they concluded that these ratios depend, besides the spin values of the isomeric and ground states, on the properties of intermediate states as well as on the angular momenta transferred in the reaction mechanisms.

In this paper, we investigate the angular momentum dependence of the isomer ratios for the $^{73}Se$ nucleus formed in a $^{70}Ge(\alpha,n)^{73}Se$ reaction. $^{73}Se$ has* a $J^{\pi} = 7/2^{+}$, $T_{1/2} \simeq 7h$s ground state and a $J^{\pi}=1/2^{-}$, $\tau_{1/2} \simeq 41$ min isomeric state as the first excited state, at only 25 keV of excitation energy. As this energy is very small compared to the excitation energies of the $^{74}Se$ compound nucleus formed in this reaction, the isomer ratios, defined as $R = \sigma^{g}/\sigma^{m}$, enable us to determine the influente of the entrance channel angular momentum on the formation mechanism of these states.

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This paper is organized as follows: in section 2 we describe the experimental methods and results obtained in the $\alpha+^{nat}Ge$ reaction. A comparison with statistical model calculations and conclusions are presented in section 3.

## 2. EXPERIMENTAL METHODS

Relative cross-sections $\sigma^{m,g}$ for isomeric and ground states formation in the reaction $\alpha+^{70}Ge$ were measured for a-particle energies ranging from 8 MeV to 28 MeV. The $\alpha$ beam was delivered by the Cyclotron CV-28 of the Instituto de Engenharia Nuclear-RJ and the energy was changed, by varying the H.F., in 2 MeV steps, in the range 20 MeV $< E_\alpha <$ 28 MeV. For energies down to 20 MeV, the beam was degraded, in approximately 1 MeV steps, by Al foils 4 mg/cm$^2$ thick, placed right in front of the targets.

In natural germanium targets, the $^{73}Se$ nucleus may be formed in the reactions $^{70}Ge(\alpha,n)^{73}Se$ and $^{72}Ge(\alpha,3n)^{73}Se$, with negative Q-values of 8 MeV and 27 MeV, respectively. As the thresholds for these reactions differ by nearly 20 MeV, there are no ambiguities in utilizing natural germanium targets in the experimental study of the $^{70}Ge(\alpha,n)^{73}Ge$ reaction, in the range from 8 MeV to 28 MeV of laboratory incident energy. Moreover, additional background originated from a-reaction with $^{72,73,74,76}Ge$ isotopes in the target is reiatively small, as can be seen in the experimental spectrum shown in the figure 1 (see below).

The Ge targets were made of natural germanium, evaporated onto a thick aluminium backing (0,2 mm), which provided mechanical rigidity and collected the recoilirig nucleus. The thicknesses of the Ge targets were estimated to be larger than 1 mg/cm$^2$. A typical experiment run was about 30 rninutes of target irradiation with an a beam current of 1 μA. These values were chosen in order to provide good statistics at the 254 keV isomeric decay, which has[4] an absolute branching ratio of only 2.5%, without strongly increasing the background originated by reactions with the Al-backing.

After irradiations, the targets were removed automatically toa low-background room and placed at 30 cm in front of a true coaxial Ge(Li) detector of 40 cm$^3$, with 2.3 keV energy resolution for the 1.33 MeV y-ray from a $^{60}Co$ source. A typical spectrum obtained at $E_\alpha$ = 22

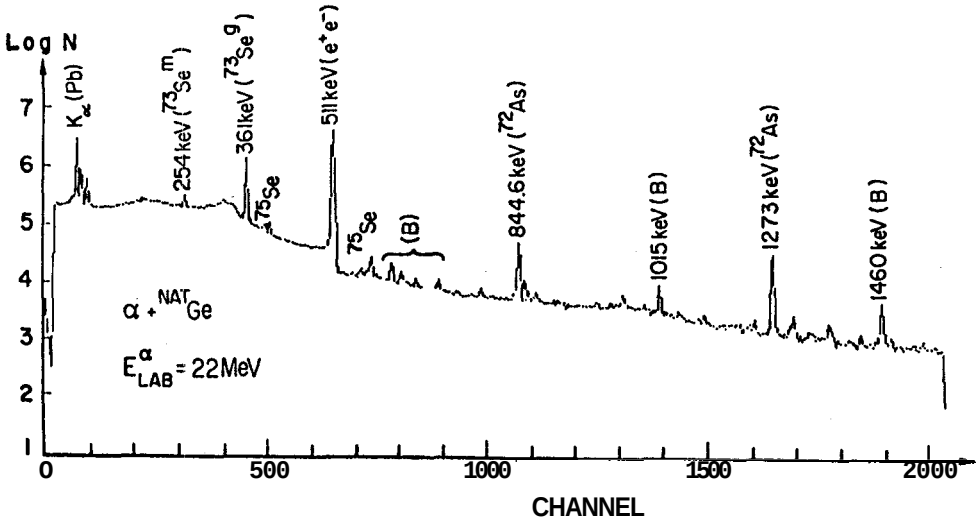


Fig.1 - γ-Ray spectrum obtained at $E_\alpha$ = 22 MeV. Lines marked (B) are activities due to the background. (Note that the vertical scale is the logarithm of the counts $N$).

MeV is shown in figure 1 and we clearly see the y-rays activities following $\beta^+$ decay of the isomeric (254 keV) and ground (361 keV) states of the $^{73}$Se residual nucleus.

The isomeric ratios were obtained at 12 incident energies by measuring the 361 keV ground and 254 keV isomeric decays, and taking into account the 73% feeding of the ground state from the isomeric state. A detailed description of the experimental method is given elsewhere[6]. As the ratios $R$ are independent of the target thickness, a whole set of germanium targets was used in these irradiations. Nevertheless, for obtaining the relative cross sections, the *same* target was irradiated at 8 different energies, with a sufficient time interval in between them, in order to avoid contribution from different energies on the $^{73}Se^{m,g}$ activities. The results are shown in figures 2 and 3 for the

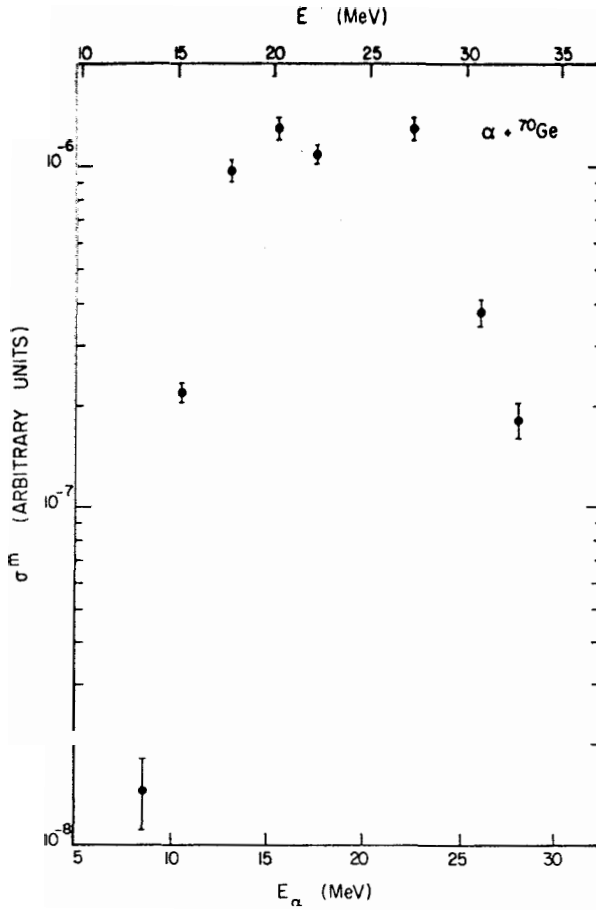


Fig.2 - Experimental excitation function for the isomeric state $J^{\pi} = 1/2^{-}$ of $^{73}Se$.

isomeric and ground states, respectively, and the relative total cross section ($\sigma^{P} = \sigma^{g} + \sigma^{m}$) for the $^{70}Ge(\alpha,n)^{73}Se$ channel is shown in figures 4 and 5, together with theoretical predictions which will be described in the next section. In figure 6, the isomer ratios $R = \sigma^{g}/\sigma^{m}$ are plotted against incident energy and they are in good agreement with early results[7] obtained with the same reaction by Demeyer et *al.* Table 1 gives the experimental values of the isomer ratio $R$.

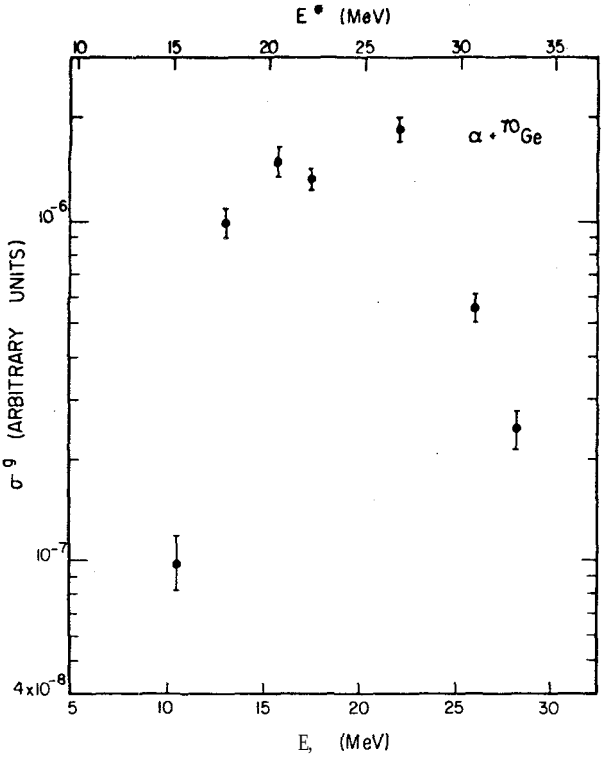


Fig.3 - Experimental excitation function for the ground state $J^{\pi} = 7/2^{+}$ of $^{73}Se$.

Table 1 - Experimental isomer ratios R obtained in the reaction $\alpha + ^{70}Ge$ (see text).

| $E_{\alpha}$ (MeV) | $E^*$ (MeV) | $R$ |
|---|---|---|
| 10,4 a) | 14,7 b) | 0,46 ± 0,02 |
| 11,7 | 15,9 | 0,84 ± 0,02 |
| 13,0 | 17,2 | 1,02 ± 0,03 |
| 15,3 | 19,3 | 1,17 ± 0,03 |
| 16,3 | 20,3 | 1,13 ± 0,02 |
| 17,5 | 21,4 | 1,14 ± 0,02 |
| 18,4 | 22,3 | 1,29 ± 0,02 |
| 20,0 | 23,8 | 1,25 ± 0,01 |
| 22,0 | 25,7 | 1,42 ± 0,03 |
| 24,0 | 27,6 | 1,41 ± 0,05 |
| 26,0 | 29,5 | 1,51 ± 0,08 |
| [illegible] | 31,4 | 1,33 ± 0,10 |

a) α-particle laboratory energy. b) Compound Nucleus $^{74}Se$ Excitation Energy.

## 3. DISCUSSION AND CONCLUSION

The excitation function for the total cross section for $^{73}Se$ forrnation was compared to statistical model predictions of the codes ALICE and JULIAN, which have been extensively described elsewhere[8,9]. In order to have a more realistic comparison with the experimental results, both codes had as an input the same compound nucleus spin distribution, calculated by the subroutine PARAP[10]. The predictions of the codes ALICE and JULIAN are displayed in figures 4 and 5, respectively. The expe-

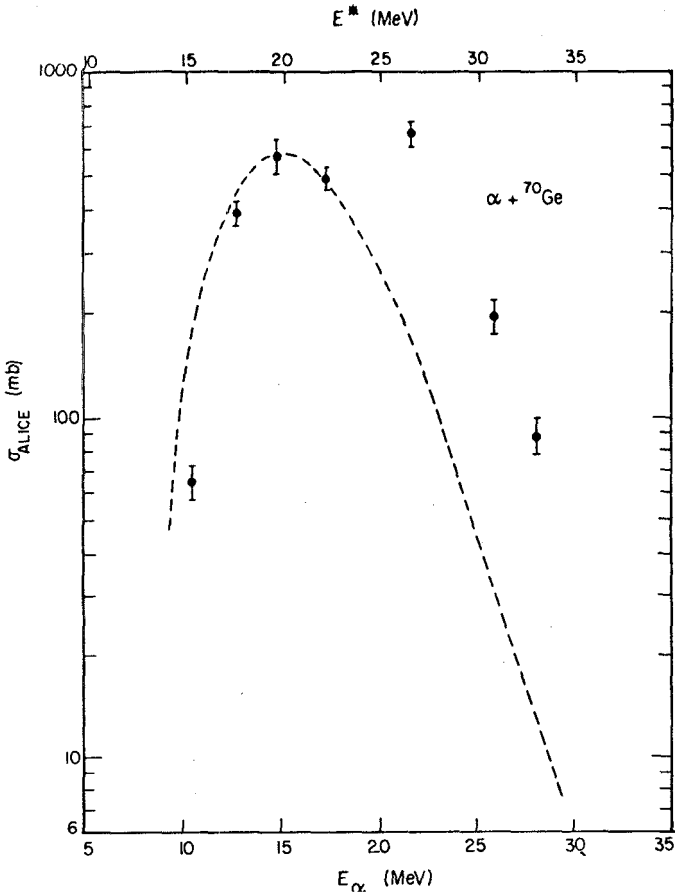


Fig.4 - Total excitation function $a^T = a^m + \sigma^g$ for the $^{70}Ge(\alpha,n)^{73}Se$ channel. The dashed curve gives the predictions of the code Alice (see text).

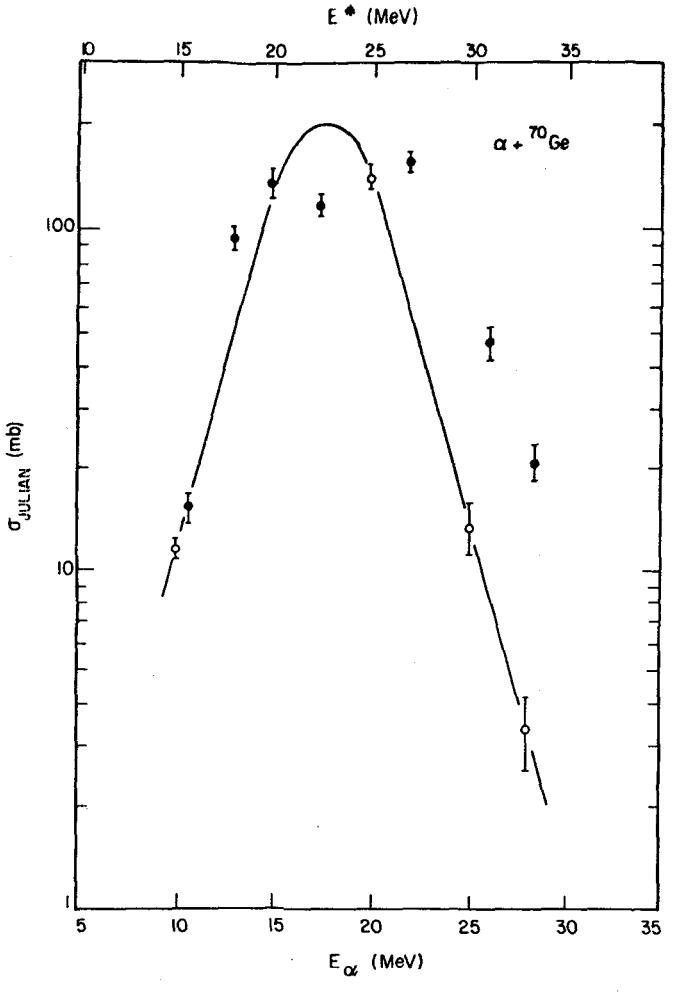


Fig.5 - Comparison between the total excitation function for the $^{70}Ge(\alpha,n)^{73}Se$ channel (black points) and the predictions of the code Julian (white points and black line).

rimental results and the calculations were normalized at 15 MeV energy and we observe that the code ALICE underestimates the experimental results at high energies almost by a factor of 10. The code JULIAN also underestimates the experimental results at high energies, but only by a factor of 2. The agreement with the code JULIAN may be irnproved by

changing, at these energies, the normalization parameter[11] in the statistical probability for y-ray competition in the deexcitation decay of the compound and residual nuclei.

We have attempted to understand our experimental data in terms of a standard statistical model calculation of the projectile energy dependence of this isomer i-atio. For practical purposes, our calculations were divided into three major parts. The first part is concerned with the formation of the compound nucleus and the subsequent statistical evaporation in which neutrons, protons, a-particle and y-rays are emitted until a population distribution for $^{73}$Se has been formed. The second part consists in selecting the portion of this population that will decay only by y-ray emission to form bound-states in the $^{73}$Se residual nucleus. Finally, the third part consists in introducing a sharp cut-off on the angular momentum population in order to reproduce the experimental isomer ratios $R$ (Fig.6).

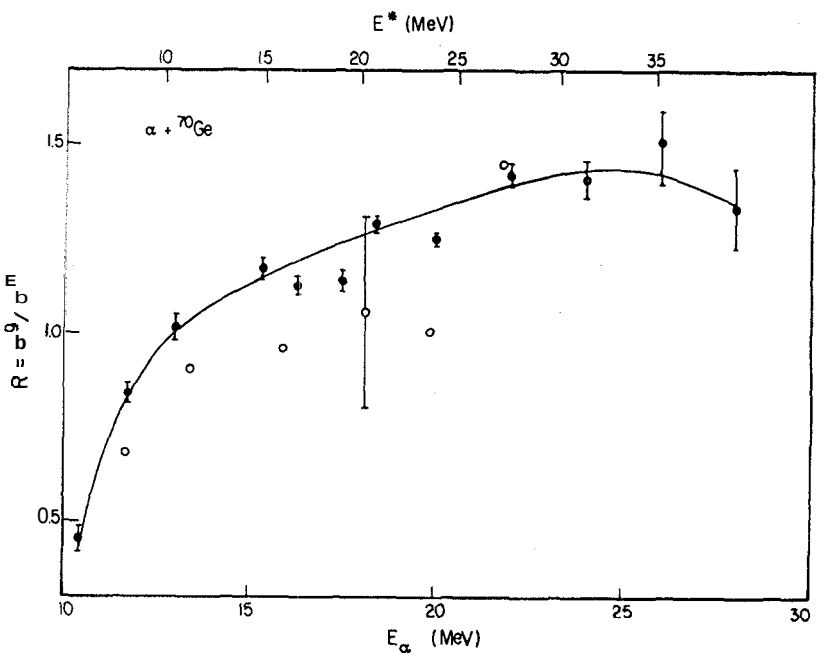


Fig 6 - Experimental (black points) isomer ratios R obtained in the α+$^{70}$Ge reaction. Early results of Demeyer et al[7] are also indicated (white points).

As the code ALICE fails to reproduce our experimental relative excitation f'unction for the $(\alpha,n)$ channel, (see fig. 4), we restrict the discussion to the calculations performed with the code JULIAN.

The $^{73}Se$ population distribution calculated following neutron decay from the compound nucleus is shown schematically in fig. 7. The top of the figure shows the compound nucleus $^{74}Se$ spin distribution, obtained by the code ALICE and given as an input to JULIAN. The $^{73}Se^*$ population is centered around spin 8 ħ and 10 MeV excitation energy and lies between the proton binding energy (-6 MeV) and the neutron binding energy (-10 MeV) which are represented by the lines $S_P$ and $S_N$ in fig.7, respectively. This means that a considerable fraction of this distribution will emit a second chance proton or high energy y-rays and only

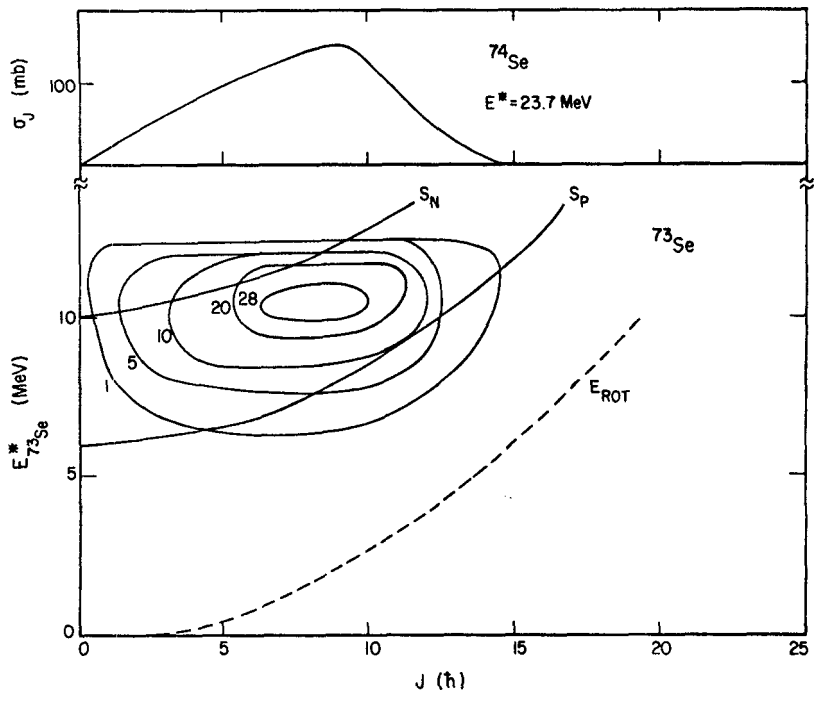


Fig.7 - $^{73}Se$ population distribution calculated with the code Julian (see text). The top of the figure shows the compound nucleus $^{74}Se$ spin distribution. $S_N$ and $S_P$ are the neutron and proton binding energies, respectively. The numbers on the distributions are in units of events/MeV/ħ.

a small fraction will deexcite by a second neutron emission. The fraction of the population surviving particle ($n$ or $p$) emission is shown schematically in fig. 8 and is now centered around spin 10 h and about

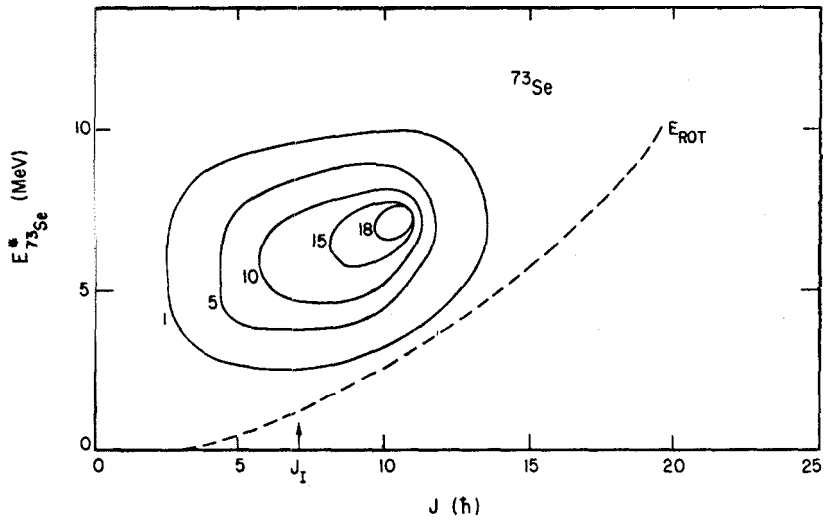


Fig.8 - Fraction of the $^{73}$Se population distribution that undergoes only y-ray deexicitation (see caption of the fig.7).

6.5 MeV excitation energy. As this population will only deexcite by γ--ray emission until the isomeric or the ground states has been formed, we may determine quantitatively the fraction of the population that will feed each state by introducing an angular momentum cut-off $J_I$ such that for $0 < J < J_I$, events located in this region will preferencially form the isomeric state, and for $J_I < J < J_{max}$, the respective events will form the ground state. The highest angular momentum in the entrance channel which forms the compound nucleus $^{74}$Se, $J_{max}$, is defined as the value for which the transmission coefficient $T$, calculated by the optical model subroutine PARAP[10], is $T(J_{max}) = 0.5$.

The values of the isomer ratios $R$ extracted from such an analysis are given in table 2 and their energy dependence is compared to the experimental results in fig. 9. An over-all good agreement is obtained between experimental results and the predictions of the code JULIAN. The error bars in the isomer ratios R are due to the Monte Carlo fea-

Table 2 - Sharp cut-off values $J_I$ of the angular momentum and calculated isomer ratios R obtained with the code Julian (see text).

| $E_\alpha$ (MeV) | $E^*$ (MeV) | $J_I(\hbar)$ | $R$ |
|---|---|---|---|
| 10,0 a) | 14,2 b) | 1 | 0.5 ± 0.03 |
| 15,0 | 19,0 | 5 | 1.04 ± 0.06 |
| 20,0 | 23,7 | 7 | 1,27 ± 0,10 |
| 25,0 | 28,4 | 9 | 1,65 ± 0,24 |
| 28,0 | 31,3 | 10 | 1,20 ± 0,46 |

a) a-particle laboratory energy. b) Compound Nucleus $^{74}Se$ Excitation Energy.

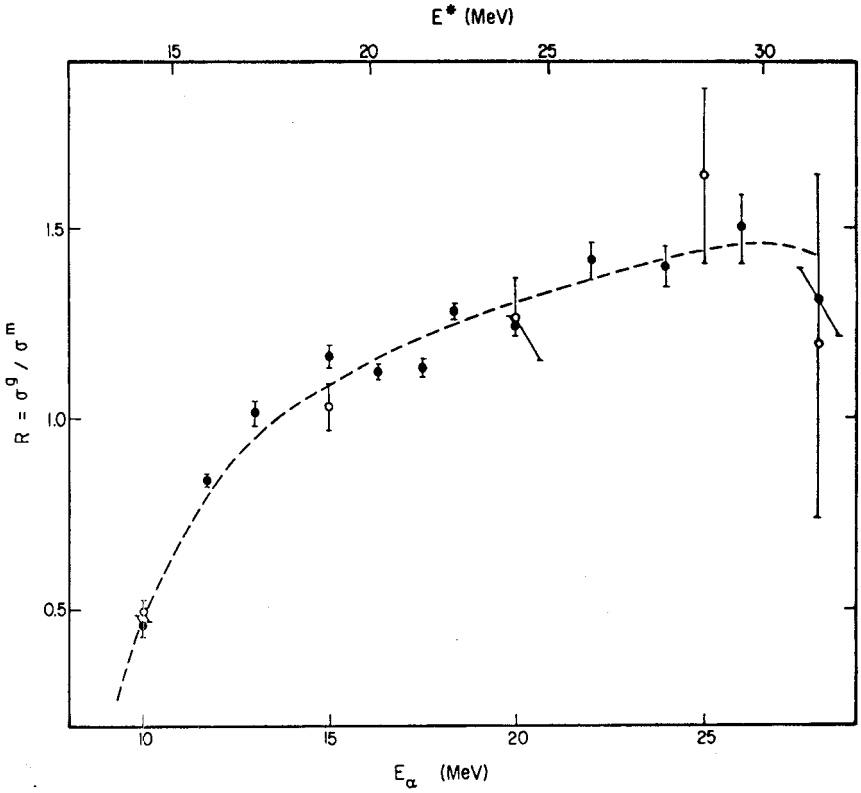


Fig.9 - Comparison between experimental isomer ratios R (black points) and predictions of the code JULIAN (white points) for the $\alpha + {}^{70}Ge$ reaction.

ture of the code JULIAN[9] and the large error bars for the two highest energies are due to the very low values of the respective cross-sections (see fig. 5). Figure 10 shows the general behaviour of $J_I$ with compound nucleus excitation energy.

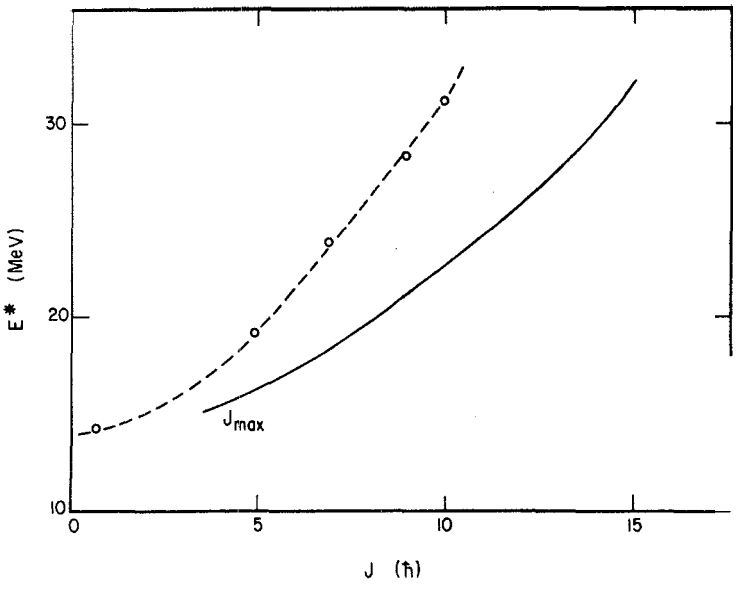


Fig.10 - Energy variation of the sharp cut-off angular momentum $J_I$ (circles) obtained with the code JULIAN (see text and table 2). Also indicated are the angular momenta $J_{max}$ in the entrance channel.

From the preceeding analysis of the $^{70}Ge(\alpha,n)^{73}Se^{m,g}$ reaction, it can be concluded that the statistical theory is suitable for a representation of the process involved. We have been able to reproduce the isomer ratios dependence on energy with a sharp cut-off angular momentum $J_I$ for isomeric and ground state formation. It would be interesting to make a comparison (which is under way) with results from $^{73}Se$ isomer ratios obtained[11] in the heavy ions reactions $^{16}O + {}^{63}Cu$ and $^{34}S + {}^{45}Sc$, where a large angular momentum population is available in the entrance channel and the compound nucleus $^{79}Rb$ is formed at very high excitation energy.

Finally, it is important to assess the absolute cross sections in order to be sure of the comparison with statistical model analysis calculations.

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**Resumo**

Razões isoméricas para o núcleo $^{73}Se^{m,g}$, produzido na reação $\alpha+^{70}Ge$ no intervalo de energia incidente $8<E_{\alpha}(MeV)<28$, foram deduzidas utilizando-se a técnica de espectroscopia $\gamma$ fora da linha. As seções de choque reiativas dos estados isomêrico e fundamental foram obtidas, utilizando alvos de germanio natural, Uma análise estatística de núcleo composto foi efetuada com os códigos ALICE e JULIAN, obtendo-se um bom acordo entre os dados experimentais e os resultados do programa JULIAN. As populações em momento angular para formação do estado isomérico foram determinadas na reação $^{70}Ge(\alpha,n)^{73}Se$.