# Probing the A~70 region with $^{6}Li$

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Reliable information on the ratio between the reduced transition probabilities to the first quadrupolar state, associated, respectively, with charge and mass excitations, was obtained along the Ge isotopic chain. This ratio informs about the isospin character of this quadrupolar excitation, an important nuclear structure indicator suited in special for a comparative evaluation. The systematic method of data acquisition and analysis, developed at the S. Paulo Pelletron Enge-Spectrograph facility for the study of inelastic scattering induced by isoscalar projectiles in the Nuclear–Coulomb Interference region was important to achieve this aim. The analysis of the inelastic scattering of $^{6}Li$ on $^{70,72,74}Ge$ resulted in ratios $B(E2)/B(IS2)e^2$ of 1.140 (35), 1.228 (36) and 0.664 (13), respectively, for the first quadrupolar excitation in the three isotopes studied, where the uncertainties are only statistical ones. Very important non-homogeneity was verified for $^{74}Ge$, with a strong predominance of the neutrons in this quadrupolar excitation.

## Introduction

Valuable information on the isospin character of collective nuclear excitations, in particular of the first quadrupolar ones, recognized as important structure indicators, can be achieved experimentally through detailed measurements of inelastic scattering induced by isoscalar projectiles in the nuclear-coulomb interference (NCI) region. Focusing on the intriguing nuclei with A~70 and Z~30 and, more particularly, on the even-A Ge nuclei, where shape coexistence and shape transition were diagnosed(1,2), the NCI studies are a specially convenient means of investigating structure changes along the chain. In fact, among other experimental evidence, two neutron transfer experiments, (p,t)(3) and (t,p)(4) reactions, had already suggested, also in this transitional mass region as is the case in the A ~ 100 one(5), that neutrons are related to the structure modifications in a manner which may not be accounted for by the B(E2) values, usually employed in the characterization of the collectivity.

At bombarding energies suitable for stable operation of the S. Paulo Pelletron accelerator, the lightest isoscalar projectile appropriate for NCI measurements, in this mass region, is $^{6}Li$. Exploring the good beam characteristics of the accelerator and the properties of the Enge split-pole magnetic spectrograph, rather forward scattering angles can be observed, resulting in very discriminative angular distributions, if the bombarding energy is conveniently chosen.

The S. Paulo Nuclear Spectroscopy Group has further developed a systematic method of analysis of the NCI[5,6], which allows to assess the relative importance of the electromagnetic and nuclear interactions, particularly for the first quadrupolar excitation. In fact, the interference pattern which is seen in the angular distribution depends strongly on the ratio between the reduced transition probabilities associated with charge and mass, B(E2)/B(IS2), of primary interest. In the ratio, scale uncertainties are cancelled and some model errors, associated with the analysis, may be reduced.

## Experimental Procedure

The good characteristics of the magnetic spectrograph, as well as the excellent beam profile of the São Paulo Pelletron accelerator and the additional care applied to focusing conditions, allow for the acquisition of data with the quality required for NCI studies in the region of A~70 with $^{6}$Li, characterizing of the shape of angular distribution. The use of clean targets, diminishing the contaminations in the spectra, is also an important aspect to be considered. In the investigation of the Ge chain, the 28.0 MeV $^{6}$Li beam of the Pelletron was focused on self-supported, isotopically enriched targets of $^{70,72,74}$Ge, after passing defining slits of 1.0 x 2.0 mm$^2$. The scattered particles impinged on a surface barrier position sensitive detector, with a sensitive area of 47 x 8 mm$^2$, positioned on the focal plane of the Enge spectrograph. Elastically scattered ions of $^{6}$Li were continuously monitored by a surface barrier detector, mounted at a fixed angle inside the scattering chamber, providing cross section normalization for the angular distributions.

In the excitation energy of interest, the background observed in the spectra is mostly due to the tail of the elastic peak and it depends crucially on the beam focusing. Figure 1 shows, as example, portions of position spectra for $^{70,72}$Ge, displaying the $2_1^+$ peak at some forward and intermediate scattering angles. An energy resolution of 34-38 keV was achieved in these spectra.

The experimental angular distributions, comprised of about 30 points each, were measured for elastic and inelastic scattering in the range $9^o \leq \theta_{lab} \leq 56^o$, with experimental statistical uncertainties lower than 10%.

## Analysis

The interest being centered in the comparative evaluation of the relative contribution of protons and neutrons to the first quadrupolar excitation along an isotopic chain, the DWBA-DOMP description employing global optical model parameters is an appropriate choice, since allows for a very consistent and uniform analysis, whenever the underlying hypotheses are met by the experimental situation. The excitation of the $2_1^+$ state in $^{74}$Ge by $^{6}$Li of 28.0 MeV was chosen as a test case to explore possible limitations of the analysis. Coupled channel calculations for this excitation, supposing $\beta_2^N$ equal to $\beta_2^C$ and including couplings to the ground and quadrupolar two phonon states[7], reveal only minor changes in the angular distribution associated with the first $2^+$ state in comparison with the DWBA-DOMP predictions without recoil. On the other hand, perfect agreement is shown between predictions including or not recoil effects.

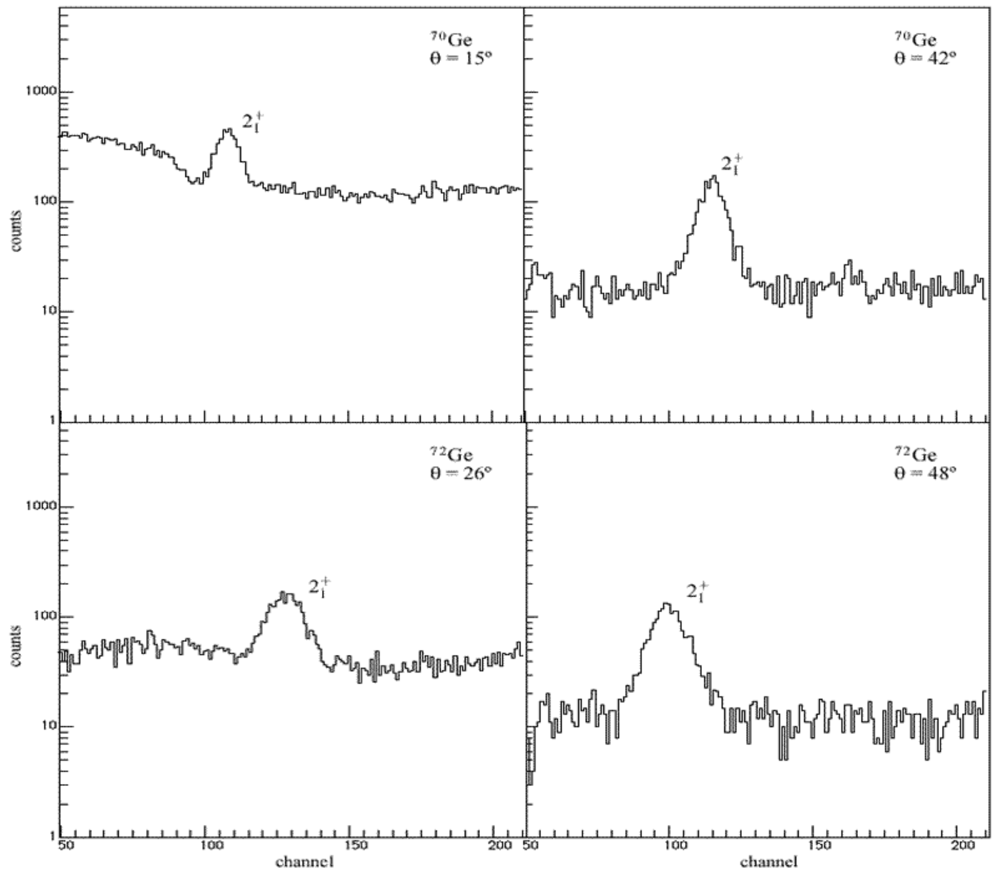


**Figure 1**: Portions of spectra of $^{70,72}$Ge($^6$Li,$^6$Li') taken at some selected forward and intermediate scattering angles, showing the peak associated with the $2_1^+$ state.

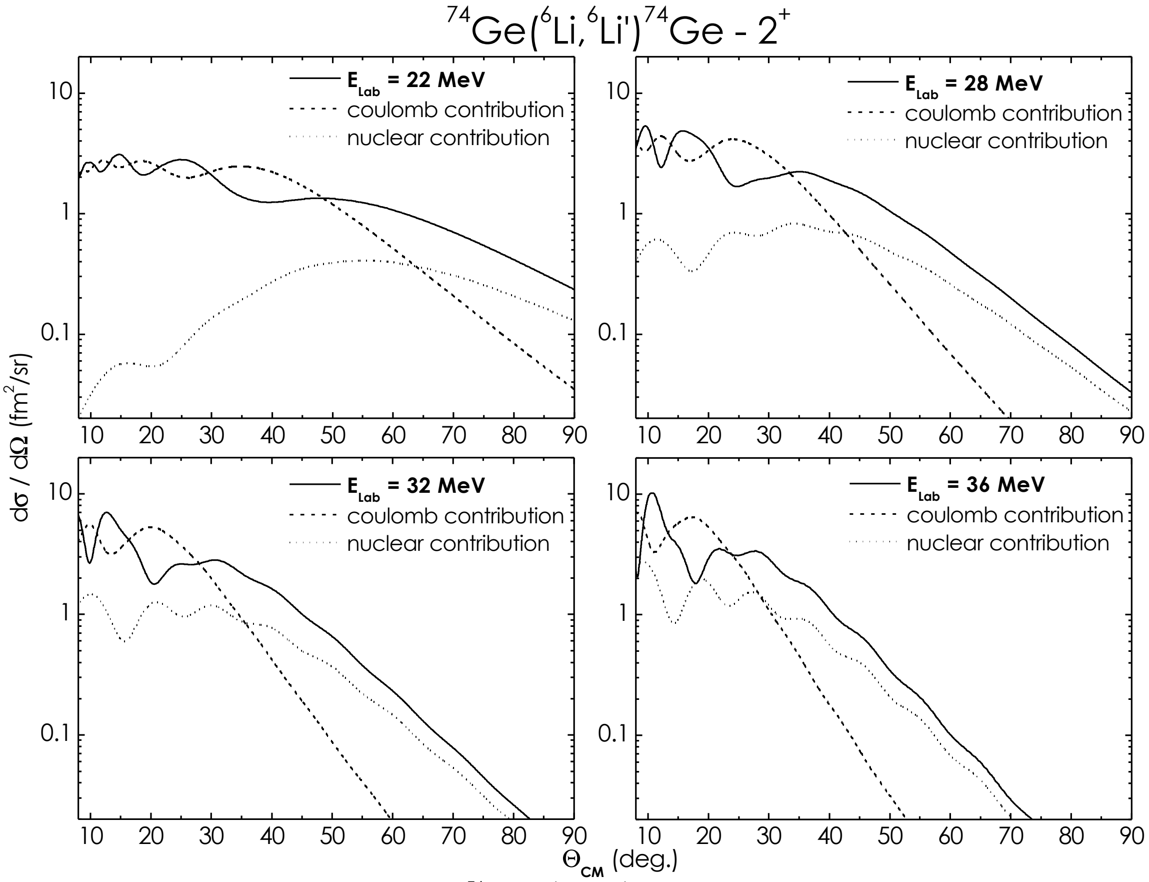


**Figure 2:** DWBA-DOMP predictions for the $^{74}$Ge ($0_1^+ \rightarrow 2_1^+$) excitation, taking C = 1. Separated and combined nuclear and coulomb contributions are shown, for the incident energies of 22, 28, 32 and 36 MeV.

An important feature for comparative analyses is that, in the DWBA-DOMP description, the same parameters are used, not only to represent the incident and emergent distorted waves, but also to describe the transition potential. For convenience of the analysis, the parameters $\delta_2^N$ (potential deformation length, taken equal to the mass deformation length characterizing the transition) and C, the last one defined through the ratio $\delta_2^C / \delta_2^N$, are chosen to describe the collective excitation and are extracted through the comparison between predicted and experimental angular distributions. To maintain free parameters under control it is of utmost importance to be able to choose a global optical model set. Such a set, although not much referred in the literature, is available for $^6$Li through the study of Cook[(8)], who analyzed a considerable amount of experimental information for $24 \leq A \leq 208$, in the incident energy range of 13-156 MeV. Those global parameters have provided very satisfactory fits in the analysis of $^6$Li elastic and inelastic data, both in the Ru[(9)] region and also in the Ge one[(10)].

The ratio of the transition probabilities B(E2)/B(IS2) is proportional to the square of the parameter C and is, therefore, directly determined, allowing to achieve a better accuracy than may be obtained through independent measurements of B(E2) and B(IS2). It is to be noted that, considering neutron and proton transition densities proportional to each other as is usual, the ratio $|M_n/M_p|$ of the quadrupolar moments of the neutron and proton distributions may also be obtained from the value of C. The value C=1 corresponds to the prediction of a homogeneous collective excitation, in which neutrons and protons contribute to the transition in the ratio of their numbers.

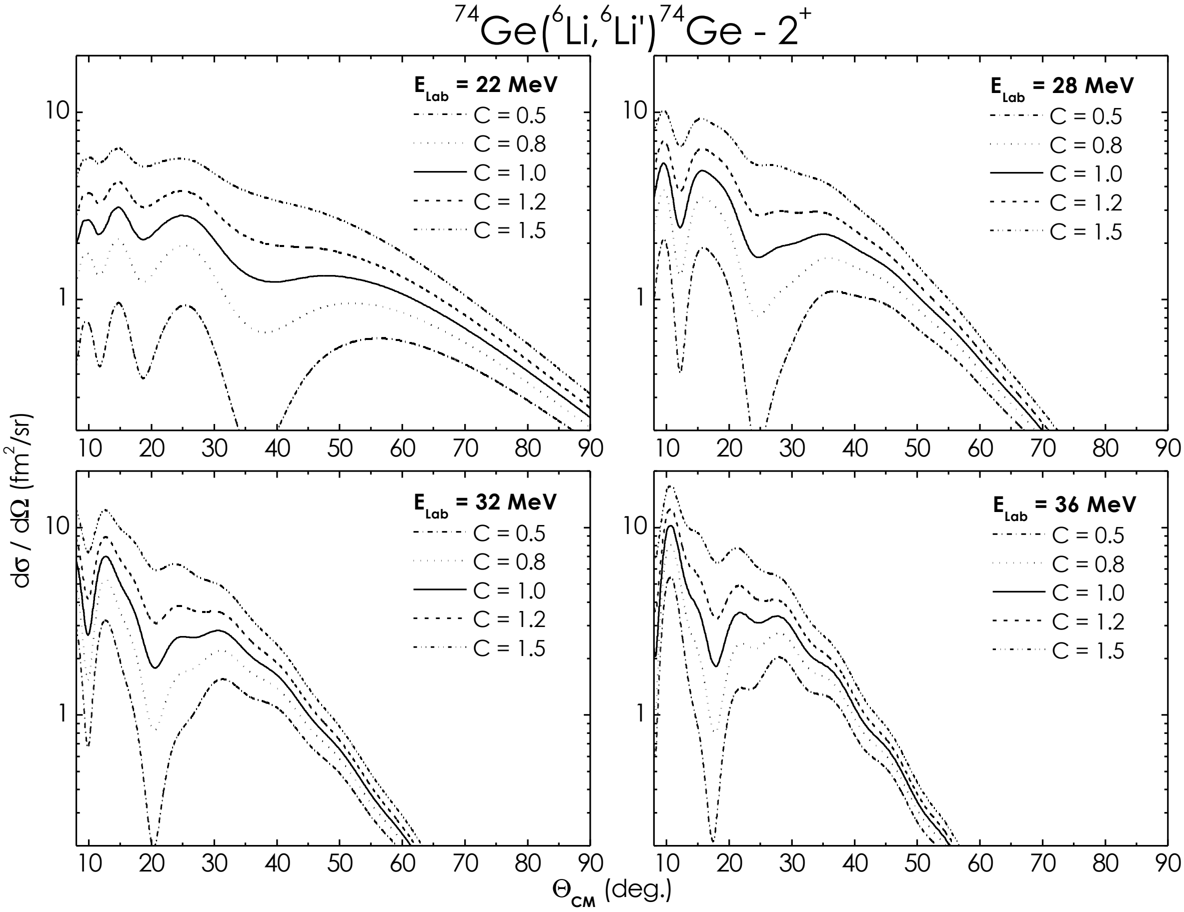


**Figure 3:** DWBA-DOMP predictions for the $^{74}$Ge ( $0_1^+ \rightarrow 2_1^+$ ) excitation, showing the effect of a range of C values on the angular distribution shape, for the incident energies of 22, 28, 32 and 36 MeV.

The discriminative power of the CNI method in the mass region of interest can be appreciated through inspection of Fig. 2 and 3, as function of $^6$Li beam energy. Both figures show DWBA-DOMP predictions for the $^{74}$Ge ($0_1^+ \rightarrow 2_1^+$) excitation, again taken as an example. Represented in Fig. 2 are, for C = 1, the separated and combined nuclear and coulomb contributions for the four incident energies of 22, 28, 32 and 36 MeV, where the extreme values are approximately the limits of the Tandem for this application. Fig. 3 illustrates, for the same incident energies, the effect of a range of values of C on the angular distribution shape, putting into evidence the changes produced in the interference pattern. The incident energy of 28 MeV was considered a convenient choice to perform the CNI analysis in this mass region, since, with it, measurements near the interference minimum, at $\theta_{c.m.} \sim 12.5^o$, are still accessible with the spectrograph, contributing to C discrimination, and, on the other hand, this energy favors the intensity of the transition, which decreases at smaller bombarding energies.

## Some Results and Discussion

The Ge chain provides an interesting testing ground for an experimental assessment of the B(E2)/B(IS2) ratio and, in the sequence, some results are presented and discussed. The DWBA-DOMP predictions without recoil effects, using the global optical model parameters of Cook [8], were fitted to the $2_1^+$ experimental angular distributions associated to the inelastic scattering of $^6$Li of 28.0 MeV by $^{70,72,74}$Ge, as can be appreciated in Fig. 4. The predicted values have been integrated numerically to account, in the center of mass system, for the scattering angles admitted through the spectrograph solid angle. In the fitting procedure the Gauss-Marquardt method [6] was applied in adjusting the parameters $\delta_N$ and C to minimize $\chi^2$. The extracted parameters with their respective statistical uncertainties and $\chi^2$ values are indicated in Fig. 4. Also shown, to illustrate the sensibility of the procedure, are the calculated angular distributions associated with C values obtained by adding or subtracting 0.100 to/from the best-fit values. To confirm the statistical adequacy of the method, Fig. 5 shows, as an example, two different views of the $\chi^2$ surface associated with the first quadrupolar excitation in $^{74}$Ge, in the space determined by the (C, $\delta_N$) plane, as obtained from a Monte Carlo simulation. For this, 10000 "new sets of experimental points" were generated by randomly choosing values from a gaussian distribution, with the given standard deviation, around each measured point. The $\chi^2$ contour lines obtained are almost perfect ellipses, in very good agreement with outcomes of the Gauss approximation.

The results of the present experiment are given in Table I. Very similar C values were obtained for $^{70}$Ge and $^{72}$Ge, but an abrupt change was detected for $^{74}$Ge, for which C=0.775 (8), clearly reveals a predominant contribution of the neutrons to its first quadrupolar excitation. Consistently, the ratio B(E2)/B(IS2)$e^2$, similar for $^{70}$Ge and $^{72}$Ge (respectively 1.140 (35) and 1.228 (36)), decreases significantly for $^{74}$Ge, reaching a value of 0.664 (13). It is to be remembered that the uncertainties refer only to propagated statistical ones.

The experimental ratios $|M_n/M_p|$, calculated from the extracted values of B(E2)/B(IS2)$e^2$ are, respectively for the isotopes of A=70 and A=72, 12% and 18% smaller than N/Z. On the other hand, a value 40% higher than the prediction of the homogeneous collective model was obtained for $^{74}$Ge, characterizing the strong predominance of the neutrons in this first quadrupolar excitation. This behavior can be associated with a change of shape between $^{72}$Ge (G.S.) and $^{74}$Ge (G.S.), pointed out before [11,12,13]. As indicated by experimental static quadrupole moments $Q_{2+}$ and B(E2) values, obtained in coulomb excitation studies [12,13], an almost spherical nature was assigned to the $^{70}$Ge and $^{72}$Ge ground and $2_1^+$ states, while a moderately deformed nature was, instead, attributed to the ground and $2_1^+$ states of the $^{74}$Ge and $^{76}$Ge.

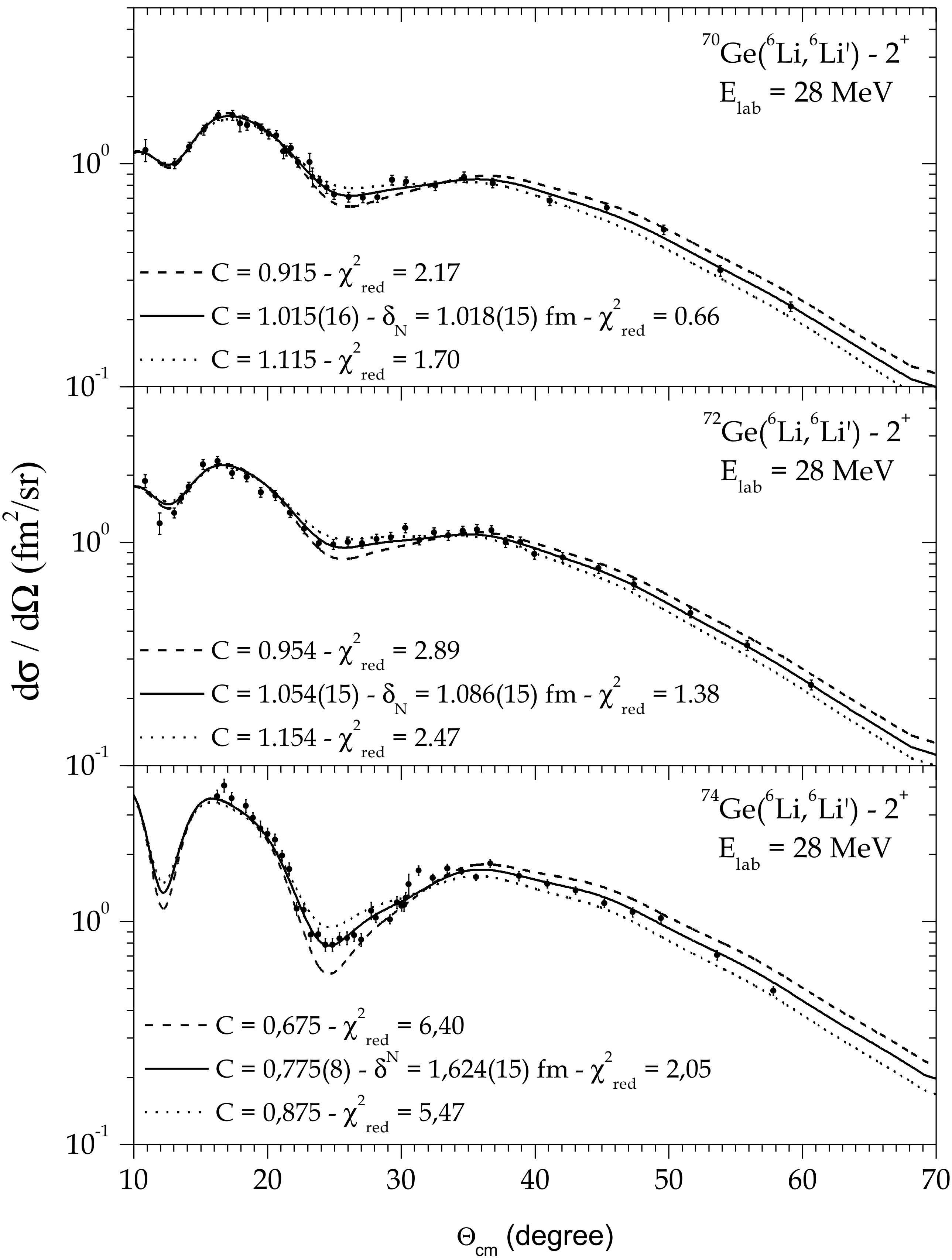


**Figure 4:** Experimental angular distributions of $^{70,72,74}$Ge($^{6}$Li,$^{6}$Li') $^{70,72,74}$Ge($2_1^+$) in comparison with the fitted DWBA-DOMP predictions, showing also the effect of small variations in C.

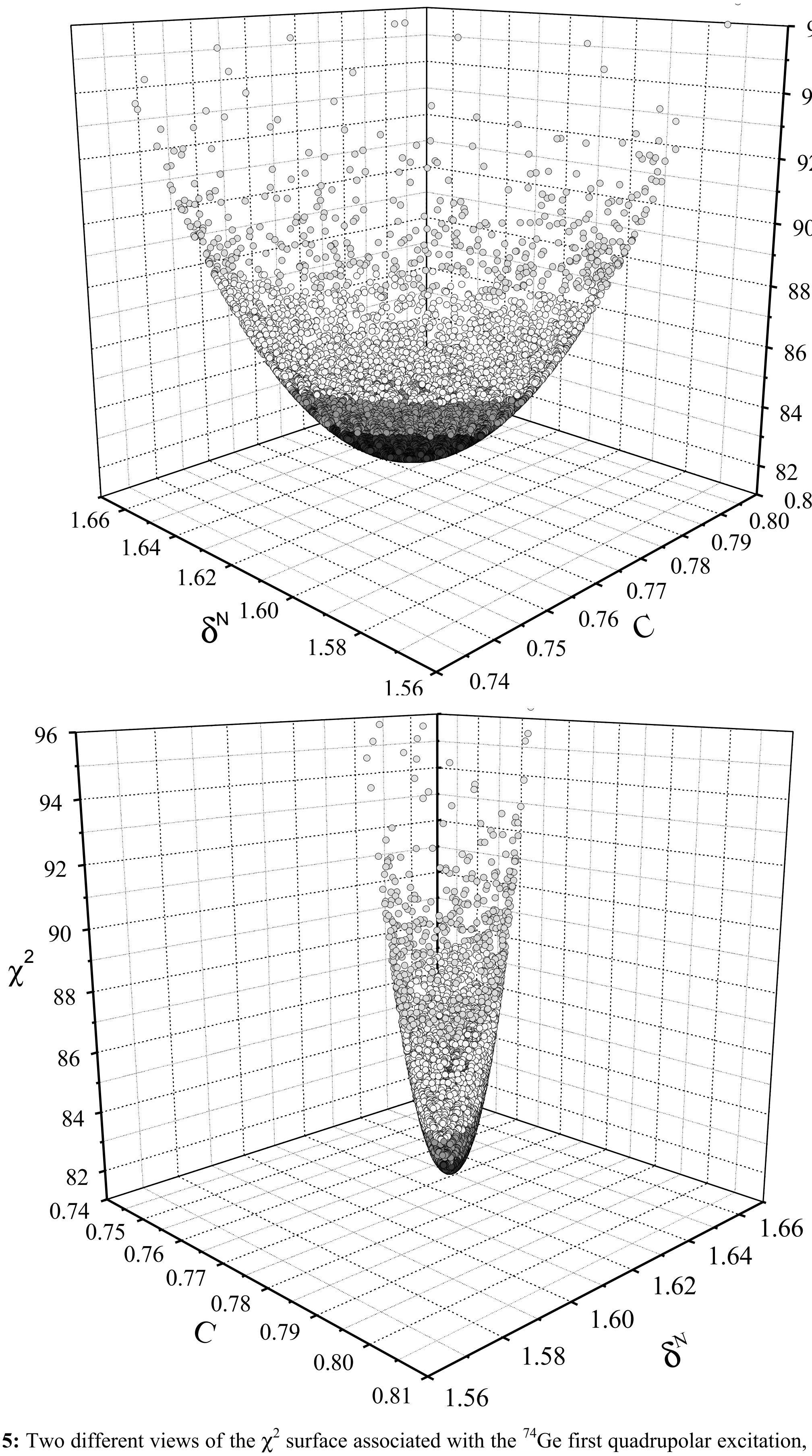


**Figure 5:** Two different views of the $\chi^2$ surface associated with the $^{74}Ge$ first quadrupolar excitation, in the space determined by the (C,$\delta_N$) plane, as obtained from a Monte Carlo simulation. For this, 10000 "new sets of experimental points" were generated randomly, choosing values from a gaussian distribution, with the given standard deviation, around each measured point.

The present results show, however, that either this deformed shape is in itself not homogeneous in protons and neutrons or that the $2_1^+$ excitation in $^{74}$Ge contains additional contributions of the neutrons, besides those built on the ground state. The good description of the $2_1^+$ excitation through the DWBA-DOMP approach, also for $^{74}$Ge, speaks in favor of the first hypothesis.

In view of the present results, in this mass region, any attempt of a theoretical interpretation for the underlying nuclear structure should be able to consider proton and neutron degrees of freedom, as separate, albeit interacting, entities.

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