Deuterons as probes in the Coulomb-Nuclear Interference region: isospin character of the first quadrupolar transition in even Palladium Isotopes

Márcia Regina Dias Rodrigues, Thereza Borello-Lewin, Lighia B. Horodynski-Matsushigue, Cleber Lima Rodrigues, José Luciano Miranda Duarte, Gilberto Mitsuo Ukita and Marcel Dupret Lopes Barbosa.

Instituto de Física, Universidade de São Paulo (IFUSP), São Paulo, Brazil

Angular distributions for the inelastic scattering of 13.0 MeV deuterons on ^{104,106,110}Pd were measured with the São Paulo Pelletron-Enge-Spectrograph facility in the range of $12^0 \leq \theta_{lab} \leq 68^0$. A Coulomb-Nuclear Interference analysis, employing the Distorted Wave Born Approximation with the Deformed Optical Model as transition potential, under well established global optical parameters, was applied to the first quadrupolar excitations. The values of C = d_L^C / d_L^N, the ratio of charge to isoscalar deformation lengths, and of d_L^N were extracted through the comparison of experimental and predicted cross section angular distributions. The ratios of reduced charge to isoscalar transition probabilities, B(EL) to B(ISL) respectively, are related to the square of the parameter C and were thus obtained with the advantage of scale uncertainties cancellation. For ^{104}Pd, the value of C = 1.18(3) reveals an enhanced contribution of the protons relative to the neutrons to the 2_1^+ excitation, while only a slight effect is found for ^{106}Pd, C = 1.06(4) and for ^{110}Pd, C = 1.07(3), in comparison with the value C = 1 expected for homogenous collective excitations.

I. Introduction

Inelastic scattering is known to be a powerful tool for studying collective states. In particular, the Coulomb-Nuclear Interference (CNI), using a probe with isoscalar character, allows for the simultaneous extraction of the isoscalar and electric reduced transition probabilities, B(ISL) and B(EL), respectively. The São Paulo Nuclear Spectroscopy with Light Ions Group developed a research line that uses CNI in the inelastic scattering of isoscalar probes, in particular deuterons, by nuclei, with the aim of following the evolution of the collective behavior throughout isotopic chains[1,2]. The adopted procedure applies the deformed optical potential model (DOMP) with global optical parameters as the nuclear transition potential in the analysis of the inelastic scattering. It is to be noted that, for the first quadrupolar excitation, the majority of the microscopic form factors do not differ substantially from the macroscopic ones in the important tail region. Through this macroscopic CNI analysis in the DWBA approach, $(d_L^N)^2$, the square of mass deformation length, is extracted as a scale factor from the fit of the predicted cross sections to the experimental data of the inelastic scattering reaction and, analyzing the characteristic changes in the angular distribution shape, the value of the ratio between charge (d_L^C) and mass (d_L^N) deformation lengths, C, is also obtained. These quantities can be put in correspondence with the value of B(ISL) and of the ratio B(EL)/B(ISL), for which, therefore, a scale uncertainty cancellation occurs, favoring more accurate results. Furthermore, for deuterons there are global optical potential parameter sets, which were extensively tested, allowing for a good control of the free parameters in the analyses.

In the A ~ 100 transitional mass region, due to the relevant role played by the neutrons, an a-priori assumption of the dominance of simple homogenous collective effects (relative contributions of protons and neutrons of about Z/N) is not indicated and a direct access to the reduced isoscalar transition probability B(IS2) (mass), besides B(E2), is demanded. Values of B(IS2) and B(E2) were simultaneously measured for ^{94,98}Mo[1] and ^{100,102,104}Ru[2] in recent CNI studies of this region by the São Paulo group.

The present work applies the CNI method to the inelastic scattering of deuterons on even palladium isotopes. Data were obtained for the ^{104,106,110}Pd(d,d')Pd (2_1^+) reactions at 13.0 MeV in the Pelletron Laboratory, using nuclear emulsion plates on the focal plane of the Enge Split Pole Spectrograph. For these excitations, no results of B(IS2) had been formerly reported in the literature.

II. Experimental Procedure

Data for the inelastic scattering of deuterons of 13.0 MeV by ^{104,106,110}Pd were obtained, using the Pelletron-Enge-Spectrograph system. The deuteron beam was extracted from a “SNICS” ion source, provided with a solid titanium deuteride cathode. The beam was focused on the target after passing defining slits of 1.2 mm width and 3.0 mm height (spectrograph object). An adequate profile of the beam is important for a good quality of the data.

Targets of isotopically enriched materials of ^{104,106}Pd (98.98%, 98.53%), with thicknesses of 20 and 35 μg/cm^2, respectively, were produced in São Paulo by the electron bombardment method. Only rather small amounts of the usual contaminations by C, N, O, Si, S, K e W were diagnosed in these targets and also in the ^{110}Pd target (64 μg/cm^2) produced formerly in Germany by a sputtering procedure.

The scattered deuterons were momentum analyzed by the Enge Magnetic Spectrograph and detected in nuclear emulsion plates (Fuji G6B, 2G and 7D, 50 μm thick), which covered 25 cm along the focal plane of the spectrograph. The greatest advantage of nuclear emulsion is that this detector does not respond to the abundant background, mostly g and X rays from (n, g) reactions in the spectrograph iron core after deuteron break-up. Spectra were taken at judiciously chosen scattering angles in a range of $12^0 \leq \theta_{lab} \leq 68^0$, in order to characterize the INC in the angular distribution corresponding to the first quadrupolar excitation. After processing, the exposed plates were scanned in strips of 200 μm across the plates. An energy resolution of 7 keV was achieved. Figure 1 displays the relevant part of the deuteron spectra corresponding to some selected scattering angles, showing the peak associated with the 2_1^+ state, at a forward angle, showing the elastic tail, and at intermediate scattering angles, one of those in the angular region where the elastic peaks of the most influent contaminants (C, N, O) cross the region of interest.

The total number of projectiles corresponding to each spectrum was obtained with the help of a calibrated current integrator connected to an aligned Faraday cup with electron suppression. The beam direction was continuously monitored. The relative normalization of the spectra was thus obtained, while the absolute normalization of the cross sections was referred to optical model predictions for the elastic scattering of deuterons on the same target, measured under similar conditions. The elastic spectra were measured at laboratory scattering angles in the range of $30^0 \leq \theta_{lab} \leq 78^0$.

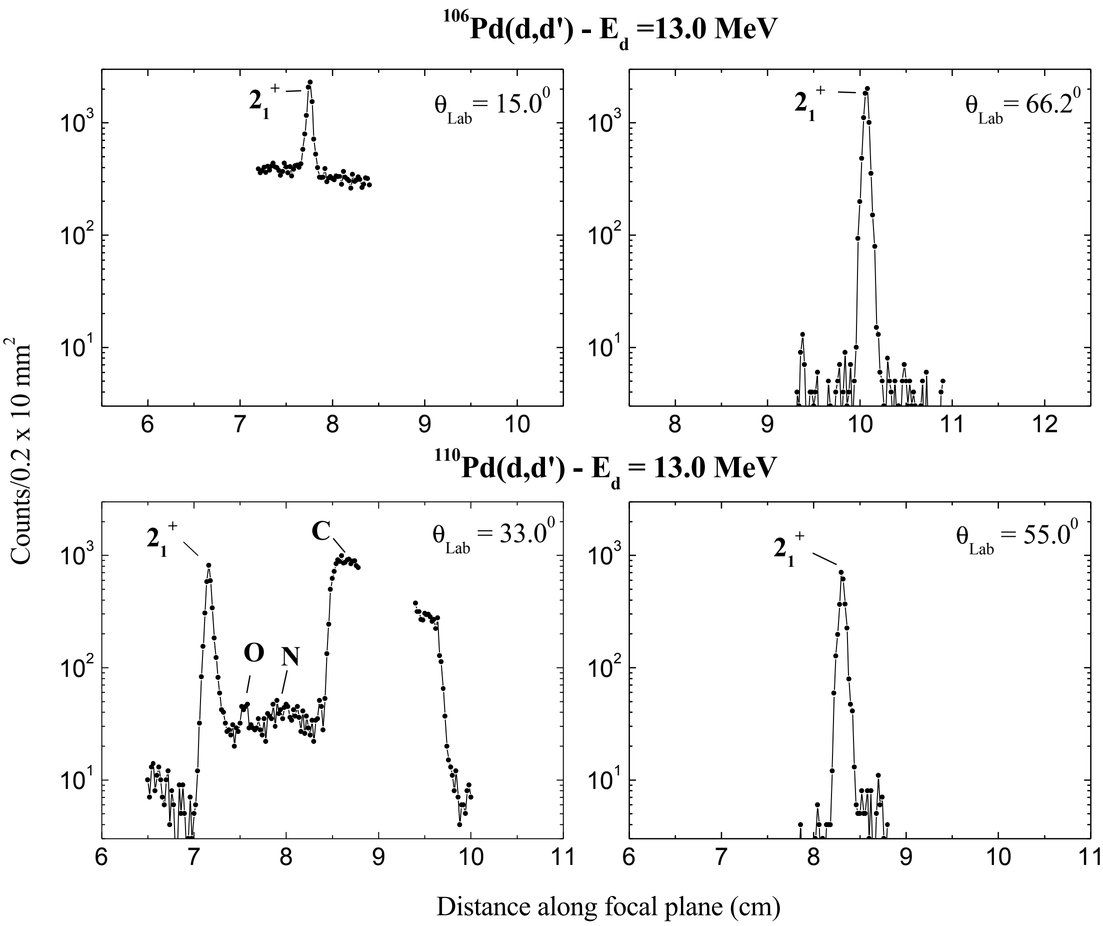

Figure 1: Portions of the spectra of inelastic scattering of deuterons of 13.0 MeV on ^{106,110}Pd, showing the peak associated with the 2_1^+ state and the elastic scattering peaks on O, N and C, where near to the one of interest.

III. Analysis

The excitation of the first quadrupolar states of ^{104,106,110}Pd was analyzed in terms of the distorted wave Born approximation (DWBA) - deformed optical potential model (DOMP) approach. The parameters of Perey & Perey[(3)], were chosen, both, for the absolute normalization of the elastic cross section, and for the generation of the distorted incident and outgoing waves in the reaction analysis and also for the transition potential to the collective state. These parameters are being systematically used by the S. Paulo Group in the CNI studies with inelastic scattering of deuterons, in this mass region. The DWBA-DOMP calculations were performed with the code DWUCK4[(4)] with the usual corrections to account for non-locality effects.

The DWBA-DOMP description of the experimental cross section is:

$$\left(\frac{d\sigma\ (\theta)}{d\Omega}\right)_{\exp} = \alpha\,\sigma_{DWBA-DOMP}(\theta)$$

In the fit of each experimental angular distribution, through the factor α, the square of the mass deformation length $\left(\delta_L^N\right)^2$ is obtained, while the characteristic shape is related to C.

In Figure 2, the curves associated with the values of C_{fitted} are results of linked parameters fitting, since C and δ_L^N are correlated. Due to the cross section not being a linear function of C, the procedure chosen for the χ^2 minimization was the iterative method of Gauss[(5)], that presents a rapid convergence. From the values of C, it is possible to calculate the ratio:

$$\frac{B(EL)}{B(ISL)} = e^2\left(\frac{\delta_L^C}{\delta_L^N}\right)^2\left(\frac{r_C}{r_m}\right)^{2L-2} = e^2C^2\left(\frac{r_C}{r_m}\right)^{2L-2}$$

where, r_C and r_m are, respectively, the characteristic reduced radii of the charge and the mass distributions of the nucleus.

The reduced isoscalar transition probability was therein related to δ_L^N, using the Bernstein[(6)] definition, through:

$$B(ISL) = \left(\delta_L^N\right)^2\left(\frac{3Z}{4\pi}R_m^{L-1}\right)^2 .$$

with $R_m = r_m A^{1/3}$.

Under further assumptions[(1)], the ratio between the quadrupolar moments of the neutron and proton distributions, $|M_n/M_p|$, an indicator of the isospin character of the nuclear transition, can be obtained through the relation:

$$\left|\frac{M_n}{M_p}\right| = \frac{A}{Z}\sqrt{\frac{B(IS2)}{B(E2)/e^2}} - 1 = \frac{A}{Z}\cdot\frac{1}{C}\cdot\frac{r_m}{r_c} - 1 .$$

The comparison between $|M_n/M_p|$ and N/Z (expected to be approximately equal for a homogeneous collective excitation) is another manner to characterize the role played by the neutrons relative to the protons in the 2_1^+ excitations.

IV. Some Results and Discussion

In the analysis of ^{104,106,110}Pd, the experimental data for the inelastic scattering to the 2_1^+ state are discriminative for C and δ_2^N when compared with the predicted angular distributions, as shown in Figure 2. In order to illustrate the sensibility to the C_{fitted} value, two curves associated with values of C ≅ C_{fitted} + 0.2, are also represented in Figure 2, with the respective value of χ^2.

The values of C and δ_2^N extracted through the inelastic scattering of deuterons of 13.0 MeV on ^{104}Pd, ^{106}Pd and ^{110}Pd, for the 2_1^+ states, are presented in Table 1. The uncertainties shown are only the statistical ones. The values of the ratios B(E2)/B(IS2), of B(IS2) and of $|M_n/M_p|$ obtained are also shown in Table 1. The uncertainties indicated were calculated by simple propagation.

For ^{104}Pd, the extracted C value reveals a non-homogeneous behavior, with an enhanced contribution of the protons relative to the neutrons to the first quadrupolar excitation, while a less pronounced effect is found for ^{106,110}Pd, although the values of C are also slightly higher than 1.00 for both.

Some other recent results obtained by the São Paulo group in the A~100 region, with the CNI methodology applied to the inelastic scattering of isoscalar projectiles, are shown in Table 2, for further consideration. The isotopes ^{94}Mo and ^{98}Mo were studied using deuterons as projectiles[(1)], while ^{100,102,104}Ru were investigated through inelastic scattering of alpha particles[(2)].

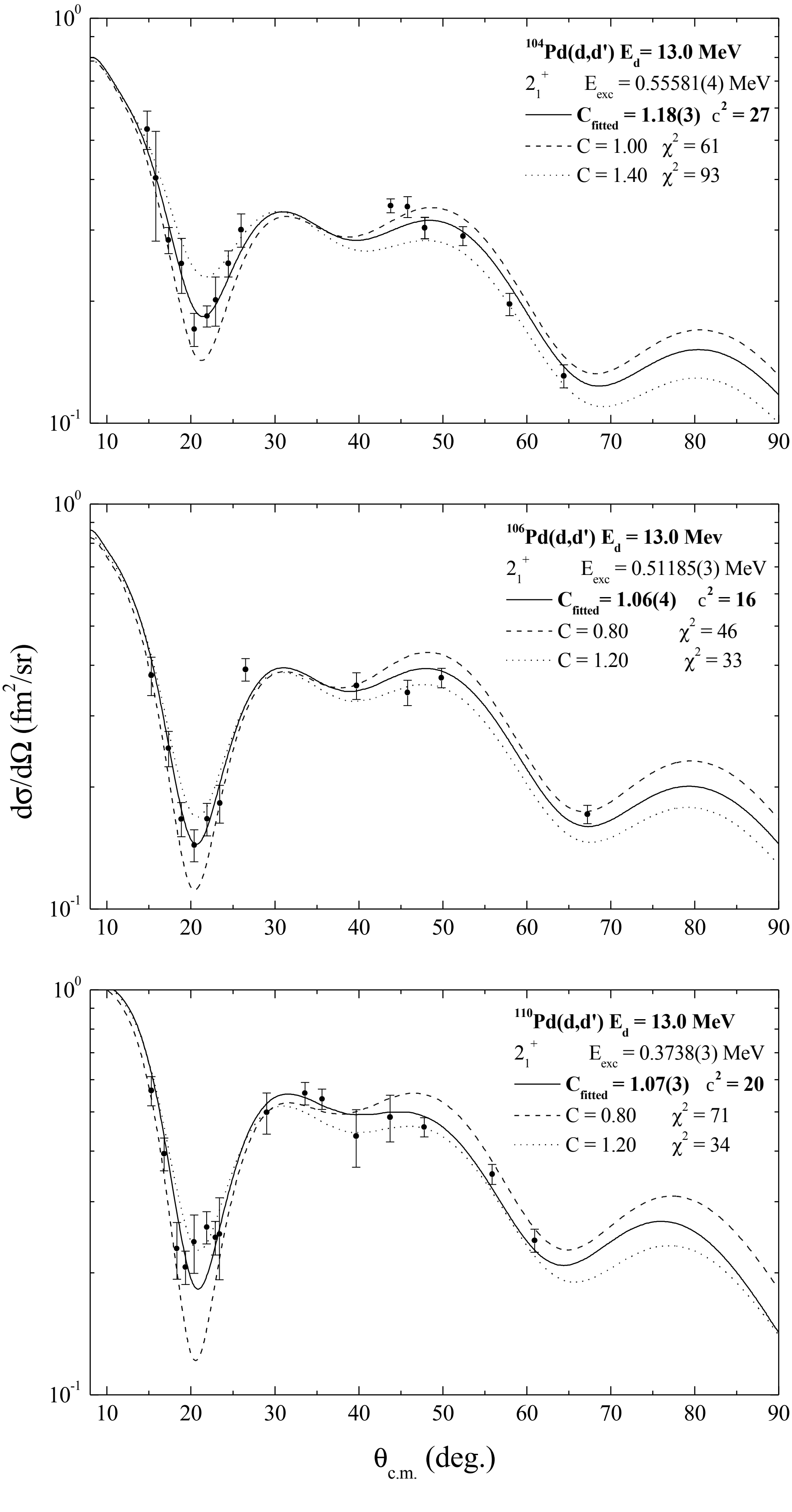

Figure 2: Experimental inelastic scattering angular distributions of deuterons of 13.0 MeV on ^{104,106,110}Pd, associated with the 2_1^+ states.

Nucleus	C	d_2^N (fm)	B(E2)/B(IS2) (e^2)	B(IS2) (b^2)	$\|M_n/M_p\|$	*N/Z*
^{104}Pd	1.18(3)	1.00(2)	1.54(8)	0.356(13)	0.82	1.26
^{106}Pd	1.06(4)	1.05(2)	1.24(9)	0.402(19)	1.07	1.30
^{110}Pd	1.07(3)	1.27(3)	1.26(8)	0.596(26)	1.13	1.39

Table 1: Results obtained in this work for Pd isotopes, through the analysis of CNI, where r_c = 1.22 fm and r_m = 1.16 fm[7].

Nucleus	C	B(E2)/B(IS2)e^2	$\|M_n/M_p\|$	*N/Z*
^{94}Mo[1]	1.123(20)	1.39(7)	0.89	1.24
^{98}Mo[1]	1.148(24)	1.46(6)	0.93	1.33
^{100}Ru[2]	1.040(32)	1.20(7)	1.19	1.27
^{102}Ru[2]	1.140(34)	1.44(8)	1.03	1.32
^{104}Ru[2]	1.220(45)	1.65(12)	0.94	1.36

Table 2: Results of CNI studies undertaken in S. Paulo.

Comparing the nuclei studied in the present work with their isotones in the Ru chain, formerly investigated, it is to be noted that the nucleus ^{102}Ru[2], in the same manner as the isotone ^{104}Pd does, reveals a more important contribution of protons than of neutrons to the first quadrupolar excitation. Following the Ru chain, although a rather intense non-homogeneity also in favor of the protons is presented by ^{104}Ru, this behavior is in strong contrast to its isotone ^{106}Pd, for which the non-homogeneity is diluted. Figure 3 shows the values of the B(E2)/B(IS2)e^2 ratios, extracted in this work for the three even isotopes of Pd analyzed, in comparison with the results obtained for even isotopes of Ru[2] and Mo[1]. It is seen that for the even Ru isotopes there is a growth as N increases, while for the even Pd isotopes a different behavior emerges, since the values associated with N = 60 and N = 64 are about the same and smaller than the ratio obtained for N = 58.

Figure 4 shows the evolution of the B(E2) values, taken from the comprehensive survey by Raman[8]. The nuclei studied recently by the São Paulo group are circled in the figure for easier identification. It is seen that, between ^{94}Mo, on one side, and ^{104}Ru and ^{110}Pd, on the other, the B(E2) values increase by more than a factor of 4, demonstrating the well known tendency to deformation, verified in this mass region for N ≥. 60. As shown by Figure 3, the values of the B(E2)/B(IS2) ratio vary from around 1.2 e^2(^{106,110}Pd and ^{100}Ru) to approximately 1.6 e^2(^{104}Pd and ^{104}Ru), therefore the neutron contribution to the first quadrupolar excitations generally lags behind the proton one in the three isotopic chains investigated for N ~ 60. No monotonic behavior is evident for this ratio, pointing out that, in this long established region of shape transitions, neutrons may be responsible for some interesting effects outside the simple collective interpretation.

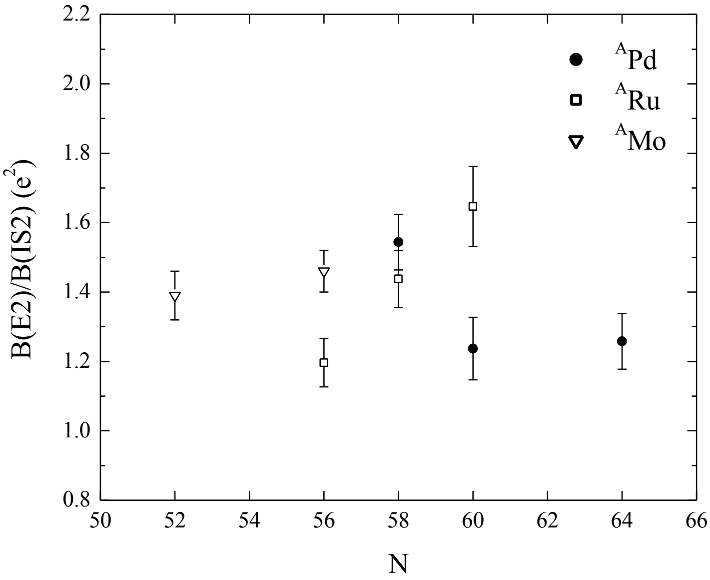

Figure 3: Ratios B(E2)/B(IS2) for $^{104, 106, 110}$Pd, present work, in comparison with the ones obtained for ^{100,102,104}Ru[2] and ^{94,98}Mo[1].

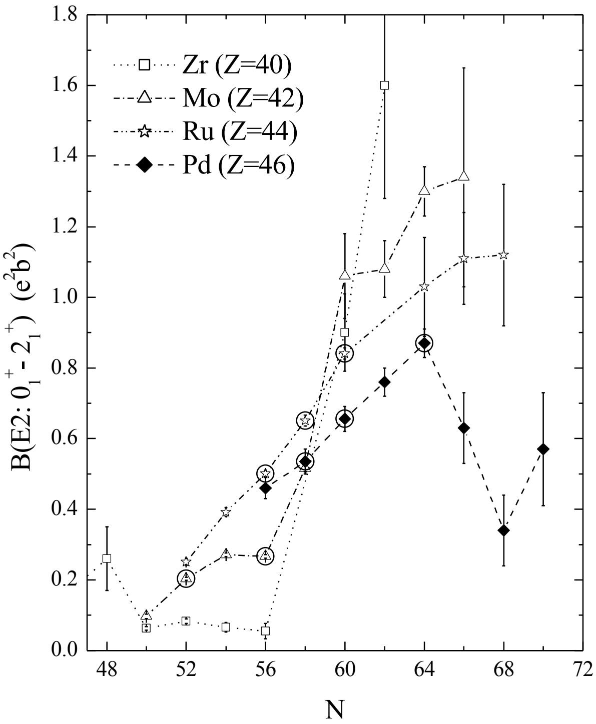

Figure 4: Evolution of the B(E2) values[8] for even-even nuclei in the region A~100.

Acknowledgments

This work was partially supported by Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP).

References

[1] G. M. Ukita, T. Borello-Lewin, L. B. Horodynski-Matsushigue, J. L. M. Duarte, and L. C. Gomes, Phys. Rev. C **64**, 014316 (2001).
[2] L. C. Gomes et al., Phys. Rev. C **54**, 2296 (1996).
[3] C. M. Perey and F. G. Perey, Atom. Data and Nucl. Data Tables **17**, No 1 (1976).
[4] P. D. Kunz, *computer code DWUCK4*, University of Colorado (1974).
[5] P. R. Bevington, Data Reduction and Error Analysis for the Physical Sciences (McGraw Hill, New York, 1969).
[6] A. M. Bernstein, V. R. Brown, and V. A. Madsen, Phys. Lett. **71B**, 48 (1977); **103B**, 255 (1981).
[7] H. S. Chung and W. D. Myers, Nucl. Phys. **A513**, 283 (1990).
[8] S. Raman et al., *Atomic Data and Nuclear Data Tables*, **36**, N° 1 (1987)