PROCEEDINGS OF SCIENCE

Isoscalar Giant Monopole Resonance in ^{60}Ni

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The decay of Giant Resonances is analyzed through the Statistical Multi-step Compound Nucleus Theory. This decay is interpreted in terms of the Damping, Preequilibrium Escape and Direct Escape Widths. An analysis of the results obtained for the total width of isoscalar electric giant monopole in ^{60}Ni isotope is made comparing with experimental data.

5th International School on Field Theory and Gravitation,
April 20 - 24 2009
Cuiabá city, Brazil

*Poster Section
†PSR thanks to CAPES for the partial support

PoS(ISFTG)082

1. Introduction

Systems excited by a small perturbation can present collective motions. In atomic nucleus these perturbations can induce collective states involving all or most of the nucleons that make up this system. This phenomenon is called Giant Resonance (GR), occurring throughout the table of nuclides and lie in the range of 10-30 MeV of the energy spectrum of nuclear excitation.

The first evidence of such nuclear collective phenomenon was observed in an experiment in 1937 during the measurement of the radioactivity induced by bombarding several samples with γ-rays by Bothe and Gentner[1]. Only after a decade, in 1947, the study of these resonances were systematized by Baldwin and Klaiber [2], when they came to find out what would be called giant dipole resonance. Other multipolarities were observed later as the giant quadrupole resonance in 1972 by Lewis and Bertrand[3], and giant monopole resonance 1977 by Youngblood et al.[4].

Studies of the characteristics of GR have been used in several areas of research, since these resonances have an important role in nuclear reactions that occur in nature. An example can be seen in the supernova star explosion. The capture rate of electrons that cools the core of the star involved in the explosion and accelerates the process of gravitational collapse is associated with the properties of Gamow-Teller giant resonance.

The intensity of the shock wave created by the collapse is directly related to the incompressibility of nuclear matter used in the description of the neutron stars, and related to the energy excitation of the GR electric monopole [5].

The beginning of activities of the Large Hadron Collider (LHC) will further boost the study of giant resonances, since the experiments of heavy ion collisions will generate several artificial nuclei and the creation of positron-electron pairs at the periphery of these collisions, along with the magnetic excitation in both ions (Magnetic Dipole GR)[6].

One of the parameters adopted for the theoretical study of excitation and decay of the GR is the width of the resonance. We can describe the GR through the superposition of coherent excitation of particle-hole type. As the GR are located above the threshold of emission of particles it is also necessary to take into account meta-stable resonant states that are a continuous part of the single particle spectrum. The total width of the resonance (Γ) is composed of two pieces: the Escape width ($\Gamma^{\uparrow}$), due to the coupling of excitations of the type of particle-hole continuum, and the Damping width ($\Gamma^{\downarrow}$) associated with the coupling of more complex intrinsic nuclear configurations.

The study presented here aims to describe the decay of the Isoscalar Giant Monopole Resonance (ISGMR) in the ^{60}Ni nucleus.

2. Theoretical Fundamentation

According to the Statistical Multi-step Compound Nuclei theory of Feshbach, Kerman and Koonin[7][8], the width (Γ_{nJ}) of a given GR with excitation energy E, angular momentum J and in the *n-th* stage chain is given by:

$$\langle \Gamma_{nJ} \rangle = \langle \Gamma^{\downarrow}_{nJ} \rangle + \sum_{\nu=n-1}^{n+1} \sum_{js} \int_0^{E-B} \langle \Gamma^{js\nu}_{nJ}(U) \rho_{s\nu}(U) \rangle dU \qquad (2.1)$$

where $\langle\Gamma^{\downarrow}_{nJ}\rangle$ is the width of damping and the remaining terms of the right hand side of the equation characterize the width of escape, with $\nu = n+1$, $\nu = n$ and $\nu = n-1$ corresponding to emission of a nucleon with the simultaneous creation of a particle-hole pair, no change in the number of excitons or an annihilation of a particle-hole pair, respectively. B is the binding energy of the emitted nucleon, U is the energy of the residual nucleus and ρ is the density of single particle levels given by:

$$\rho_{ph}(E,J) = \frac{g(gE)^{N-1}}{p!h!(N-1)!}R_N(J) \tag{2.2}$$

where

$$R_N(J) = \frac{(2J+1)}{\pi^{\frac{1}{2}}N^{\frac{3}{2}}\sigma^3}e^{-(J+1/2)^2/N\sigma^2} \tag{2.3}$$

is the distribution of spins of single-particle levels. The parameter *cut-off* of single-particle spin (σ) and the spacing between the levels (g) are functions that depend on the number of nucleons (A)[7]:

$$g \sim \frac{3A}{4\pi^2}\,, \qquad \sigma = \left[\frac{\sqrt{12}}{45\pi}\frac{A^{5/3}}{g}\right]^{1/2}. \tag{2.4}$$

In this model we assume the excitons interaction is a force of the type δ:

$$V(\mathbf{r}_1,\mathbf{r}_2) = V_0\left(\frac{4}{3}\pi r_0^3\right)\delta(\mathbf{r}_1-\mathbf{r}_2) \tag{2.5}$$

where V_0 is an overall strength and $r_0 = 1,25fm$ is the nuclear radius constant.

The calculation of the widths is done assuming the factorization of the total width in energy dependent and angular momentum dependent parts. In general the widths will take the form:

$$\langle\Gamma_{nJ}\rangle = X_{nJ}Y_n(E) \tag{2.6}$$

Accordingly, the X functions contains the angular momentum structure included in the δ-force and the distribution of spins of single-particle levels, while the Y functions contains all the dependence originating in the final density of levels.

In this work we adopt that the decay of the GR occurs in the first stage of the chaining. All the processes initiate with a configuration of $1p-1h$ and evolve to $1p-1h$ or $2p-2h$, depending on the considered case (see Figure 1). The total width of the GR is given by:

$$\langle\Gamma_{nJ}\rangle = \langle\Gamma^{\downarrow}_{nJ}\rangle + \langle\Gamma^{\uparrow\text{preeq}}_{nJ}\rangle + \langle\Gamma^{\uparrow\text{dir}}_{nJ}\rangle \tag{2.7}$$

The Y functions represented in the diagrams of Figure 1, for direct and preequilibrium escapes widths are given by[9][10][11]:

$$Y_n^{\uparrow n}(E) = \int_0^{E-B}\omega(p-1,h,U)dU \tag{2.8}$$

$$Y_n^{\uparrow n+1}(E) = \int_0^{E-B}\frac{1}{2}\frac{g^3}{\omega(p,h,E)}\frac{\omega(p,h-1,U^N)}{N(N-1)}dU \tag{2.9}$$

and, for damping

$$Y_n^{\downarrow}(E) = {}_aY_n^{\downarrow} + {}_bY_n^{\downarrow} \tag{2.10}$$

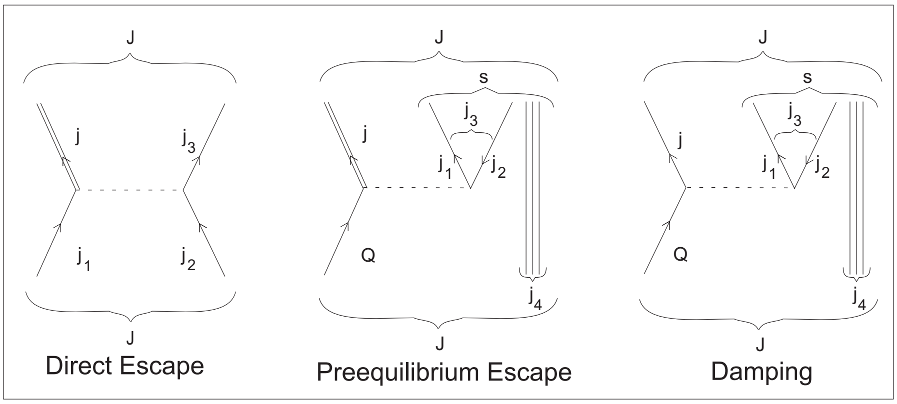

Figure 1: Schematic representation for the angular momentum structure of the GR decay.The up-going (down-going) line represents particles (holes), the dashed horizontal line represents scattering interaction process and the double line denotes a nucleon emitted in the escape processes. The three vertical lines represent those nucleons not included in the interaction.

with:

$$
{}_aY_n^{\downarrow} = \frac{1}{2}\frac{g^4}{\omega(p,h,E)}\left[\frac{\omega(p-1,h,E^{N+1})-\omega(p-1,h,(E-B)^{N+1})}{(N-1)N(N+1)} - \frac{B\omega(p-1,h,(E-B)^N)}{(N-1)} - \frac{B^2\omega(p-1,h,(E-B)^{N-1})}{2(N-1)}\right] \tag{2.11}
$$

and

$$
{}_bY_n^{\downarrow} = \frac{1}{2}\frac{g^4}{\omega(p,h,E)}\left[\frac{\omega(p,h-1,E^{N+1})-\omega(p,h-1,(E-B)^{N+1})}{(N-1)N(N+1)} + \frac{B\omega(p,h-1,(E-F)^N)}{N} + \frac{\omega(p,h-1,E^2(E-F)^{N-1})-\omega(p,h-1,(E-B)^2(E-F)^{N-1})}{2(N-1)}\right] \tag{2.12}
$$

In these expressions, the density of particle-hole $\omega(p,h,E)$ is given by:

$$
.\omega(p,h,E) = \frac{g^N}{p!h!(N-1)!}\sum_{i=0}^{p}\sum_{k=0}^{h}(-1)^{i+k}\binom{p}{i}\binom{h}{k}\Theta\left(E-\alpha_{ph}-iB-kF\right)\left(E-A_{ph}-iB-kF\right)^{N-1} \tag{2.13}
$$

where B is the binding energy and F the Fermi energy,

$$
\alpha_{ph} = \frac{1}{2}\left(\frac{p^2+p}{g}+\frac{h^2-h}{g}\right) \qquad \text{and,} \qquad A_{ph} = \frac{1}{2}\left(\frac{p^2+p}{g}+\frac{h^2-3h}{g}\right) \tag{2.14}
$$

The expressions for X function calculation [7][8][10][11] are:

$$
X_J = 2\pi\sum_{jj_1j_2j_3}\frac{(2j+1)(2j_3+1)F(J)R_1(j_3)}{R_2(J)}\begin{pmatrix} j & j_3 & J \\ \frac{1}{2} & -\frac{1}{2} & 0 \end{pmatrix}^2 I^2(j_1,j_2,j_3,j)\Delta(jj_3J), \tag{2.15}
$$

$$
X_J^{\uparrow} = 2\pi\sum_{jQj_1j_2j_3j_4}\frac{(2j+1)F(j_3)(2j_3+1)R_1(Q)R_{N-1}(j_4)}{R_N(J)}\begin{pmatrix} j & Q & j_3 \\ \frac{1}{2} & -\frac{1}{2} & 0 \end{pmatrix}^2 I^2(j_1,j_2,j_3,J)\Delta(QJj_4), \tag{2.16}
$$

$$X_{nJ}^{\downarrow} = 2\pi \sum_{Qjj_1j_2j_3j_4} \frac{R_1(Q)R_{N-1}(j_4)(2j_3+1)F(j_3)(2j+1)R_1(j)}{R_N(J)} \begin{pmatrix} j & j_3 & Q \\ \frac{1}{2} & -\frac{1}{2} & 0 \end{pmatrix}^2 I^2(j_1,j_2,Q,j)\Delta(j_4QJ). \tag{2.17}$$

where:

$$F(j_c) = (2j_a+1)R_1(j_a)(2j_b+1)R_1(j_b) \begin{pmatrix} j_a & j_b & j_c \\ \frac{1}{2} & -\frac{1}{2} & 0 \end{pmatrix}^2 \Delta(j_aj_bj_c), \tag{2.18}$$

The $R_N(J)$ functions are given by equation (2.3) and the triangular delta function, $\Delta(j_aj_bj_c)$, ensures angular momentum conservation, $(|\mathbf{j}_a - \mathbf{j}_b| \leq \mathbf{j}_c \leq |\mathbf{j}_a + \mathbf{j}_b|)$. The integrals that appear in the equations above are defined by

$$I(j_1,j_2,Q,j) = \left(\frac{4}{3}\pi r_o^3\right) V_o \frac{1}{4\pi} \int_0^\infty R_{j_1}(r)R_{j_2}(r)R_Q(r)R_j(r)\frac{dr}{r^2} \tag{2.19}$$

where the $R_j(r)$ functions are the radial wave functions of harmonic oscillator.

3. Results and Discussions

In our calculations (Table 1)[11], we obtained a total width of $2,67$ *MeV* for the ISGMR, very close to the value $2,70 \pm 0.30$ *MeV* experimentally obtained [12]. The calculations for this resonance show a predominant damping width of approximately $\sim 70\%$ of the GR total width, and $\sim 50\%$ of total width due to proton contribution.

Theoretical Results (*MeV*)				
	$\Gamma^{\downarrow}$	$\Gamma^{\uparrow preeq}$	$\Gamma^{\uparrow direct}$	Total
Proton	1.32	0.03	0.18	1.53
Neutron	0.54	0.55	0.05	1.14
Total	1.86	0.58	0.23	2.67

In order to find the energy spectrum of single particle (hole) and to simulate the coupling to the continuous, in the case of the escape widths,it was used the BARRIER code [13]. The configuration space for single hole states is the same as that found in usual calculations of the shell model. For the single particle states we adopt the following levels: $(2p_{1/2}, 1g_{9/2}, 1f_{5/2}, 2d_{5/2})$ and $(2p_{3/2}, 2p_{1/2}, 1f_{5/2})$ for neutrons and protons, respectively. For the single particle states located above the threshold of reaction, the simulated spectra in the continuum of single particle is $(3s_{1/2}, 2d_{3/2})$ for the neutron preequilibrium process. For the direct escape the states of single-particle in the continuum are $(3s_{1/2}, 2d_{3/2}, 3p_{3/2}, 1h_{11/2}, 3p_{1/2}, 2f_{7/2})$ and $(1g_{9/2}, 2d_{5/2}, 3s_{1/2}, 2d_{3/2})$ for neutrons and protons, respectively.

The ISGMR results show that the contribution of the preequilibrium process corresponds to approximately $\sim 20\%$ of the total width of the resonance. We did not observe significant contribution to escape preequilibrium proton channel. In the direct escape channel the levels $(2d_{3/2})$ and $(3s_{1/2})$ contribute approximately $\sim 90\%$ of direct escape widths of neutron and proton, respectively.

According to Matsuo et al [14] the damping mechanism masks the real type of decay of GR. This can be interpreted in our results in the appearance of large values of the damping widths, and that the processes of escape may occur in later stages in the chaining. However, the method used here provides a good estimate of the total width for the ISGMR. In this regard, note that we are using an approach that carries the entire evolution of the system excited in the first degree of complexity (first stage of the chaining) and a factorization of the widths in terms of energy and angular momentum that takes into account the statistical decay process as a whole. The great advantage of the method used here is that with relatively simple calculations, we have a good idea about the fragmentation of ISGMR in the first stage of the decay chain. The good results found here suggest that the choice was appropriate.

4. Final Remarks

Finally, in this work we present a calculation for the total width of isoscalar giant monopole resonance in the ^{60}Ni nucleus. The results of our research are really encouraging. The importance of the use of this theory is the development of a useful tool for the understanding of giant resonances that appear throughout the table of nuclides. Moreover, we intend to use this theory in the study of artificial nuclei originating from the collision of nuclei of heavy ions in the LHC experiment and to the understanding of giant resonances associated with the incompressibility of nuclear matter in neutron stars.

References

[1] W. Bothe and W. Gentner, Zeits. f. Physik **104** (1937) 685.

[2] G. C. Baldwin and G. S. Klaiber, Phys. Rev. **71** (1947) 3.

[3] M. B. Lewis and F. E. Bertran, Nucl. Phys. **A 196** (1972) 337.

[4] D.H.Youngblood, C .M. Rosza, J.M. Moss, D.R. Brown and J.D. Bronson, Phys. Rev. Lett. **39** (1977) 1188.

[5] N. K. Glendening, Compact stars: Nuclear physics, particle physics, and general relativity, Springer-Verlag, New York 2000.

[6] G. Baur, Nucl. Phys. **B** (Proceedings Supplements) (2008)

[7] H. Feshbach, A.K.Kerman and S.Koonin, Annals of Physics **125**,(1980)429.

[8] R. Bonetti, M. b. Chadwick, P. E. Hodgson, B. V. Carlson and M. H. Hussein, Physics Reports **202**, No. 4 (1991) 171-231.

[9] P. Obložinský, Nucl. Phys. **A453**,127(1986).

[10] M. O. Roos, H. Dias, O. Rodriguez, N. Teruya e M.S.Hussein, Phys. Rev. **C 66**, (2002) 024611.

[11] P. S. Rocha, Tese de Mestrado, Instituto de Física, Universidade Federal de Mato Grosso, 2009.

[12] S. Shlomo e D. H. Youngblood, Phys. Rev. **C 47** (1993) 529.

[13] F. Garcia, O. Rodriguez, E. Garrote, R. Capote, F. Guzman, Comp. Phys. Comm. **120** (1999) 57.

[14] M . Matsuo, T. Døssing, B. Herskind, S. Leoni, E. Vigezzi, R. A. Broglia, Phys. Lett. **B465** (1999) 1-7.