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Evolution of giant dipole resonance width at low temperatures – New perspectives

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Abstract. High energy photons from the decay of giant dipole resonances (GDR) built on excited states provide an excellent probe in the study of nuclear structure properties, damping mechanisms etc., at finite temperatures. The dependence of GDR width on temperature (T) and angular momentum (J) has been the prime focus of many experimental and theoretical studies for the last few decades. The measured GDR widths for a wide range of nuclei at temperatures ($1.5 < T < 2.5$ MeV) and spins (upto fission limit) were well described by the thermal shape fluctuation model (TSFM). But, at low temperatures ($T < 1.5$ MeV) there are large discrepancies between the existing theoretical models. The problem is compounded as there are very few experimental data in this region. At Variable Energy Cyclotron Centre, Kolkata, a programme for the systematic measurement of GDR width at very low temperatures has been initiated with precise experimental techniques. Several experiments have been performed by bombarding 7–12 MeV/nucleon alpha beam on various targets (^{63}Cu, ^{115}In and ^{197}Au) and new datasets have been obtained at low temperatures ($T < 1.5$ MeV) and at very low spins ($J < 20\hbar$). The TSFM completely fails to represent the experimental data at these low temperatures in the entire mass range. In fact, the GDR width appears to be constant at its ground state value until a critical temperature is reached and subsequently increases thereafter, whereas the TSFM predicts a gradual increase of GDR width from its ground state value for $T > 0$ MeV. In order to explain this discrepancy at low T, a new formalism has been put forward by including GDR-induced quadrupole moment in the TSFM.

Keywords. Low-temperature giant dipole resonance width; adiabatic thermal shape fluctuation model; BaF_2 detectors.

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1. Introduction

One of the fascinating and extensively studied subjects in modern nuclear structure physics is the observation of giant dipole resonance (GDR) mode, which demonstrates a simple and well-organized collective motion in complex many-body system like atomic nuclei, presumptively chaotic due to their intrinsic complexity. In the liquid drop picture, the GDR mode can be viewed as a small-amplitude, high-frequency, out-of-phase vibration of neutron and proton fluids in a spatial dipole pattern. Like any damped oscillation, the GDR excitation function is Lorentzian in shape and characterized by three important parameters, namely, centroid energy, resonance width, and strength. All the parameters have very special physical significances. The strength parameter is a very useful benchmark to determine whether a resonance qualifies as giant resonance or not. The centroid energy is inversely proportional to the linear dimension of nucleus within which the vibrations are confined and provides an idea about the nuclear shape. The resonance width Γ_{GDR} is defined as the full-width at half-maximum (FWHM) of the GDR lineshape and is related to various damping mechanisms of the collective motion inside nuclear matter. The damping of giant collective vibration inside the nuclear medium occurs either due to escape of resonance energy by means of particle or photon emission (escape width) or due to its redistribution in other degrees of freedom within the system (spreading width) [1]. In medium and heavy nuclei, it turns out that the escape width only accounts for a small fraction and the major contribution of the large resonance width comes from the spreading width [2,3]. The general trend of the resonance width, as deduced from the Lorentzian fit to the cross-section data, has been found to be the smallest for the closed shell nuclei and larger for the nuclei between shells [1]. However, it needs to be mentioned that for deformed nuclei, the width was obtained by fitting one single Lorentzian to the overall GDR lineshape. Such fits never resulted in a systematic mass dependence of the width. Recently, an empirical formula has been derived for the spreading width by separating the deformation-induced widening from the spreading effect, requiring the integrated Lorentzian curves to fulfil the dipole sum rule [4].

The dependence of GDR width on temperature (T) and angular momentum (J) has been the prime focus of many experimental and theoretical studies for the last few decades [5]. The measured GDR widths for a wide range of nuclei, temperatures ($1.5 < T < 2.5$ MeV) and spins (upto fission limit) were well described by the thermal shape fluctuation model (TSFM) [6,21]. In the recent years, great interest is being shown to understand the correct description of damping mechanisms contributing to the GDR width, particularly at low temperatures (T) [7–9]. The width of GDR, built on the excited states, has been found to increase monotonically ($\sim T^{1/2}$) [5] beyond $T > 1.5$ MeV. One should expect a gradual increase in the GDR width from its ground state value ($T = 0$ MeV) with the increase in temperature as predicted by TSFM. However, temperature region below 1.5 MeV has rarely been investigated to verify if such a behaviour is really true. In Sn and nearby nuclei ($A \sim 120$), mostly investigated so far, only a single GDR width measurement exists for $T < 1.2$ MeV which lies well below the TSFM prediction [7]. On the other hand, the phonon damping model (PDM) [10] which considers the coupling of the GDR phonon to particle–particle and hole–hole configurations as the mechanism for the increase of GDR width attributes this suppression to thermal pairing which contributes even beyond 1 MeV. These two models clearly disagree with one another at temperatures below 1.5 MeV highlighting the importance of microscopic effects responsible for this unusual phenomenon. In order to address these issues and to test the validity of the theoretical models, a systematic comparison between experiment and theory over a range of temperatures for several nuclei is required. However, the measurement of GDR widths at low temperatures is experimentally very challenging due to the difficulties in achieving low excitation energy and spins. Traditional heavy-ion fusion reactions are limited to higher temperatures due to the presence of Coulomb barrier in the entrance channel and are always associated with broad J distributions. Inelastic scattering [7,11,12] has been used as an alternative approach with the advantage that the angular momentum transfer will be relatively low, but, the excitation energy windows are uncertain at least to about 10 MeV and hence, the estimated temperatures are less precise. Due to these reasons, very few and widely separated ($\sim$ 0.25 MeV) data points with large error bars are available. At Variable Energy Cyclotron Centre (VECC), Kolkata, alpha-induced fusion reaction with precise experimental techniques has been used to investigate the low-temperature region. Several experiments have been performed by bombarding 7–12 MeV/nucleon alpha beam on various targets (^{63}Cu, ^{115}In and ^{197}Au). In this paper, an overview of the low-temperature GDR width studies, done at VECC is presented.

2. Experimental details and data analysis

The first experiment was carried out to investigate the $A\sim120$ mass region. A self-supporting 1 mg/cm^2 thick target of ^{115}In (99% purity) was bombarded with beams of ^{4}He. Three different beam energies of 30, 35 and 42 MeV were used to form the compound nucleus ^{119}Sb at 31.4, 36.2 and 43.0 MeV excitation energies, respectively. The LAMBDA high energy photon spectrometer [13] (98 large BaF_2 detectors arranged in two blocks of 7 $\times$ 7 each) was used to measure the high-energy γ-rays ($\geq$4 MeV) at angles 55°, 90° and 125° with respect to the beam axis. The detector arrays were positioned at a distance of 50 cm from the target. Since the GDR parameters depend on both the excitation energy and the angular momentum populated, it is important to separate the two effects in order to understand their individual contributions. Hence, along with the LAMBDA spectrometer, a 50-element low-energy γ multiplicity filter [14] was used (in coincidence with the high-energy γ-rays) to estimate the angular momentum populated in the compound nucleus in an event-by-event mode, as well as, to get a fast start trigger for the time-of-flight (TOF) measurements. The filter was split into two blocks of 25 detectors each and were placed on top and bottom of a specially designed scattering chamber at a distance of 5 cm from the target in a staggered castle-type geometry. The TOF technique was used to discriminate the neutrons from the high-energy γ-rays. The pulse shape discrimination (PSD) technique was adopted to reject the pile-up events in the individual detector elements by measuring the charge deposition over two integrating time intervals (30 ns and 2 μs) [13]. The neutron evaporation spectra were measured using seven liquid scintillator (BC501A, 5″ diameter and 7″ long) based neutron time-of-flight detectors [15] in coincidence with the multiplicity filter. The neutron detectors were placed at 30°, 45°, 75°, 90°, 105°, 120° and 150° angles with respect to the beam direction and at a distance of 150 cm from the target.

The measured fold distribution from the multiplicity filter was mapped onto the angular momentum space using a Monte Carlo GEANT3 [16] simulation. The procedure is described in detail in [14]. The energy of the evaporated neutrons has been measured using TOF technique, whereas the neutron gamma discrimination was achieved by pulse shape discrimination (PSD) and TOF. The neutron TOF spectra were converted to neutron energy spectra using the prompt gamma peaks in the TOF spectra as the time reference.

The evaporated neutron energy spectra, after transformation from laboratory frame to centre-of-mass frame, were compared with CASCADE [18] calculation using chi-square minimization technique in the energy range of 2–8 MeV for the determination of level density parameter ($\tilde{a} = A/a$). The high-energy γ-ray spectra were generated in the offline analysis using the cluster summing technique [13] in which each detector element was required to satisfy the prompt time gate and pulse shape discrimination gate. The measured high-energy γ-ray spectra at 90° were compared with a modified version of the statistical model code CASCADE [18] along with a Bremsstrahlung component. The slope parameters (E_0) of the Bremsstrahlung shape at different beam energies have been extracted from angular distribution studies. The extracted values of the slope parameters were consistent with the systematics $E_0 = 1.1[(E_{\mathrm{Lab}} - V_{\mathrm{c}})/A_{\mathrm{p}}]^{0.72}$, where E_{Lab}, V_{c} and A_{p} are the beam energy, Coulomb barrier and the projectile mass, respectively [19]. The Coulomb barrier in the studied reaction is 15.1 MeV. In CASCADE calculation, the level density prescription of Ignatyuk [20] has been taken with the asymptotic level density parameter as extracted from the corresponding neutron evaporation spectrum. The simulated spin distributions deduced from the experimental multiplicity distributions were used as inputs for different folds. The predictions from the CASCADE calculations and the Bremsstrahlung contributions were convoluted with the detector response and compared with the experimental γ-ray spectra for different folds. The best fit was obtained using a χ^2 minimization technique in the region of 8–20 MeV. In order to highlight the GDR region, both the data and calculated spectra were linearized by dividing with a statistical gamma spectrum assuming constant E1 strength (figure 1). The average temperature was estimated using the relation $\langle T \rangle = [(E^* - E_{\mathrm{rot}} - E_{\mathrm{GDR}})/\tilde{a}]^{1/2}$, where E^* is the excitation energy and E_{rot} is the energy bound in nuclear rotation at average J corresponding to a particular fold. The GDR centroid energies (E_{GDR}) were found to be constant at around 15 MeV. More details about the experimental set-up, data analysis etc., can be found in [22].

3. Results and discussions

The GDR widths measured in the low-temperature range of 0.9–1.4 MeV in the present study are shown in figure 2 along with other measurements reported earlier for ^{120}Sn ([7] and references therein). The continuous line represents the adiabatic thermal shape fluctuation calculation [21] at low spin. It is evident that the temperature dependence of the GDR width determined from this experiment differs substantially from the adiabatic thermal shape calculation at low temperatures. In $A \sim 120$ mass region, where shell effects are small, the GDR width is expected to increase with the increase in temperature, from its ground state value in a manner consistent with the properties of hot liquid drop [21]. In contrast, the systematic experimental data show the GDR width to be constant till $T \sim 1$ MeV and increases thereafter. The extracted GDR widths at temperatures $T < 1$ MeV, match pretty well with the ground state width of ^{119}Sb (4.5 MeV, dashed line in figure 2) as calculated using the spreading width parametrization [4] $\Gamma = 0.05 E_{\mathrm{GDR}}^{1.6}$ considering its small ground state deformation ($\beta = -0.12$) [23]. The discrepancy between the experimental data and TSFM indicate failure of the model in the present form in describing the evolution of the GDR width with temperature below 1.5 MeV. A similar suppression of

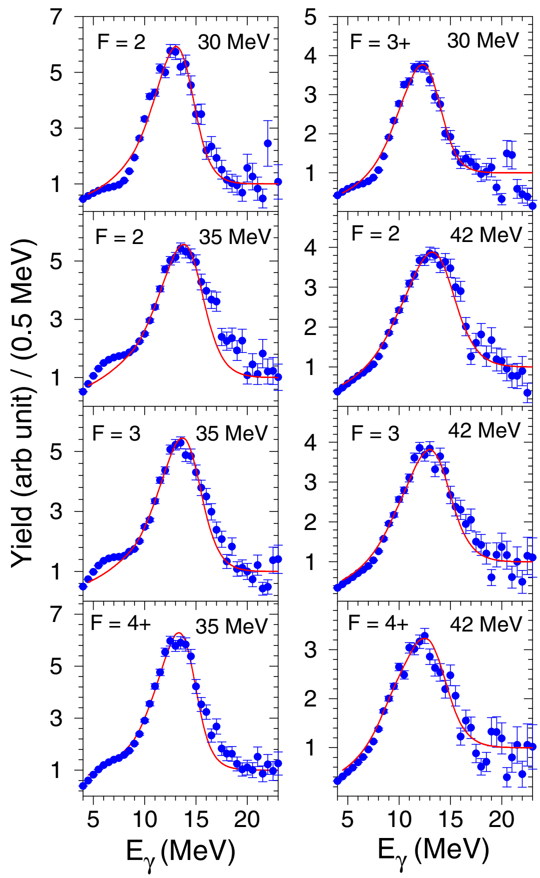

Figure 1. Divided plots of the measured γ-spectra (blue circles) and the best fitted CASCADE calculations (red continuous lines) for different folds (F) at incident energies of 30, 35 and 42 MeV.

width compared to TSFM was observed, in the mass region ~ 117, at a still lower temperature (0.68 MeV) by measuring the high-energy γ-rays from the hot fission fragments produced in ^{252}Cf fission [9]. At these low temperatures, shell effect might play significant roles and should be incorporated properly for a better explanation of the experimental data. But, even after incorporating shell corrections, the situation does not improve [21]. It is therefore, needed to have a re-look into the formulation of the model with the incorporation of any other microscopic effects that may be responsible for such a deviation. The microscopic phonon damping model (PDM) [10] (the dotted curve in figure 2), though not widely used, better explains the trend of the data at this low-temperature region. The model calculates GDR width and the strength function directly in the laboratory frame without any need for an explicit inclusion of thermal fluctuation of shapes. It has been shown that the thermal pairing effect plays an important role in lowering the GDR width at $T \leq 2$ MeV [10].

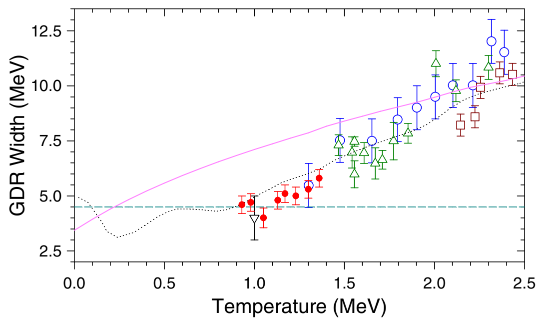

Figure 2. Plot of GDR width with temperature. The red filled circles are the values for ^{119}Sb deduced from the present work. For comparison, data for ^{120}Sn from previous works are shown. The black downward triangle is from [7]. The green upward triangles and blue open circles are taken from [21] while the brown open squares are obtained from [17]. The pink continuous line represents the TSFM calculation [21], while the black dotted line corresponds to the phonon damping model calculation [10]. The green dashed line is the ground state width of ^{119}Sb (discussed in the text).

The above experimental work establishes the fact that the GDR width for near ^{120}Sn nuclei [22] remains constant at ground state value till $T \sim 1$ MeV and increases subsequently thereafter. Motivated by this, an attempt has also been made to verify such behaviour for the ^{63}Cu and ^{208}Pb nuclei with the same experimental approach as discussed in §2. The experiments were performed at the Variable Energy Cyclotron Centre, Kolkata, using ^{4}He beams produced from the K-130 room temperature cyclotron. Excited ^{201}Tl and ^{63}Cu compound nuclei were produced by bombarding self-supporting targets of ^{197}Au and ^{59}Co, respectively. The initial excitation energies for ^{201}Tl were 32.7, 39.6 and 47.5 MeV corresponding to incident energies of 35, 42 and 50 MeV, respectively, while it was 38.6 MeV for ^{63}Cu at 35 MeV incident energy. The details about the experimental set-up, data analysis and the statistical model calculation for the extraction of GDR width have been reported in [24]. The measured GDR widths for ^{63}Cu and ^{201}Tl are shown as filled circles in figure 3 together with the experimental data of ^{63}Cu [21,25] and ^{208}Pb [11], reported earlier.

The TSFM (continuous line) fails to describe the GDR width even after incorporating the shell effect (which is strong in ^{208}Pb region). The discrepancy, therefore, clearly indicates that the shell effect alone cannot describe the suppression of the GDR width at these low temperatures and the suppression is a general feature for all the nuclei in the entire mass range. Interestingly, for ^{63}Cu and ^{201}Tl also, GDR widths remain constant at the ground state value up to a certain temperature $T_{\rm c}$ (well above $T = 0$ MeV) and increases thereafter. This critical temperature $T_{\rm c}$, which has been measured to be ∼1 MeV for ^{120}Sn region, are found to be ∼1.3 and 0.9 MeV for ^{63}Cu and ^{201}Tl, respectively. It has been observed that $T_{\rm c}$ decreases with the increase in mass and shows a linear behaviour with $1/A$ (figure 4a).

To explain the critical behaviour in the variation of GDR width at low temperatures, it has been argued that the GDR vibration itself induces a quadrupole moment causing the nuclear shape to fluctuate even at $T = 0$ MeV [24]. Therefore, when the giant dipole

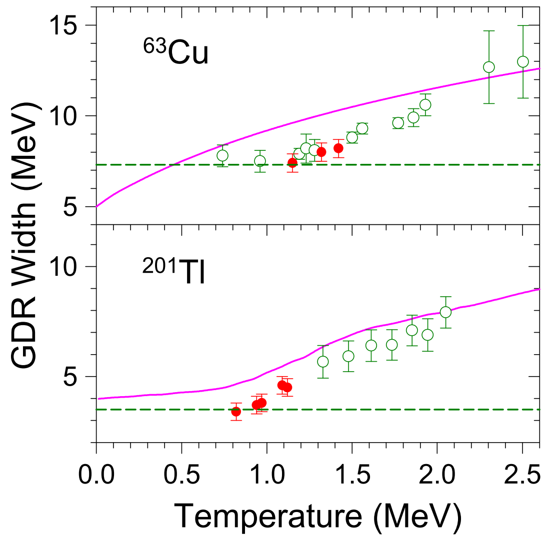

Figure 3. The GDR widths as a function of temperature for ^{63}Cu and ^{201}Tl. The filled circles are the data from the recent work [24] and the open circles are from the earlier works in these regions. The continuous lines are the results of TSFM calculations including shell effects.

vibration with its own intrinsic fluctuation (β_{GDR}) in shape is used as a probe to view the thermal shape fluctuations ($T > 0$), it is unlikely to feel the thermal fluctuations that are smaller than its own intrinsic fluctuation. If this argument is true, the GDR widths should remain constant at the ground state values until a critical temperature (T_{c}) and the effect of the thermal fluctuations on the experimental GDR width (i.e., increase of the GDR width) should appear only when it becomes greater than the intrinsic GDR fluctuation [24]. In the case of angular momentum dependence of GDR width, it has been shown that even though the equilibrium deformation of a nucleus increases with the increase in angular momentum, an increase of GDR width is not evident experimentally until the equilibrium deformation (β_{eq}) increases sufficiently to affect the thermal average. In particular, as long as β_{eq} is less than the variance $\Delta\beta = \sqrt{\langle\beta^2\rangle - \langle\beta\rangle^2}$ the increase of GDR width is not significant. In a similar way, the effect of thermal fluctuations on the width should not be evident when $\Delta\beta$ due to the thermal fluctuations is smaller than the intrinsic GDR fluctuation (β_{GDR}) due to its induced quadrupole moment.

According to the above argument, the critical temperature should depend on the competition between β_{GDR} and $\Delta\beta$. Hence, the variance of the deformation ($\Delta\beta$) for ^{63}Cu, ^{119}Sb and ^{201}Tl as a function of temperature has been calculated using the formalism described in [26]. Recently, the quadrupole moment (Q_{Q}) induced by the GDR motion has been calculated under the framework of time-dependent Hartree–Fock theory by Simenel *et al* [27,28]. The Q_{Q}, induced by GDR motion, has been interpreted within the Goldhaber–Teller (GT) mode [29] assuming that harmonic displacement of proton and neutron fluids induce a prolate shape with a quadrupole moment proportional to the

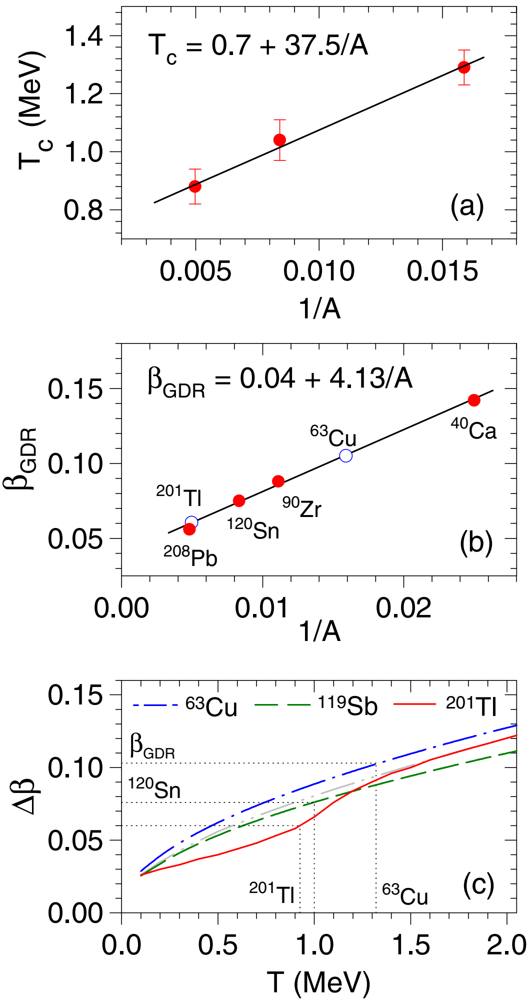

Figure 4. (**a**) Critical temperature vs. $1/A$. Experimental data (symbols) fitted with a linear function (continuous line). (**b**) β_{GDR} vs $1/A$. Estimated values from the quadrupole moment (filled circles) fitted with a linear function (continuous line). The β_{GDR} values extracted from this systematics for ^{63}Cu and ^{201}Tl are shown with open circles. (**c**) The variance of the deformation as a function of T for ^{63}Cu, ^{119}Sb and ^{201}Tl. The dotted line represents the calculation for ^{201}Tl without including shell effect. The corresponding β_{GDR} is compared with $\Delta\beta$ (thin continuous line) [24].

square of the distance between the two spheres [28]. The β_{GDR} values were estimated from the quadrupole moment and shown in figure 4b (discussed in [24]). The β_{GDR} also show a $1/A$ behaviour similar to the critical temperature. The β_{GDR} values for ^{63}Cu and ^{201}Tl were estimated from the systematics in figure 4b and compared with the corresponding $\Delta\beta$ values. Interestingly, the temperatures at which β_{GDR} is equal to $\Delta\beta$ correspond to the experimentally measured critical temperatures (figure 4c). It has also been shown in this figure that the shell effect indeed plays an important role for ^{201}Tl in correctly reproducing the experimentally measured critical temperature. Without the inclusion of the shell effect, the values of $\Delta\beta$ and $\beta_{\rm GDR}$ for ^{201}Tl are equal at $T \sim 0.55$ MeV, whereas the experimental result shows $T_{\rm c} \sim 0.9$ MeV. The inclusion of the shell effect in $\Delta\beta$ for thermal fluctuations leads to a higher $T_{\rm c}$, because for temperatures $T < T_{\rm c}$, $\beta_{\rm GDR}$ dominates and only after $T_{\rm c}$ the thermal fluctuations take over, leading to an increase in GDR width.

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References

[1] M N Harakeh and A van der Woude, *Giant resonances, fundamental high-frequency modes of nuclear excitation* (Clarendon Press, Oxford, 2001)
[2] P F Bortignon *et al*, *Nucl. Phys. A* **460**, 149 (1986)
[3] P Donati *et al*, *Phys. Lett. B* **383**, 15 (1996)
[4] A R Junghans *et al*, *Phys. Lett. B* **670**, 200 (2008)
[5] M Thoennessen, *Nucl. Phys. A* **731**, 131 (2004) and references therein
[6] Y Alhassid, B Bush and S Levit, *Phys. Rev. Lett.* **61**, 1926 (1988)
[7] P Heckman *et al*, *Phys. Lett. B* **555**, 43 (2003)
[8] F Camera *et al*, *Phys. Lett. B* **560**, 155 (2003)
[9] Deepak Pandit *et al*, *Phys. Lett. B* **690**, 473 (2010)
[10] Nguyen Dinh Dang and Akito Arima, *Phys. Rev. C* **68**, 044303 (2003)
[11] T Baumann *et al*, *Nucl. Phys. A* **635**, 428 (1998)
[12] E Ramakrishnan *et al*, *Phys. Rev. Lett.* **76**, 2025 (1996)
[13] S Mukhopadhayay *et al*, *Nucl. Instrum. Methods A* **582**, 603 (2007)
[14] Deepak Pandit *et al*, *Nucl. Instrum. Methods A* **624**, 148 (2010)
[15] K Banerjee *et al*, *Nucl. Instrum. Methods A* **608**, 440 (2009)
[16] R Brun *et al*, GEANT3, CERN-DD/EE/84-1, 1986
[17] M P Kelly, K A Snover, J P S van Schagen *et al*, *Phys. Rev. Lett.* **82**, 3404 (1998)
[18] F Puhlhofer, *Nucl. Phys.* **280**, 267 (1977)
[19] H Nifennecker and J A Pinston, *Ann. Rev. Nucl. Part. Sci.* **40**, 113 (1990)
[20] A V Ignatyuk, G N Smirenkin and A S Tishin, *Sov. J. Nucl. Phys.* **21**, 255 (1975) [*Yad. Fiz.* **21**, 485 (1975)]
[21] D Kusnezov, Y Alhassid and K A Snover, *Phys. Rev. Lett.* **81**, 542 (1998) and references therein
[22] S Mukhopadhyay *et al*, *Phys. Lett. B* **709**, 9 (2012)
[23] P Moller *et al*, *At. Data Nucl. Data Tables* **59**, 185 (1995)
[24] Deepak Pandit *et al*, *Phys. Lett. B* **713**, 434 (2012)
[25] M K Habior *et al*, *Phys. Rev. C* **36**, 612 (1987)
[26] Deepak Pandit *et al*, *Phys. Rev. C* **81**, 061302(R) (2010)
[27] C Simenel and Ph Chomaz, *Phys. Rev. C* **68**, 024302 (2003)
[28] C Simenel and Ph Chomaz, *Phys. Rev. C* **80**, 064309 (2009)
[29] M Goldhaber and E Teller, *Phys. Rev.* **74**, 1046 (1948)