Giant monopole resonance in Pb isotopes

E. Khan
Institut de Physique Nucléaire, Université Paris-Sud, IN2P3-CNRS, F-91406 Orsay Cedex, France
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The extraction of the nuclear incompressibility from isoscalar giant monopole resonance (GMR) measurements is analyzed. Pairing may play a role in the shift of the GMR energy between the doubly closed shell ^{208}Pb nucleus and other Pb isotopes. Pairing effects are predicted microscopically using the constrained Hartree-Fock-Bogoliubov method. Accurate measurements of the GMR in open-shell Pb isotopes are necessary.

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It has been shown recently, using the tin isotopic chain, that pairing has an effect on nuclear incompressibility [1,2]. In Ref. [1], including pairing effects in the description of the isoscalar giant monopole resonance (GMR) allowed part of the so-called Sn softness to be explained [3,4]: pairing decreases the predicted centroid of the GMR, located at ∼16 MeV, by a few hundred keV. In Ref. [2], an explicit decreasing correlation was found between the nuclei incompressibility, obtained from the energy of the GMR, and the magnitude of the pairing gap.

With the recent advent of accurate microscopic models in the pairing channel, such as fully self-consistent quasiparticle random phase approximation (QRPA) [1,5], it is now possible to accurately predict the GMR position and to study small but non-negligible effects such as pairing. Using a microscopic approach is crucial: the GMR is built mainly from particle-hole configurations located far from the Fermi level, where pairing does not play a major role. However, giant resonances are known to be very collective [6] and pairing may still have a sizable effect on the GMR properties—around 10% on the centroid [2], which is the level of accuracy of the current analysis for the extraction of K_∞ [7,8].

Experimentally, the measurement of the GMR on an isotopic chain facilitates the study of superfluidity on the GMR properties [3], and the possibility of measuring the GMR in unstable nuclei emphasizes this feature [9]. It is therefore necessary to go toward the measurement of the GMR on several nuclei, such as in an isotopic chain. The overused method of precise GMR measurements in a single nucleus, such as for ^{208}Pb, may not be the relevant approach. Other nuclei have been used, such as ^{90}Zr and ^{144}Sm. Indeed, considering the available GMR data from which the K_∞ value has been extracted, ^{208}Pb is stiffer than Sn, Zr, and Sm nuclei: K_∞ is about 20 MeV larger, both in nonrelativistic and in relativistic approaches [7,8]. Instead of asking why tin is so soft [4], one could ask why ^{208}Pb is so stiff. Recent results in cadmium isotopes also confirm that open-shell nuclei provide a value of K_∞ that is lower than that extracted from ^{208}Pb [10].

It should be emphasized that it is not possible to describe GMR in both Pb and other open-shell nuclei by using the same functional [2]. This is valid for both nonrelativistic and relativistic calculations. In Ref. [2], it was shown how pairing effects play a role in the Sn isotopic chain: the energy of GMR is increased for doubly magic Sn isotopes due to the vanishing of pairing in these nuclei. The aim of the present work is to look for a possible similar effect in the Pb isotopic chain. Indeed ^{204,206}Pb nuclei are stable, but almost all the experimental effort in past decades was devoted to the measurement of GMR in ^{208}Pb. It would be interesting to perform accurate GMR measurements on open-shell ^{204,206}Pb nuclei via inelastic alpha scattering in direct kinematics.

Even with the inclusion of pairing effects, the SLy4 functional [11], which accurately describes GMR in ^{208}Pb, still overestimates GMR in Sn isotopes (see Fig. 1 of Ref. [2]). Hence, an additional shell effect may be at work, which could explain the discrepancy of the extracted K_∞ values between ^{208}Pb and Sn isotopes: the SLy4 ($K_\infty = 230$ MeV) [11] functional allows the ^{208}Pb GMR to be described, whereas the SkM* ($K_\infty = 215$ MeV) [12] functional is in agreement with the Sn data. The puzzle of the stiffness of ^{208}Pb may come from its doubly magic behavior: a possible explanation is that the experimental $E_{\rm GMR}$ data are especially increased in the case of doubly magic nuclei, as observed in ^{208}Pb, compared to the GMR data available for other nuclei (such as in the tin isotopic chain).

To consider the effects of pairing on GMR, it is necessary to use a fully microscopic method, including an accurate pairing approach. We use the constrained Hartree-Fock method, extended to the Bogoliubov pairing treatment (CHFB) [2,13]. It should be noted that the extension of the CHF method to the CHFB case was recently demonstrated in Ref. [13]. The CHF(B) method has the advantage of very precisely predicting the centroid of the GMR using the m_{-1} sum rule [14,15]. The whole residual interaction (including spin-orbit and Coulomb terms) is taken into account and this method is by construction the best to use to predict the GMR centroid [15]. The monopole operator $\hat{Q}$ is introduced as a constraint,

$$\hat{H}_{\rm cons} = \hat{H} + \lambda\hat{Q}, \tag{1}$$

with

$$\hat{Q} = \sum_{i=1}^{A} r_i^2, \tag{2}$$

where the m_{-1} value is obtained from the derivative of the mean value of this operator:

$$m_{-1} = -\frac{1}{2}\left[\frac{\partial}{\partial\lambda}\langle\hat{Q}\rangle\right]_{\lambda=0}. \tag{3}$$

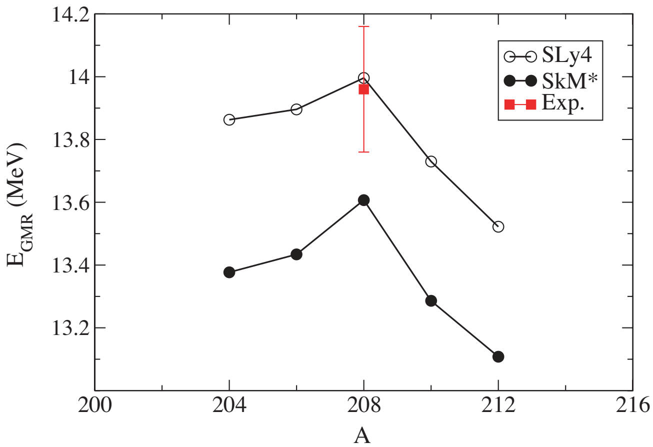

FIG. 1. (Color online) Excitation energies of GMR in $^{204-212}$Pb isotopes calculated with the CHFB method and the SLy4 and SkM* interactions. The experimental data are taken from Ref. [19].

The m_1 sum rule is extracted from the double commutator using the Thouless theorem [16]:

$$m_1 = \frac{2\hbar^2}{A}\langle r^2\rangle. \tag{4}$$

Finally the GMR centroid is given by $E_{\rm GMR} = \sqrt{m_1/m_{-1}}$. All details on the CHF(B) method can be found in the literature [7,13,14].

The present work uses the Hartree-Fock-Bogoliubov (HFB) approach in coordinate space [17] with Skyrme functionals and a zero-range surface pairing interaction:

$$V_{\rm pair} = V_0\left[1 - \left(\frac{\rho(r)}{\rho_0}\right)\right]\delta\left(\mathbf{r_1} - \mathbf{r_2}\right). \tag{5}$$

This interaction describes a large variety of pairing effects in nuclei [18]. The magnitude of the pairing interaction, V_0, is taken as -735 MeV fm^{-1} for SLy4 and -700 MeV fm^{-1} for SkM*: it is adjusted to describe the trend of the neutron pairing gap of Pb isotopes. The single quasiparticle spectrum is considered up to 60 MeV. Previous CHFB calculations for Sn isotopes are described in Ref. [2].

Figure 1 displays the GMR energy for $^{204-212}$Pb nuclei obtained from microscopic CHFB predictions using two functionals: SLy4 [11] ($K_\infty = 230$ MeV, which describes well the ^{208}Pb GMR data) and SkM* [12] ($K_\infty = 215$ MeV, which describes well the open-shell GMR data, such as for tin isotopes). As expected, GMR energy is predicted higher in the SLy4 case than in the SkM* case. For both interactions, the striking feature of Fig. 1 is the increase of the GMR centroid located at the doubly magic ^{208}Pb nucleus. This feature indicates that pairing effects should be considered to describe the behavior of nuclear incompressibility, and that the vanishing of pairing makes the nuclei stiffer to compress, confirming our previous statement on the stiffness of ^{132}Sn compared to that of open-shell Sn isotopes [2]. Pairing effects (CHFB calculations) decrease the centroid of the GMR as observed in open-shell Pb isotopes compared to ^{208}Pb. This confirms again the results of [1,2] in the tin data and may show that the effect of pairing on GMR may be universal.

It should be noted that GMR was measured for ^{206}Pb several decades ago [20], providing a centroid value of 14.0 ± 0.3 MeV. Therefore, no deviation was found with respect to ^{208}Pb. However, this measurement has been performed above 12°; at such a large angle, the GMR cross section is very weak, compared to the giant quadrupole resonance (GQR) cross section, and it is difficult to extract a value of the GMR centroid because both the GQR and the high-energy background are important. Hence, the measurement was not optimal, especially when typical 500 keV effects were sought. Therefore, it would be of particular interest to measure GMR in ^{206}Pb at 0°, allowing for a larger GMR cross section. Furthermore, there are no GMR data for ^{204}Pb. The accuracy of future GMR measurements in ^{204,206}Pb will be crucial. Moreover, it should be mentioned that a somewhat lower value for the GMR centroid of ^{208}Pb has been found in the RCNP experiment (13.5 ± 0.2 [21]), compared to the experiment at Texas A&M University [19]: a current debate exists about the reason for such variations. An accurate experiment on Pb isotopes that includes ^{208}Pb should also help solve this issue.

We now study the hypothesis that an effect besides pairing is contributing to the specific increase of the GMR energy in doubly magic nuclei. This effect on GMR can be evaluated phenomenologically by calculating the predicted position of the GMR centroid with SLy4 in the ^{208}Pb case, and with SkM* in the open-shell ^{204,206,210,212}Pb nuclei: SkM* allows for a good description of GMR in open-shell nuclei such as tin isotopes, where this effect may be at work. Under this hypothesis the increase of GMR in a doubly closed shell ^{208}Pb would be larger—about 500 keV (from ^{206}Pb with SkM* to ^{208}Pb with SLy4 in Fig. 1). If only pairing effects played a role, the variation of the GMR position is about 100 to 200 keV; it is crucial that future measurements are performed to within this accuracy.

Various effects, which deserve further study, may generate the specific increase of the GMR centroid in doubly magic nuclei. For instance, the surface oscillations of these nuclei may be different from that of other nuclei. Another possibility could be related to the difficulty of describing masses with a single functional on both doubly magic and other nuclei, namely the so-called mutually enhanced magicity (MEM) described in Refs. [22,23]: functionals designed to describe masses of open-shell nuclei cannot predict the masses of doubly magic nuclei such as ^{132}Sn and ^{208}Pb, which are systematically more bound than predicted [23]. To evaluate the MEM effect, it may be necessary to take into account quadrupole correlation effects due to the flatness of the mean-field potential for open-shell nuclei [24]. However, the MEM effect is not yet well understood in the case of nuclear masses, and no model currently exists to take into account microscopically the MEM effect on the GMR centroid.

A measurement of GMR in ^{204}Pb and ^{206}Pb compatible with the present predictions would be a step toward solving the Sn softness problem. It would also mean that K_∞ may not be determined by measuring GMR in a single nuclei such as ^{208}Pb, but the whole isotopic chain should be measured to provide a general view of the various effects on GMR. Experimentally, measurements of the GMR in unstable nuclei should also help in investigating this issue [9]. Additional theoretical investigations are also necessary to predict GMR, including the MEM effect in a microscopic way, or other interpretations.

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