

# Two particle transfer reactions: the search for the Giant Pairing Vibration

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**Abstract.** We discuss different points that are fundamental to determine the actual magnitude of the cross sections measured in two-particle transfer reactions between heavy ions. These are important issues to consider when the aim is the experimental observation of the somewhat elusive Giant Pairing Vibrations.

In this contribution we address the subject of two-particle transfer in reactions involving heavy ions. Among the variety of still open aspects of these reactions, our emphasis is placed here on the identification of the predicted so-called "Giant Pairing Vibrations" (GPV) [1]. The existence of pair correlations is known to provide an enhancement in the magnitude of the ground-state to ground-state transition matrix elements between systems that differ by a number of two nucleons. Interest in the Giant Pairing modes emerged when it was realized that analogous enhancements should also be expected from particle-particle correlations involving transitions to higher single-particle shells, much in the same way as the ones responsible for the existence of the more familiar Giant Surface Vibrations.

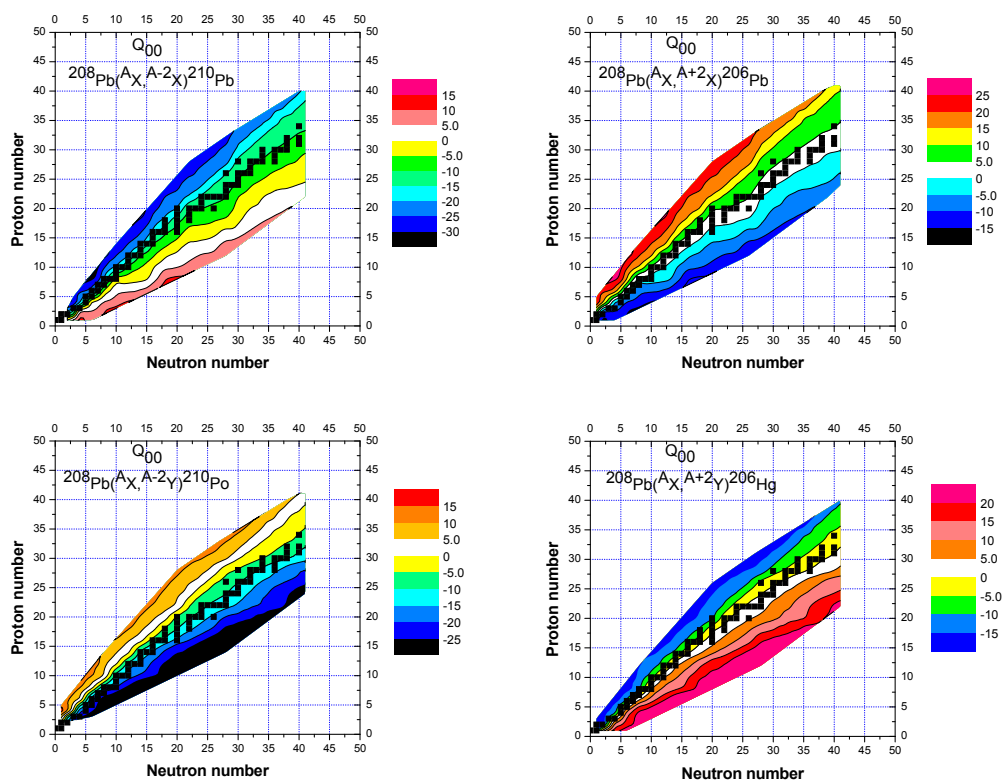
The nuclear structure information contained in the size of the transition matrix elements is, however, only a part of the story. To arrive to the actual magnitude of the cross sections, the dynamical characteristics of the waves describing the incoming and outgoing nuclear currents must also be taken into account. How this is implemented in practice depends very much on the characteristics of the formalism employed. We shall here refer, concretely, to the language invoked in the semiclassical treatment, where the matching conditions between the entrance and exit orbits of relative motion are expressed in terms of the bombarding energy, the reaction Q-value and the existence of an optimal match [2]. All of these quantities are determined by the prevalent experimental conditions.

In reactions between ordinary systems, with similar binding energies, the Q-value for particle transfer tends to be small, a situation that favors the particle-transfer between ground states. For precisely the same reason the transfer into the predicted high-energy range of the Giant Pairing Vibrations is normally unfavored and it is therefore not so much of a surprise that these modes have not been readily observed [3].

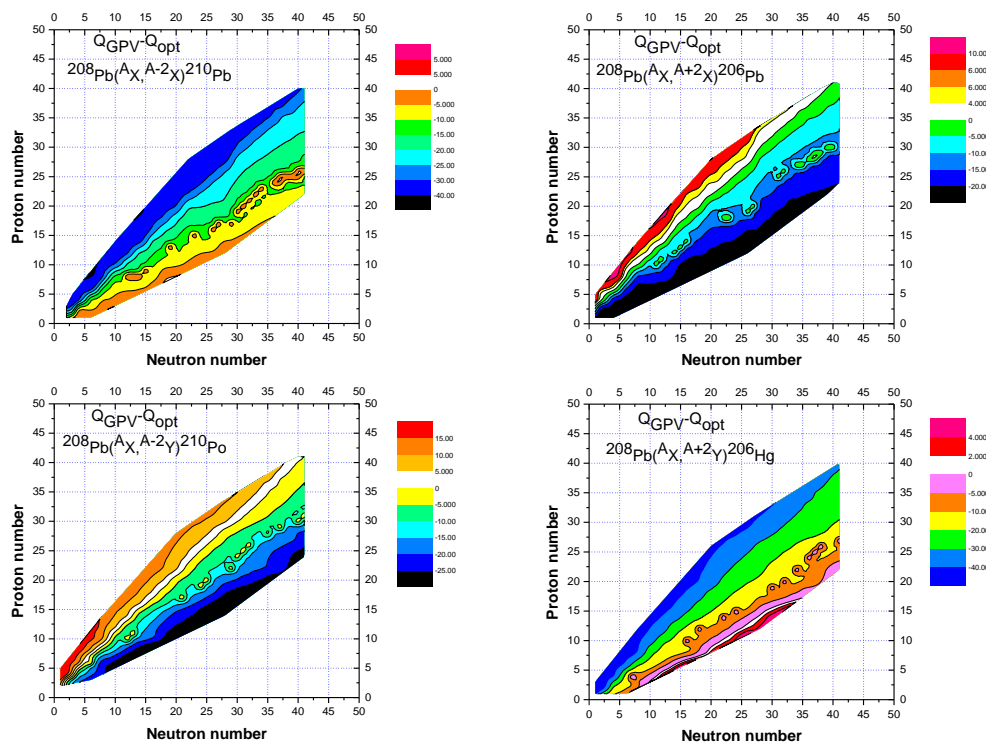


In reference [4] the authors pointed out the importance of taking into account properly the existence of the optimal  $Q$ -values to understand the apparent lack of experimental evidence. Their conclusions, however, were reached in the context of the macroscopic model for pair transfer [5]. The concept of a generalized one-body pair-creation field is not very useful in the investigation of transitions to individual states since the excitation energy of the addition or removal modes is not directly associated with the reaction  $Q$ -value (cf. reference [6], chapt. 9, and [5]). We side-step here the use of the macroscopic pair-transfer model and procure to describe the process in the more conventional language of a transition between two well-defined nuclear states.

For a ground-state to ground-state transition, the  $Q$ -value is obtained directly from the masses of the constituent particles of the reacting nuclei, namely  $Q = \sum_i m_i c^2 - \sum_f m_f c^2$  where  $i$  and  $f$  stand to indicate the “initial” and “final” character of the fragments involved. A positive sign of  $Q$  reveals if a process liberates energy and may occur spontaneously. Otherwise, the incident beam energy is always available to make even endothermic processes possible. In fact, if the reaction in question is not meant to induce a transition between the ground states but to some net excitation  $E^*$  the bombarding energy should be raised accordingly. The relevant parameter  $\chi$  then changes from that maximum value  $\chi = Q$  to  $\chi = Q - E^*$ . In what follows -



**Figure 1.** Contour plots of the ground state  $Q$ -value (in MeV) obtained for the  $^{208}\text{Pb}$  target using as projectiles all known nuclei up to proton and neutron number equal to 50. The four frames correspond to 2-neutron stripping (upper left), 2-neutron pick-up (upper right), 2-proton stripping (lower left) and 2-proton pick-up (lower right). The black squares correspond to the stable nuclei.



**Figure 2.** The same than figure 1, but for the quantity  $Q_{GPV} - Q_{opt}$  (in MeV). For the calculation of  $Q_{GPV}$  the energy of the GPV has been assumed to be 12 MeV. The  $Q_{opt}$  has been calculated for a projectile energy (in the c.m. reference frame) corresponding to 20 % above the corresponding Coulomb barrier of the projectile-target interaction.

aiming to the GPV - we shall take a characteristic value  $E^* \approx 12$  MeV. We stress that this is only for illustration purposes and that there is no problem adopting any other values if deemed more appropriate.

Since the nuclear masses are available as electronic tables in [7] we can propose a quick survey of the characteristic numbers involved. Our strategy will be to chose a given target candidate and explore a wide range of possible projectiles. The idea is to put in evidence those reactions that significantly deviate from the aforementioned tendency to favor low-excitation energy transitions and, instead, identify those that would help populate the GPV modes. Let us here note that the existing records automatically end whenever the projectile mass has not been determined.

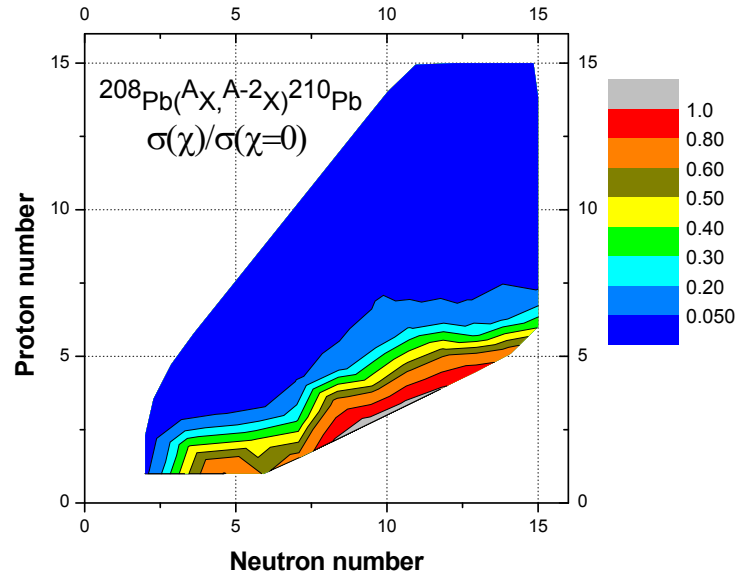
As an illustration of this procedure we first take, as a target, the nucleus of  $^{208}\text{Pb}$ . We then plot the two-particle transfer reaction  $Q$ -values as a function of the number of protons and neutrons of the projectile. The results are shown, as contours of the resulting surface, in figure 1. The four frames correspond to two-neutron pick-up, two neutron stripping, two-proton pick-up and two-proton stripping. As it is apparent from the figure positive  $Q$ -values are mostly obtained using neutron-rich projectiles in connection with two-neutron stripping and two-proton pick-up, while proton-rich projectiles lead to positive  $Q$ -values for two-neutron pick-up and two-proton stripping.

For the optimal  $Q$ -values in the absence of angular-momentum transfer, we can use the

following expression [2] which is not undisputed but somewhat author-dependent,

$$Q_{opt} = \frac{Z_d(Z_b - Z_A)e^2}{r_0} - \frac{1}{2} \frac{m_d(m_b - m_A)}{m_a + m_A} v_0^2 + m_{aA} \ddot{r}_0 \delta r_0 \quad (1)$$

where the indexes  $A$  and  $a$  refer to the initial particles in the reaction,  $B$  and  $b$  are the final particles,  $Z_d$  and  $m_d$  are the total charge and mass of the transfer particles,  $v_0$  and  $\ddot{r}_0$  are the velocity and the acceleration at the distance of closest approach  $r_0$  and  $\delta r_0 = m_d/2((R_A - R_a + r_0)/m_A - (R_a - R_A + r_0)/m_a)$ . in terms of the radii  $R$  of the initial reaction partners. As we mentioned earlier, the relevant quantity to investigate the eventual population of a GPV of excitation energy  $E^*$  is the difference between the parameter  $\chi = Q - E^*$  and the optimal  $Q$ -value, i.e.  $\chi - Q_{opt}$ . This quantity is plotted in figure 2 as a function of the number of protons and neutrons of possible projectiles using the same organization of the frames as in figure 1.

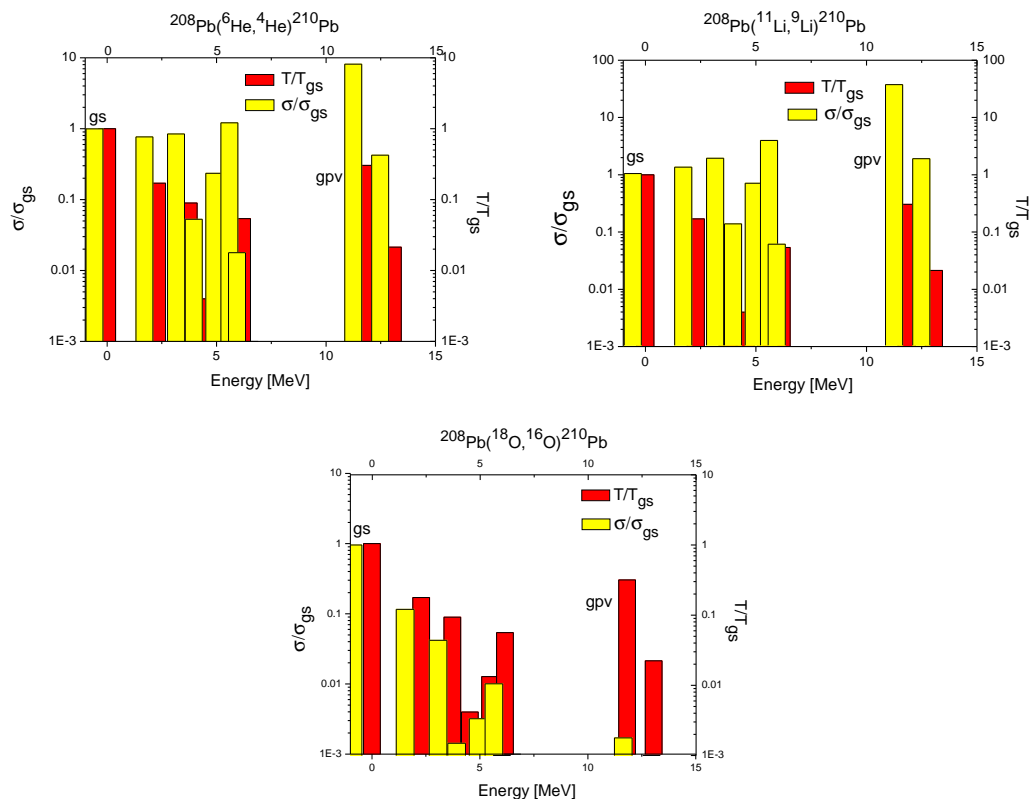


**Figure 3.** Contour plot of the cut-off exponential factor of equation (2), obtained for the excitation of the GPV in  $^{210}\text{Pb}$  in two-neutron stripping reactions, using as projectiles all known nuclei up to proton and neutron number equal to 15. The black squares correspond to the stable nuclei, while the two circles indicate the two Borromean nuclei  $^6\text{He}$  and  $^{11}\text{Li}$ .

One can easily judge the quantitative effect of the numbers displayed in figure 2. This is done taking into account that the actual magnitude of the measured transfer cross sections is modulated by a gaussian factor centered at the optimal  $Q$ -value according to the expression [2]

$$\sigma(\chi) = \sigma(\chi = Q_{opt}) \exp \left[ - \frac{(\chi - Q_{opt})^2}{2\hbar^2 \kappa \ddot{r}_0} \right] \quad (2)$$

where  $\kappa$  is the slope of the two-particle transfer effective form factor ( $\kappa \approx 1\text{fm}$ ). It is thus the exponential factor in equation (2) that gives us a practical tool for guidance in the search for the most suitable projectiles. The contours of this quantity are displayed in figure 3 for the case

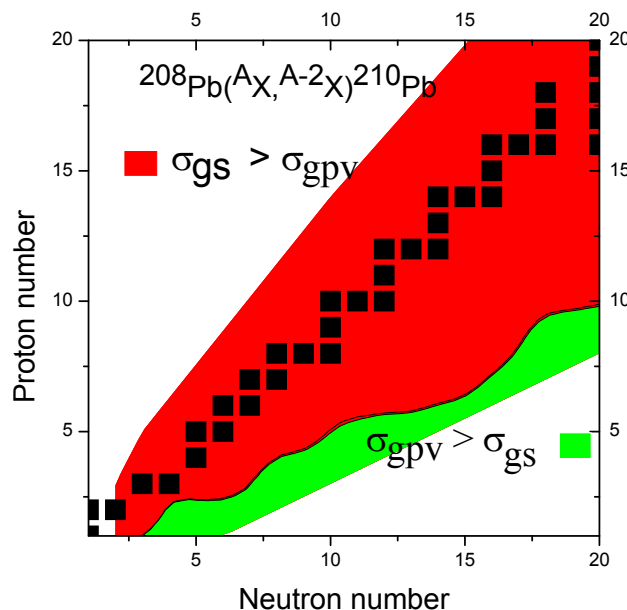


**Figure 4.** Pair addition strength distribution, normalized to the ground state, to all  $0^+$  states in  $^{210}\text{Pb}$  (red bars) compared to the normalized pair transfer cross section (yellow bars) in the case of  $^6\text{He}$  (upper left),  $^{11}\text{Li}$  (upper right) and  $^{18}\text{O}$  (lower frame) .

of two-neutron stripping, for the excitation of the GPV in  $^{210}\text{Pb}$ , using as projectiles all known nuclei up to proton and neutron number equal to 15 .

As a further example we show in figure 4 the addition-pair strength distribution, normalized to the ground state, to all  $0^+$  states in  $^{210}\text{Pb}$  compared to the corresponding normalized pair transfer cross sections in the case of  $^6\text{He}$ ,  $^{11}\text{Li}$  and  $^{18}\text{O}$ . The pair strength has been calculated using discrete particle-particle RPA, starting from single particle levels taken from reference [8], with a pairing constant  $G$  adjusted to fit the difference of the ground state energies ( $^{210}\text{Pb} - ^{206}\text{Pb}$ ). The calculation shows the prediction of a strong high-lying state at 12 MeV (GPV). As far as the calculation of the relative two particle transfer cross section, in all cases the bombarding energy has been chosen 20 % larger than the corresponding Coulomb barrier. It is apparent from the figures that, due to the  $Q$ -value effect, the population of the high-lying in the two-particle transfer process is strongly depressed in the case of the  $^{18}\text{O}$  induced reaction, a case in which the  $Q$ -value is already negative for the g.s. transition, and hence even more negative for the GPV region. On the converse, in the case of  $^6\text{He}$  and  $^{11}\text{Li}$  projectile the ground state  $Q$ -value is positive, leading to a  $Q$ -value for the GPV close to the optimal value.

More generally, if we concentrate on the excitation of the Giant Pairing Vibration, we consider again in figure 5 the full variety of projectiles and evidence (in the lighter green color), those that, because of favorable  $Q$ -value, lead to a population of GPV larger than that of the ground state.



**Figure 5.** The figure refers to the case of two-neutron stripping reaction on  $^{208}\text{Pb}$  with different projectiles. The lighter green area shows the part of the nuclear chart corresponding to the projectiles that, because of favorable Q-value, are expected to lead to a population of GPV larger than that of the ground state.

In this contribution we have tried to provide orientation for a judicious choice of reaction conditions that may shed experimental evidence on the predicted existence of Giant Pairing Vibrations. There is indeed flexibility in some choices that we have made but, in general, our estimates are based on rather well-established features of semiclassical reaction theory. As such we trust that the guidelines we have developed would be useful to optimize the search for these high-lying collective pairing modes.

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