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Pair clustering and giant pairing resonances

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Giant pairing resonances, i.e., collective two-particle excitations built upon high-lying single-particle states, are studied in the lead region. Two-particle 0^+ states ($T=1$) outside the ^{208}Pb core are found to be clustered in the nuclear surface. Our calculation shows that these states are the most excited in two-particle transfer reactions.

Although giant resonances may be considered as collective modes in which a considerable portion of the nucleons move together, one may also think of them as excitations of high-lying shell-model configurations.[1,2] In this case, one finds that all these configurations contribute in phase to the electromagnetic transition matrix element that describes the decay of the giant resonance mode. This property applies also to the first excited state with spin and parity the same as those of the giant resonance. But the number of configurations that contribute to the giant resonance is much larger than the corresponding number contributing to the first excited state. As a result, the giant resonance takes most of the transition strength, i.e., it exhausts 20%–90% of its sum rule. From a microscopic point of view, giant resonances are generally considered to be particle-hole excitations of various kinds. So, the Gamow-Teller resonance consists of a proton-neutron particle-hole excitation.[2] Both Gamow-Teller and multipole giant resonances have in the last decade been the subject of intense studies.

It is well known that particle-hole and particle-particle excitations are formally related to each other.[3] The collectivity of the particle-hole modes is measured in terms of the value of the matrix elements of the corresponding electromagnetic transition operators, while the pairing collectivity is measured in terms of the value of the two-particle transfer matrix elements.[3,4] This analogy may be brought further by considering also giant pairing resonances[5] (GPR), i.e., collective two-particle excitations built up from high-lying shell-model configurations.

One important feature of the pairing states is that they should be strongly excited in two-particle transfer reactions. This can be seen by writing the pairing (two-particle) wave function in terms of its single-particle configurations. One finds that all these configurations contribute in phase to the two-particle transfer form factor.[3,6] It is for this reason that one usually states that the proper probe to analyze the collective features of pairing modes is two-particle transfer reactions.

Recently, it was shown that in normal pairing modes the corresponding pair of nucleons have a strong tendency to cluster in the nuclear surface.[7,8] The formation of the clustering of the pair of particles found in Ref. 7 proceeds through many configurations. These configurations are needed to take into account the influence of the continuum part of the single-particle spectrum. Although the GPR is built up from high-lying single-particle states, one may expect that the corresponding GPR wave function is also localized in space. One may then think that this clustering favors the transfer of the particles as an entity.

Pairing modes play an important role in the formation of the α particle in α-decay processes. The inclusion of proton and neutron pairing states to describe the mother nucleus is necessary in order to obtain a value of the α width which is close to the corresponding experimental value. In fact, one obtains an enhancement of the calculated α width of as much as five orders of magnitudes by including those pairing modes within a large shell-model configuration space.[9,10] The physical reason for this tremendous enhancement is that through the neutron (proton) pairing mode the pair of neutrons (protons) becomes clustered in the nuclear surface. In Refs. 9 and 10, where the decay of ^{212}Po was studied, the pairing modes were the ground states of ^{210}Pb (neutron pairing) and ^{210}Po (proton pairing). Yet, through this mechanism no neutron-proton interaction was included in the formalism (i.e., no neutron-proton cluster was present) and the enhancement of the α-decay width was not enough to obtain the corresponding experimental value. In Ref. 11 it was found that there was a state in ^{210}Bi which was as much clustered as the pairing modes. This state is the first calculated 0^+ state in ^{210}Bi which lies at approximately 5 MeV of excitation energy. This state actually corresponds to the neutron-proton pairing excitation, where the neutron moves in the shells above $N=126$ [i.e., the shells that originate the pairing state ^{210}Pb(g.s.)], while the proton moves in the equivalent isobaric analog shells. This neutron-proton pairing state is of great importance to cluster neutrons and protons. Together with the proton-proton and the neutron-neutron pairing states, the neutron-proton pairing mode induces the clustering of the four nucleons that eventually constitutes the α particle. What we are saying is, in fact, that in α decay the neutron-proton giant pairing resonance plays a fundamental role. Moreover, to each pairing state should correspond two other $T=1$ states. In our case, to the ground state of ^{210}Pb should correspond the state ^{210}Bi$(0^+;1)$ discussed above plus a 0^+ state in ^{210}Po which corresponds to the pairing excitation of the second major shell above $Z=82$.

In this paper we analyze the clustering features of these states. At the same time we calculate the two-particle transfer reactions leading to the $T=1$ states analogous to ^{210}Pb(g.s.). The single-particle states are those of Ref. 10, which include five major shells. Within this single-particle representation we diagonalized a surface delta force to obtain the pairing wave functions. As expected, the main components of the ground state (i.e., collective) wave functions agree within 10% with those of the Kuo-Brown interaction.[12] The calculation of the two-particle transfer cross section was performed within the distorted-wave Born approximation (DWBA) using the code DWUCK4.[13] One may argue that two step processes are known to play an important role in two-particle transfer reactions.[14–16] But the contribution of these processes seems to be proportional to the first order contribution given by DWBA.[16,17] Moreover, in Ref. 17 no reason was found to question spectroscopic conclusions computed with one-step codes. Therefore, relative cross sections (as those calculated in this paper) would not be affected by two step processes.

As in α decay, only the singlet ($S=0$) component of the wave function enters in our calculation. Although we do not mention it explicitly, it is this component we discuss here.

The clustering features of ^{210}Pb(g.s.) and ^{210}Po(g.s.) were already shown in Ref. 7. In Fig. 1 we present the square of the wave functions of ^{210}Bi(0^+;1) and ^{210}Po(0^+;GPR). One can indeed say that the nucleons in these states are clustered at least as much as those in the pairing ground states.

We carry out the calculation of the two-particle transfer cross sections leading to the three $T=1$ pairing states mentioned above for different projectiles and laboratory energies. As projectiles, we use light ions because the corresponding cross sections have a very typical angular distribution.[18] This feature would favor light ion projectiles in an experimental search of the GPR. Moreover, we also used heavy projectiles in our calculations (using code TWOFF[19]) with the optical model parameters of Ref. 6 and with laboratory energies of 104 and 200 MeV. We could reproduce the low energy cross section given in Ref. 20, but the calculated heavy ion cross section leading to the GPR was smaller than the one corresponding to light projectiles.

The results of our calculations will be discussed separately for each case. The ^{208}Pb(t,p)^{210}Pb(g.s.) reaction has been

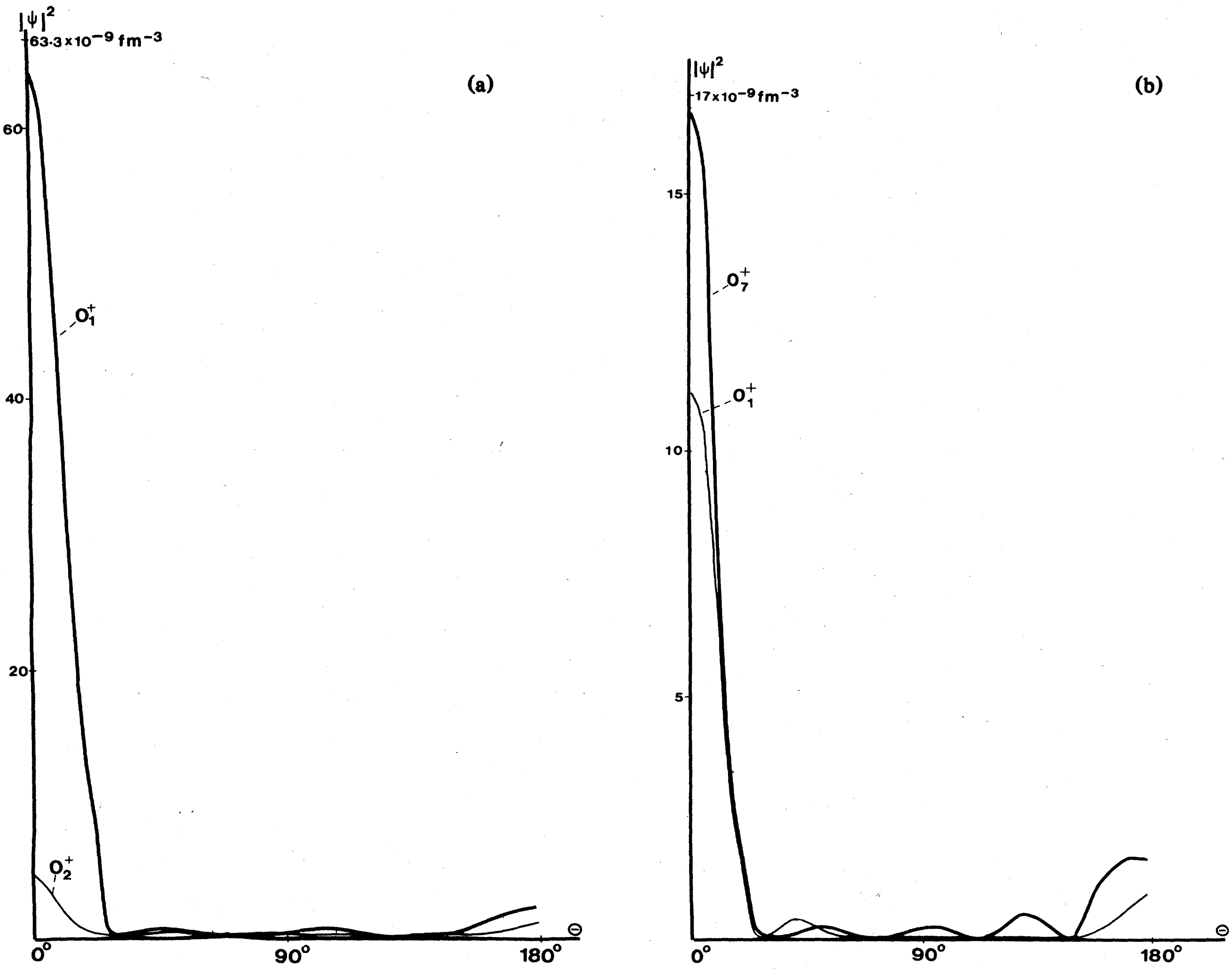

FIG. 1. Square of the two-particle wave function as a function of the angle θ between the position vectors $\vec{r}_1$ and $\vec{r}_2$. In this figure it is $r_1=r_2=7.8$ fm. (a) The first two 0^+ states in ^{210}Bi. (b) The first (ground state) and the seventh (GPR) states in ^{210}Po. This figure shows that the two particles in the GPR state are even more clustered than in the normal pairing state.

abundantly analyzed in the past (see Ref. 4, and references therein) and it will not be discussed here.

The ^{208}Pb(^{3}He,p)^{210}Bi(0^{+};1) reaction was calculated using the optical model parameters and laboratory energy (40.8 MeV) of Ref. 21. In this reference a number of low-lying states in ^{210}Bi were measured. We calculated the corresponding cross sections with the code DWUCK4 which uses the zero range approximation for the projectile. Since the low-lying states in ^{210}Bi are produced by neutrons and protons moving in different major shells, no 0^{+} state was observed in Ref. 21 (in contrast to the other nuclei studied in this paper). Therefore, we could not calculate a relative cross section between the GPR and any observed 0^{+} state. In cases like this, one needs to estimate the absolute cross sections. We did this estimation proceeding, as usually done in the literature,[22] introducing a normalization constant N between the experimental cross sections and the corresponding theoretical values. The value of N might be very dependent upon the spin and parity of the excited state (in which case one may doubt the validity of the approximation used in the calculation, e.g., zero range approximation, etc.). With the definition of N used in Ref. 22 [for details see Eq. (1) of Ref. 22] we obtained all the measured absolute cross sections of Ref. 21 with N in the range $20 < N < 30$. We feel, therefore, confident that the same factor would be needed to obtain the cross section leading to the ^{210}Bi(0^{+};1) state. Using this normalization factor we obtained a value for the cross section which lies between 54 and 81 μb/sr. This value is about five times larger than the largest cross section measured in Ref. 21.

The ^{208}(^{3}He,n)^{210}Po reaction was measured at a laboratory energy of 33.3 MeV in Ref. 22 and the ^{210}Po(g.s.) and ^{210}Po(0^{+};2) states were observed. Defining a relative cross section (at 0^{0}) as

$$R(\lambda)=\sigma[^{210}\mathrm{Po}(\lambda)]/\sigma[^{210}\mathrm{Po}(\mathrm{g.s.})]$$

the experiment of Ref. 22 gives $R(0^{+};2)=1.2\pm0.3$.

Using the same optical model parameters and laboratory energy as in Ref. 22, we obtained $R(0^{+};2)=0.6$, a value that can be considered reasonably good. The state ^{210}Pb(GPR) lies, according to our calculation, at 13.3 MeV of excitation energy. Our calculated cross section gives R(GPR) $=1.1$ which is, again in this case, the largest one.

In conclusion, we can say that the three $T=1$ pairing states built over ^{208}Pb are highly excited in two-particle transfer reactions. The results of our calculation indicate that the giant pairing resonances are the most excited states in these reactions. One may then wonder why the GPR states have not been observed experimentally so far. One reason may be that contaminations of different kinds (in the case of ^{210}Po the isotope ^{12}C is an important source of contamination[22]) may be present at high excitation energy. It is to be hoped that this experimental hindrance can be overcome.

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