EXPERIMENTAL EVIDENCE FOR LOW-LYING MANY-QUASIPARTICLE STATES IN NICKEL ISOTOPES

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It has been found that low-lying states are strongly excited in nickel isotopes by α-transfer reactions induced by 48-MeV oxygen ions on iron targets, i.e., via the four-particle, two-hole components of the nuclear wave functions.

The discovery of rotational bands in ^{16}O has demonstrated[1,2] the coexistence of deformed states together with spherical ones. The near degeneracy of spherical and deformed states is linked to the magnitude of the interaction energy of four nucleons in the same space state (LS) or in an aligned quartet (j-j) which is large compared with interquartet interaction energies.[3] The quartet structure of deformed states was made evident by their selective excitations via α-transfer or α elastic-scattering reactions and also by calculations based on a treatment of 4p-4h (four-particle, four-hole) excitations.[3]

In medium and heavy spherical nuclei, made of one proton or neutron open shell, one has to expect a different kind of "deformed" states based on the excitation of two core particles coupled into a quartet with two of the outside nucleons.[3] This can be understood by comparing the phenomenological 4p-4h and 4p-2h excitation energy in ^{60}Ni:

$$^{60}\mathrm{Ni}(4\mathrm{p}\text{-}4\mathrm{h}) = {}^{64}\mathrm{Zn} + {}^{56}\mathrm{Fe} - 2\times{}^{60}\mathrm{Ni} + \mathcal{C} + 16X$$

$$= (2.28 - 1 + 16X)\ \mathrm{MeV},$$

$$^{60}\mathrm{Ni}(4\mathrm{p}\text{-}2\mathrm{h}) = {}^{62}\mathrm{Zn} + {}^{56}\mathrm{Fe} - 2\times{}^{58}\mathrm{Ni} + \mathcal{C} + 8X$$

$$= (-1.23 - 1 + 8X)\ \mathrm{MeV},$$

where X is the particle-hole average repulsive matrix element (between 0.5 and 1.0 MeV) and $\mathcal{C}$ is the Coulomb attraction between the particle and holes which we estimate at -1 MeV.

The 4p-2h states may thus appear between 2 MeV (for $X=0.5$ MeV) and 6 MeV (for $X=1$ MeV), while the 4p-4h states are at least 5 to 9 MeV higher. The fact that the 4p-2h appears lower than the 4p-4h is due (a) to their smaller shell-model energy, two particles being raised from the core instead of four; and (b) to the smaller number of repulsive particle-hole bonds in the 4p-2h states.

It is well known that (^{6}Li, d) and (^{7}Li, t) reactions have been used in recent years to excite selectively such kinds of states in light nuclei. But all attempts with targets of $A > 40$ have failed, because the cross sections are found to decrease drastically with increasing mass. Another drawback of these reactions is the possible competition of compound nucleus formation with the direct α transfer, and the presence of a high breakup background.

We report the first α transfer in the nickel isotopes, through the reactions ^{54,56}Fe(^{16}O, ^{12}C)^{58,60}Ni, carried out in the vicinity of the Coulomb barrier.

Our reasons for the choice of ^{16}O instead of ^{6,7}Li to induce α-transfer reactions were the following: (1) The large deformation of both target and projectile, due to the larger Coulomb polarization, decreases the Coulomb barrier for the α's and increases the LS components of the nuclear wave functions, favoring the α structure.[3] (2) The competition with compound nucleus formation with emission of ^{12}C is strongly hindered at low energies. (3) The breakup of ^{16}O in the Coulomb field is expected to end mostly with four α particles that will not contaminate the ^{12}C channel; the breakup into $^{12}\mathrm{C}+\alpha$ is then less probable giving smaller background. (4) The unavoidable contamination of the ^{12}C spectra by the reaction ^{12}C(^{16}O, ^{12}C)^{16}O is rapidly eliminated from the region of interest by the kinematics.

The experiment was performed with the 48-MeV oxygen beam of Saclay's High Voltage Engineering Corporation model FN tandem Van de Graaff accelerator, separated isotopes, and solid state detectors. The overall resolution was ~200 keV. The solid-state-detector telescope consists of two very thin surface barriers ΔE_1 and ΔE_2 (13 μm) and a thicker one E (230 μm). A 1000-μm-thick counter was set in anticoincidence to reject all the light particles. The electronic setup performed a double identification with a CAE 90-10 computer on line. Simultaneously the pulse heights from ΔE_1, ΔE_2, and E were recorded digitally on magnetic tapes. The ^{16}O elastic scattering pulses were rejected in a first analogous stage of the setup.

The ^{16}O elastic scattering was obtained in a

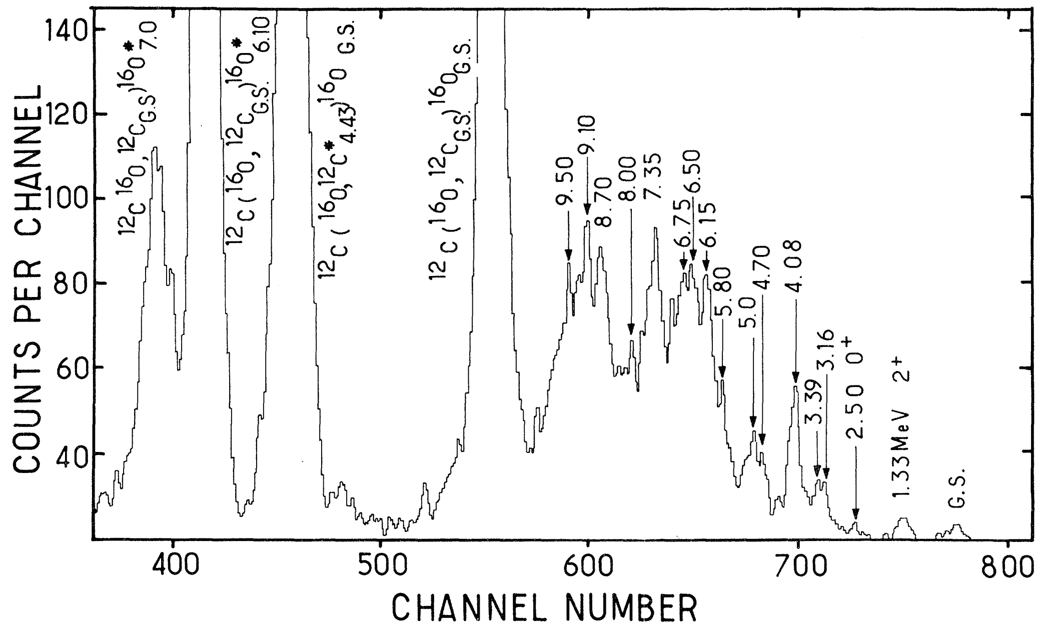

FIG. 1. Carbon spectrum from ^{56}Fe target obtained at 35° laboratory angle with a solid-state–detector telescope at an oxygen incident energy of 48 MeV; integrated charge, 7300 μC.

separate run between 20° and 80° (c.m.) and deviates from pure Coulomb scattering at 50° (c.m.); using the usual "quarter-point recipe," the interaction radius is found to be about $1.55(54^{1/3}+16^{1/3})$ fm.

Measurements were carried out at 35° laboratory angle for ^{56}Fe(^{16}O, ^{12}C)^{60}Ni (Fig. 1) and at 40° and 50° laboratory angle for ^{54}Fe(^{16}O, ^{12}C)^{58}Ni (Figs. 2 and 3). At 60° and 70° (lab) the cross sections are too small to be measured. Some of the observed peaks may possibly result from the emission of an excited ^{12}C nucleus in its 2^+ (4.43-MeV) state. However, there is no evidence in ^{60}Ni spectrum of a peak corresponding to the ^{60}Ni ground state with ^{12}C left in its 4.43-MeV state, thus the 4.5-MeV group seen in ^{58}Ni cannot be

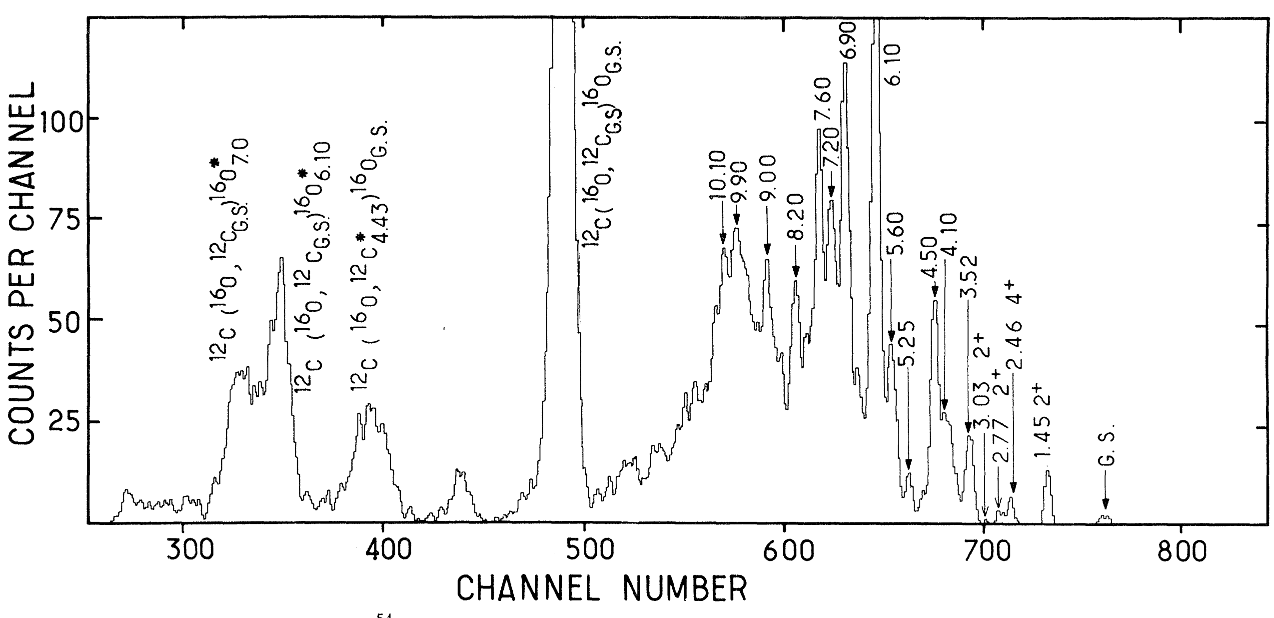

FIG. 2. Carbon spectrum from ^{54}Fe target obtained at 40° laboratory angle with a solid-state–detector telescope at an oxygen incident energy of 48 MeV; integrated charge, 18 000 μC.

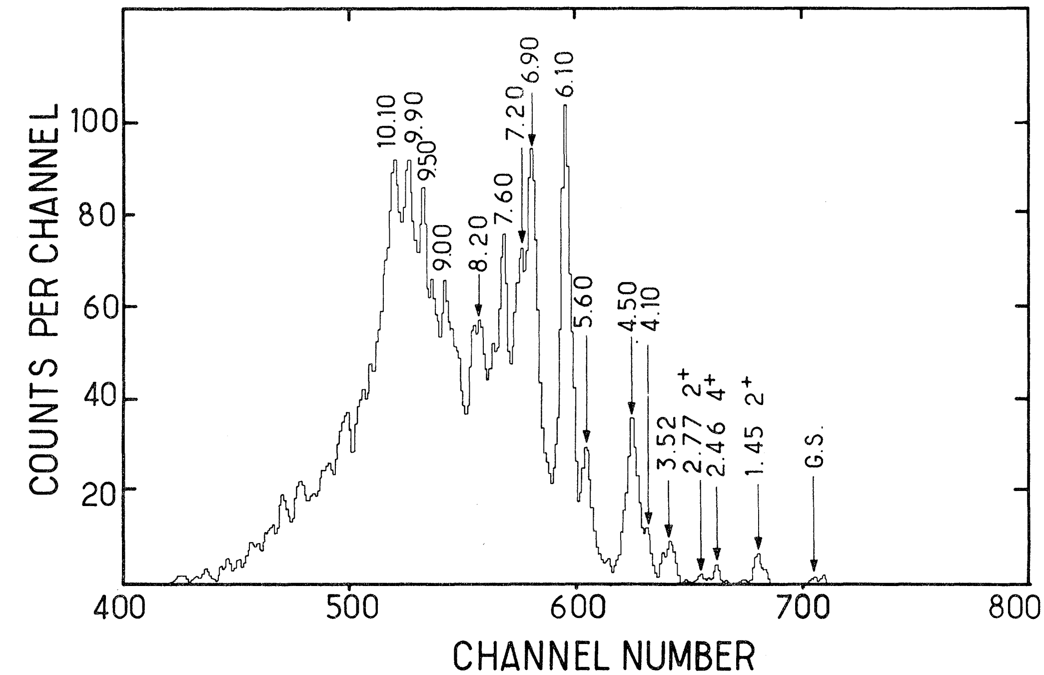

FIG. 3. Carbon spectrum from ^{54}Fe target obtained at 50° laboratory angle with a solid-state–detector telescope at an oxygen incident energy of 48 MeV; integrated charge, 10 000 μC.

entirely attributed to ^{12}C*. Furthermore, no systematic 4.4-MeV intervals are observed between excited groups. This point will be checked again when other projectiles are available.

These spectra exhibit the following characteristic features. The ground states and the first few vibrational levels of ^{58}Ni and ^{60}Ni are weakly excited ($d\sigma/d\Omega \leq 50$ μb). The cross section rises steeply above 4 MeV excitation energy and up to 10 MeV discrete groups of levels are strongly excited ($100 \leq d\sigma/d\Omega \leq 200$ μb). The density of the groups between 4 and 10 MeV is much smaller than that observed in (p, p') (about 80 levels between 4 and 8 MeV), thus demonstrating the very strong selectivity of the process. The continuum under the peaks can be due to these levels and to the possible breakup of ^{16}O into ^{12}C + α. (The kinematic upper limit of breakup is under the 6.1-MeV group.) The decrease observed above 10 MeV excitation is probably due to the Coulomb effects: A short run performed with the 56-MeV oxygen beam on ^{54}Fe at 40° (lab) shows greater cross sections and more groups between 10 and 14 MeV of excitation energy.

In a calculation based on the diagonalization of deformed 4p-4h and 4p-2h configurations followed by a projection procedure, Jaffrin[4] gives a description of quasirotational bands in medium-weight spherical nuclei. In the case of ^{58}Ni and ^{60}Ni the agreement in energy position between experiment and the "band" states constructed from $(2p^{3/2})^4(1f^{7/2})^{-2}$ and from $(2p^{3/2})^2(1f^{7/2})^{-2}$ configurations is satisfactory. Let us note that in these calculations there is a large deviation from the $I(I+1)$ law due to the small orbital angular momentum of the excited particles.

Since the separation energy of an α particle in ^{58}Ni is 6.4 MeV, the levels above these energies are unbound, the re-emission of the α's being delayed by the 11-MeV Coulomb barrier. Thus, one can expect some broadening of the levels.

Tentatively, the relatively great number of peaks can be explained by interpreting these groups as the result of single 4p-2h configurations, spread by their coupling with the continuum; this yields the observed gross structure which in turn is split by the coupling with closed channels.[3]

It is quite clear that more experiments and more calculations are needed to obtain a complete understanding of these states. But it has been shown now that low lying excited states built with many quasiparticles is a property of medium A nuclei, as well as of lighter ones, and that there is a way to reach them experimentally which is open to Van de Graaff tandems or cyclotrons of standard energies.

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[1]E. B. Carter, G. E. Mitchell, and R. H. Davis, Phys. Rev. 133, B1421 (1964).

[2]G. E. Brown, in *Proceedings of the International Congress on Nuclear Physics, Paris, France, 1964,* edited by P. Gugenberger (Centre National de la Recherche Scientifique, Paris, France, 1964), Vol. I, p. 129; G. E. Brown and A. Green, Nucl. Phys. 85, 87 (1966); G. Ripka, in *Advances in Nuclear Physics,* edited by M. Baranger and E. Vogt (Plenum, New York, 1968), Vol. I, p. 183.

[3]V. Gillet, in *Proceedings of the International Conference on Properties of Nuclear States, Montreal, Canada, 1969,* edited by M. Harvey *et al.* (Presses de l'Université de Montreal, Montreal, Canada, 1969), p. 483, and the included references.

[4]A. Jaffrin, in *Proceedings of the International Conference on Properties of Nuclear States, Montreal, Canada, 1969,* edited by M. Harvey *et al.* (Presses de l'Université de Montreal, Montreal, Canada, 1969), pp. 338, 340, and private communication.

PROGRESSIVE DEFORMATION OF THE CRUST OF PULSARS*

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It is shown that the crust of pulsars can deform in a gradual plastic manner in spite of its extreme density and strength. This deformation leads to stronger damping of pulsar rotation and to higher magnetic moments and also to rarer starquakes than calculated for a rigid crust.

The gradual slowing down of the rotation rate of a pulsar due to damping by its magnetic or gravitational radiation produces enormous forces acting on the solid crust of these objects. In the two-component model of pulsars a small superfluid and superconducting core is surrounded by a thick superdense solid crust made of essentially unscreened nuclei arranged in a body-centered cubic "metallic" lattice in which the internuclear spacing $b = 5\times10^{-12}$ cm exceeds the nuclear size by a factor of about 10. Thus the lattice is very "open." Other important parameters are[1] $T\sim10^{8}$ K, melting temperature $T_M\sim10^{10}$ K, Debye temperature $\theta_D\sim1.5\times10^{9}$ K, density $\sim10^{13}$ g cm^{-3}, and shear modulus $\mu\sim10^{30}$ dyn cm^{-2}. It is of interest to estimate the possibility that this very unusual solid deforms in a plastic manner in the equally unusual situation.

It is well known that for $T>0.5T_M$ metals deform by diffusion-controlled mechanisms, while for $T<0.5T_M$ the "exhaustion" or "logarithmic" mode of deformation is prevalent. The first has a high and approximately constant activation energy; in the second the apparent activation energy is proportional to temperature. While the atomic mechanisms of these two processes are reasonably well understood, a quantitative prediction of deformation rates is usually not possible and, therefore, it is necessary in this case to make a comparison with data obtained in the laboratory using dimensional analysis. The temperature of the pulsar crust, scaled down by comparing with either T_M or θ_D, corresponds to about 10 K for normal metals and thus to the region of the "logarithmic" mechanism in which the plastic strain is given by $\epsilon = BT\sigma\ln(1+Et)$, where σ is stress, t is time, and B and E are time- and stress-independent constants. For large t the rate of strain is given by

$$\dot{\epsilon} = BT\sigma t^{-1}, \tag{1}$$

which does not depend upon the rather poorly reproducible values of E. Many metals (Fe, Al, Mg, Cd, Hg, Nb) are known to obey these laws down to temperatures well below 4 K. The best recent data are those of Arko and Weertman[2] obtained on Cd and Hg down to 2 K. In particular, the data for Cd ($T_M = 593$ K, $\theta_D = 165$ K, $\mu = 2\times10^{11}$ dyn cm^{-2}, $b = 3$ Å) at 4.2, 7.4, and 14.5 K give, for that range of temperatures, $B\simeq2\times10^{-12}$ or $B = B_0b^2\mu^{-1}$ with $B_0\simeq4\times10^{14}$, all in cgs units. The quantity B is usually interpreted in terms of the number and mobility of crystallographic lattice defects which can be displaced by shear. Substituting in the above formulas T, b, and μ values appropriate for the pulsar crust, one ob-