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Authors

Oliveira, J.R.B.
Frauendorf, S.
Deleplanque, M.A.
et al.

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J.R.B. Oliveira, S. Frauendorf, M.A. Deleplanque, R.M. Diamond,
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J.R.B. Oliveira, S. Frauendorf, M.A. Deleplanque,
R.M. Diamond, F.S. Stephens, C.W. Beausang

Nuclear Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

J.E. Draper, C. Duyar, E. Rubel

University of California
Davis, California 95616

J.A. Becker, E.A. Henry, N. Roy

Lawrence Livermore National Laboratory
University of California
Livermore, California 94550

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Rotation-Induced Transition from Superfluid to Normal Phase in Mesoscopic Systems: ^{168}Yb and Adjacent Nuclei

J.R.B.Oliveira,* S.Frauendorf,† M.A.Deleplanque,
R.M.Diamond, F.S.Stephens, C.W.Beausang‡

Nuclear Science Division, Lawrence Berkeley Laboratory,
1 Cyclotron Rd., Berkeley, CA 94720

J.E.Draper, C.Duyar, E.Rubel

University of California, Davis, CA, 95616

J.A.Becker, E.A.Henry, N.Roy

Lawrence Livermore National Laboratory, Livermore, CA 94550

The transition from strong static pairing to weak static pairing and its consequences to the excitation spectrum of a mesoscopic system are investigated. New levels have been measured in ^{168}Yb. A reasonable description of the $A \approx 168$ isotopes spectra is obtained. The adequacy of the phase transition concept is discussed.

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Shortly after the discovery of pair correlations of the BCS type in nuclei, Mottelson and Valatin [1] predicted that pairing should collapse in rapidly rotating nuclei much like superconductivity in a strong magnetic field. How this transition actually takes place has been a subject of study in high-spin nuclear physics ever since. In nuclei only a small number of particles (typically 10) participate in the pairing correlations, and the fluctuations of the pairing field create a substantial part of the total correlation energy. The adequacy of the phase transition concept is therefore questionable. The transition from the "superfluid" to the "normal nuclear phase" is analogous to the transition from deformed to spherical nuclei, with vibrations around the equilibrium shapes. Following Refs. [2,3] we call dynamic pairing the oscillations of the pairing field around its static value, which vanishes at high spin. The dynamic pairing correlations decrease the moment of inertia of all low-lying configurations by about the same amount [2], while affecting very little the relative excitation spectrum. As pointed out in Refs. [3–5] the disappearance of static pairing corresponds then to a major change of the excitation spectrum, from the quasiparticle (qp) to the particle-hole (ph) spectrum. The former is characterized by strong alignment of the single qp angular momentum with the rotational axis, and related band crossings that strongly depend on parity and weakly on the particle number, N. The latter shows small alignment in general, and a characteristic individuality with respect to N. Examples of the appearance of the ph spectra at high spin have been discussed in Refs. [3–5]. The purpose of the present work is to understand the excitation spectra over a wide frequency range. We studied experimentally the ^{168}Yb nucleus and propose a calculation scheme, based on a schematic frequency dependence of the pairing gap, which describes the transition from the qp to the ph picture.

The high-spin states of ^{168}Yb have been measured by means of in-beam gamma-ray spectroscopy with the High Energy Resolution Array (HERA) at the 88-Inch

Cyclotron of the Lawrence Berkeley Laboratory. HERA consists of 20 Compton-suppressed Germanium detectors and an inner ball of 40 BGO detectors. The ^{168}Yb nucleus was produced in the reaction ^{124}Sn(^{48}Ca,4n) at 210 MeV. A gamma-gamma coincidence matrix containing 315 million counts was generated, with requirements of fold > 17 and sum energy > 13 MeV in the inner-ball detectors. The level scheme based on the present work is presented in fig. 1. Five bands previously reported by Bacelar *et al.* [4] were confirmed (1 to 5 in fig. 1) and extended by one or two higher-lying transitions. In addition, four new bands (6–9, fig. 1), two extending up to $I \approx 40\hbar$, were observed. Part of band 6 had been independently observed by Khazaie *et al.* [6] but we disagree as to how this band decays to the ground-state band. In fig. 1 the dashed transitions indicate the intensity flow from band 6 to the ground-state band, according to our coincidence data. The actual linking transitions, however, were not observed. Spin values of bands 5 to 9 are tentative and are based on the coincidence relations of the transitions (and $\gamma-\gamma$ directional correlations in the case of band 7) and the relative intensities of the bands at high spin, which correlate rather strongly with the proximity to the yrast line. The lower members of bands 8 and 9 are also seen to feed low-lying states of the other bands but again the linking transitions were not found. Fig. 2(c) shows the experimental Routhians e' (excitation energies in the rotating frame [7]) relative to band 2, as a function of the rotational frequency ω.

The expected change of the neutron spectrum is calculated from the quasiparticle energies in a deformed rotating potential (Cranked Shell Model [7, 8], with deformation parameters from Ref. [8]), in which the static pairing-gap parameter Δ decreases linearly from the full value (0.8 MeV) at $\omega = 0.25$ MeV (where the AB crossing occurs) to zero at $\omega = 0.5$ MeV. In this frequency interval a crossing occurs in each band, leading to a substantial decrease in Δ according to microscopic calculations

[2]. The chemical potential is adjusted to give the right particle number for the yrast configuration. The spectrum generated by exciting pairs of qp is depicted in fig. 2(a). At the top of the figure we provide the scale for Δ. Since the qp formalism does not distinguish between particles and holes, for small Δ (large ω) the spectrum contains besides the ph excitations in the $N = 98$ system a number of spurious particle-particle and hole-hole states (since the single-particle (sp) occupation numbers are close to 0 or 1) belonging to $N = 96$ and 100. They can be eliminated by comparing with ph states calculated from the sp energies without pairing. All the remaining physical (ph) states are shown in fig. 2(b) at $\omega > 0.5$ MeV (only the bands that exist at high spin were traced down to low ω for simplicity). On the other hand, all low-lying qp configurations are physical for large Δ (since each qp has comparable particle and hole components). The qp states do not always connect continuously with ph states, usually because of avoided crossings between spurious and physical ones where they interchange character. We reconnect (diabatically) the physical branches by interpolation, as demonstrated in fig. 2(a) (around $\omega = 0.5$ MeV). Although rough and not free from ambiguities, this procedure provides a reasonable description of the transition region between the large Δ and zero Δ spectra, as seen from the comparison between figures 2 (b) and (c). There is only one low-lying configuration which is not observed experimentally, the lowest positive parity ($\pi = +$), zero signature ($\alpha = 0$) configuration. An assignment of this configuration to band 6 is not excluded; however, our spin and energy estimates result in high alignment and this is more consistent with a proton configuration, which still has strong pairing. For this reason band 6 was left out of fig. 2(c). Figures 3, 4, and 5 demonstrate that the same approach describes well the excitation spectra in the adjacent isotopes.

The nuclei of the ^{168}Yb region show a transition from a qp to a ph spectrum in the frequency range from 0.3 to 0.4 MeV. It reflects the disappearance of static pairing at high spin. That transition is described quite well by our method. In mesoscopic systems such as nuclei, the presence of fluctuations and configuration dependence make the transition from superfluid to normal very diffuse. In a macroscopic system the very large number of particles allows for relatively small fluctuations and yields a sharp phase transition. In superconductors, for example, the relation between magnetization and magnetic field has a singularity at the critical field where the phase transition occurs. In nuclei the analogous relation between the canonical variables I and ω shows a steep rise in the transition region but its shape varies considerably from band to band. Although some aspects of the destruction of static pairing by rotation resemble a phase transition, there are also significant differences to it.

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[*] On leave from the Universidade de São Paulo, S. Paulo, SP, Brazil

[†] On leave from the Institut für Kern und Hadronen Physik, FZ- Rossendorf, PF.19 0-8051 Dresden,Germany

[‡] University of Liverpool, Liverpool L69 3BX, United Kingdom

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FIGURES

FIG. 1. The level scheme of ^{168}Yb. The different bands are numbered for further reference.

FIG. 2. Band structure of ^{168}Yb. The Routhians are plotted relative to the lowest $(\pi,\alpha) = (-,1)$ configuration (band 2). The solid, dashed, dot-dashed and dotted lines correspond to $(\pi,\alpha) = (+,0)$, $(+,1)$, $(-,0)$, and $(-,1)$, respectively. (a) Zero, 2 and 4 quasiparticle states calculated with decreasing pairing gap Δ (see text). Diabatic interpolations are shown as thin lines for the two lowest $\pi = +$ states only. (b) Physical states selected from (a). On the inset at the bottom right, the particle-hole excitations of the $(-,1)$ core (band 2) are shown (in this case the solid, dashed, dot-dashed and dotted lines correspond to $(\pi,\alpha) = (+,1/2)$, $(+,-1/2)$, $(-,1/2)$, and $(-,-1/2)$, respectively); they are strictly valid only above $\omega = 0.5$ MeV where $\Delta = 0$ (the corresponding Nilsson labels are, from top to bottom: $([512]5/2^-)^2$, $[642]5/2^+$, $[521]1/2^-$, $[521]1/2^-$, and $[642]5/2^+$). (c) Experimental relative Routhians. Experimental points are indicated by the numbers and correspond to the in-band quadrupole transitions in fig. 1.

FIG. 3. Band structure of ^{166}Yb. (a) Calculation with decreasing Δ. (b) Experimental results [9]. The line conventions are the same as in fig. 2.

FIG. 4. Band structure of ^{167}Yb. (a) Calculation with decreasing Δ. (b) Experimental results [4, 6]. The line conventions are the same as in the inset of fig. 2(b).

FIG. 5. Band structure of ^{169}Yb. (a) and (b), same as in fig. 4.

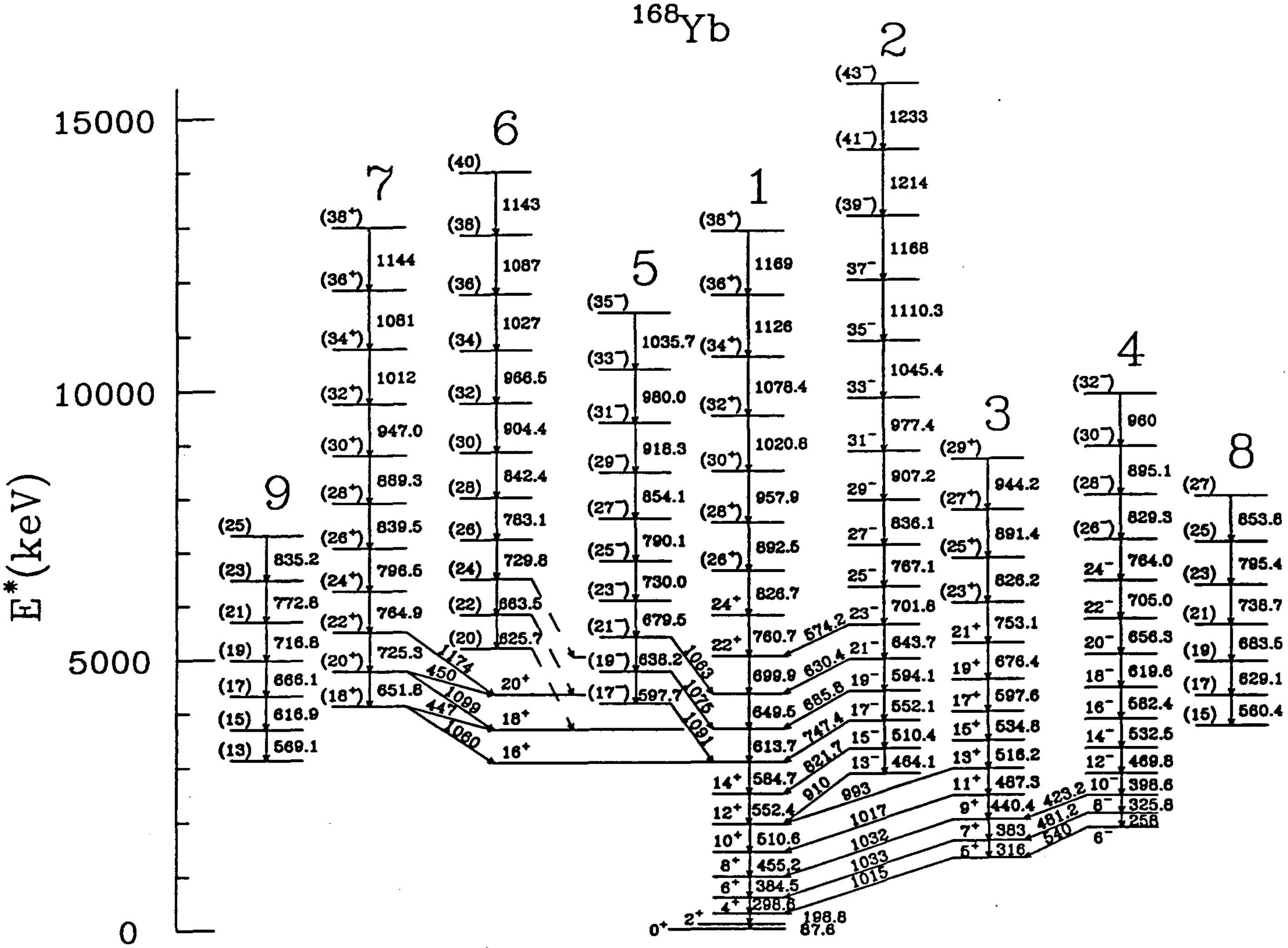

FIG. 1.

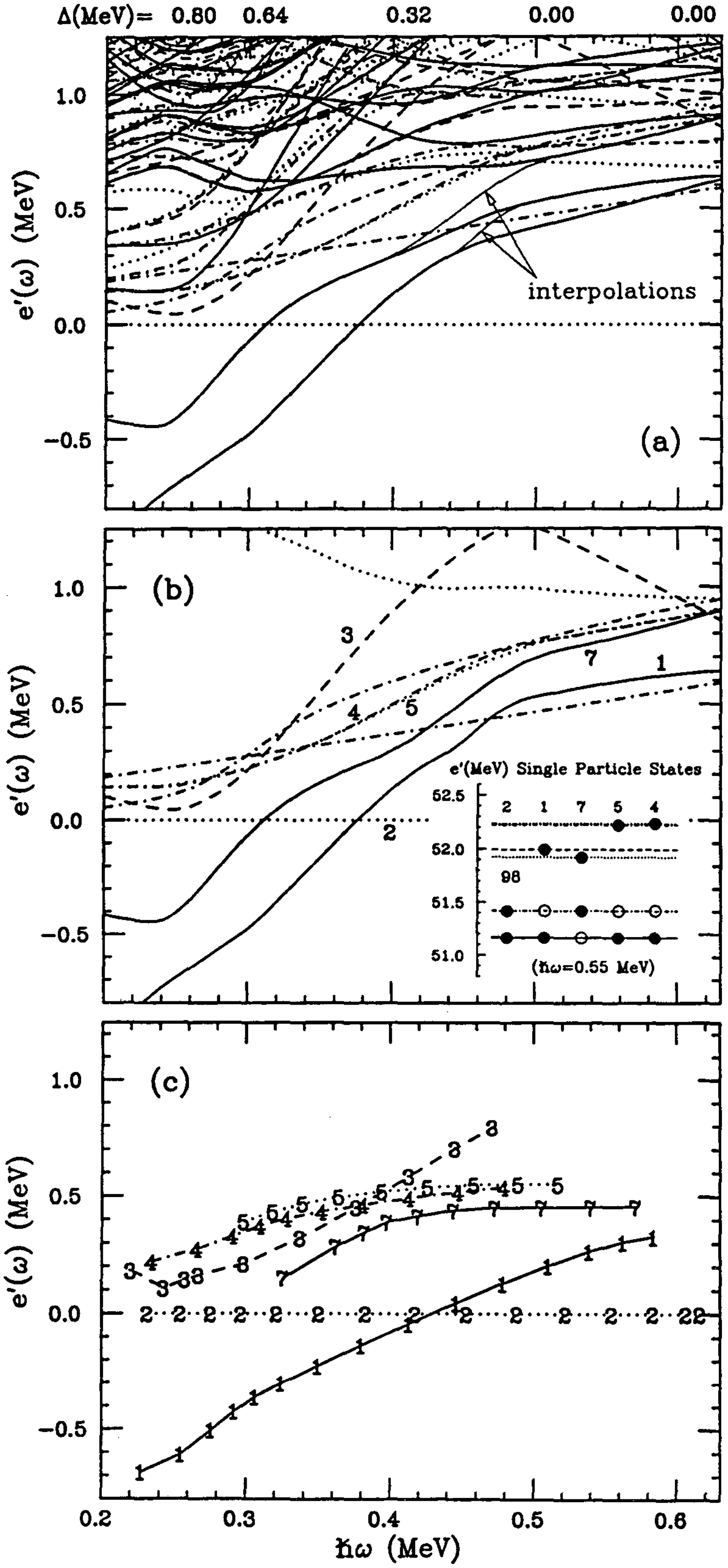
Δ(MeV)= 0.80 0.64 0.32 0.00 0.00
e'(ω) (MeV)
1.0
0.5
0.0
−0.5
interpolations
(a)
(b)
3
4
5
7
1
2
e'(MeV) Single Particle States
52.5
52.0
51.5
51.0
2 1 7 5 4
98
(ħω=0.55 MeV)
(c)
0.2
0.3
0.4
0.5
0.6
ħω (MeV)

FIG. 2.

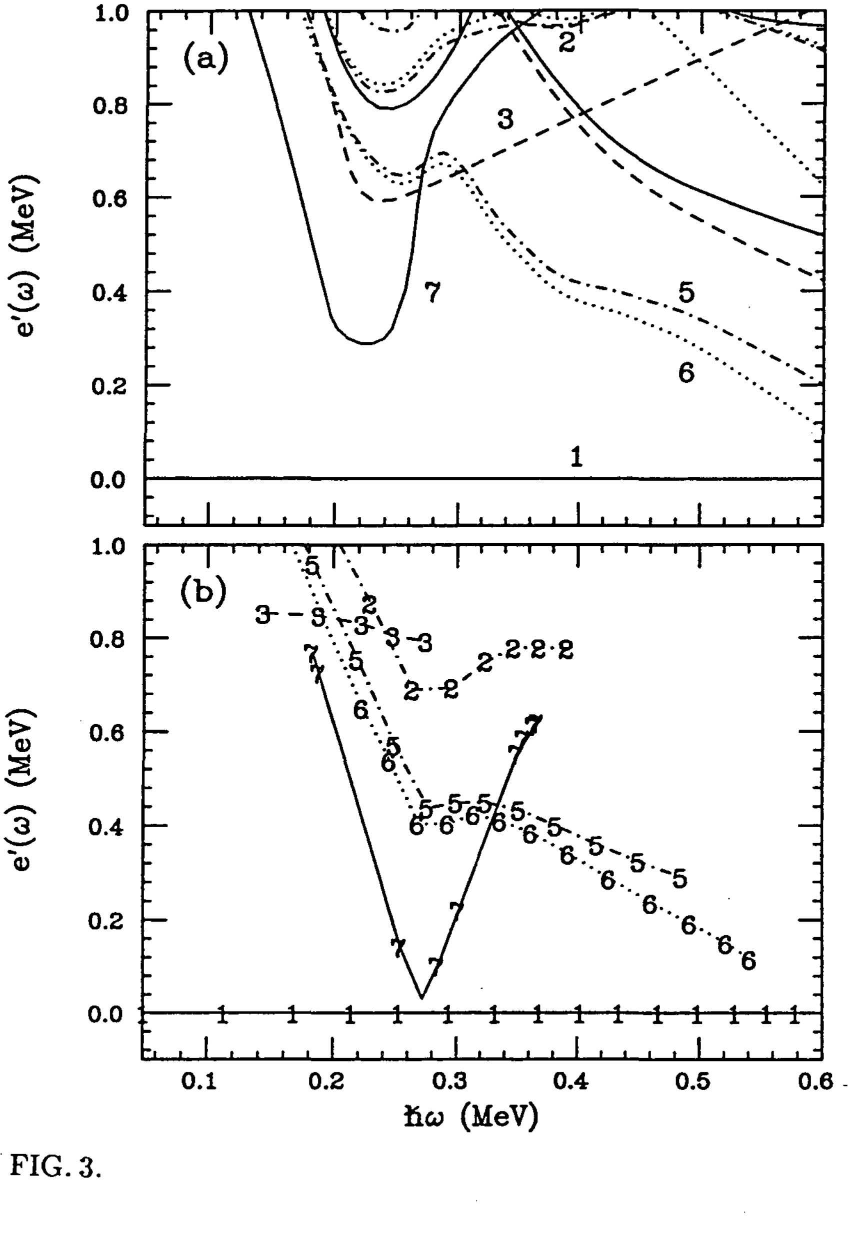

FIG. 3.

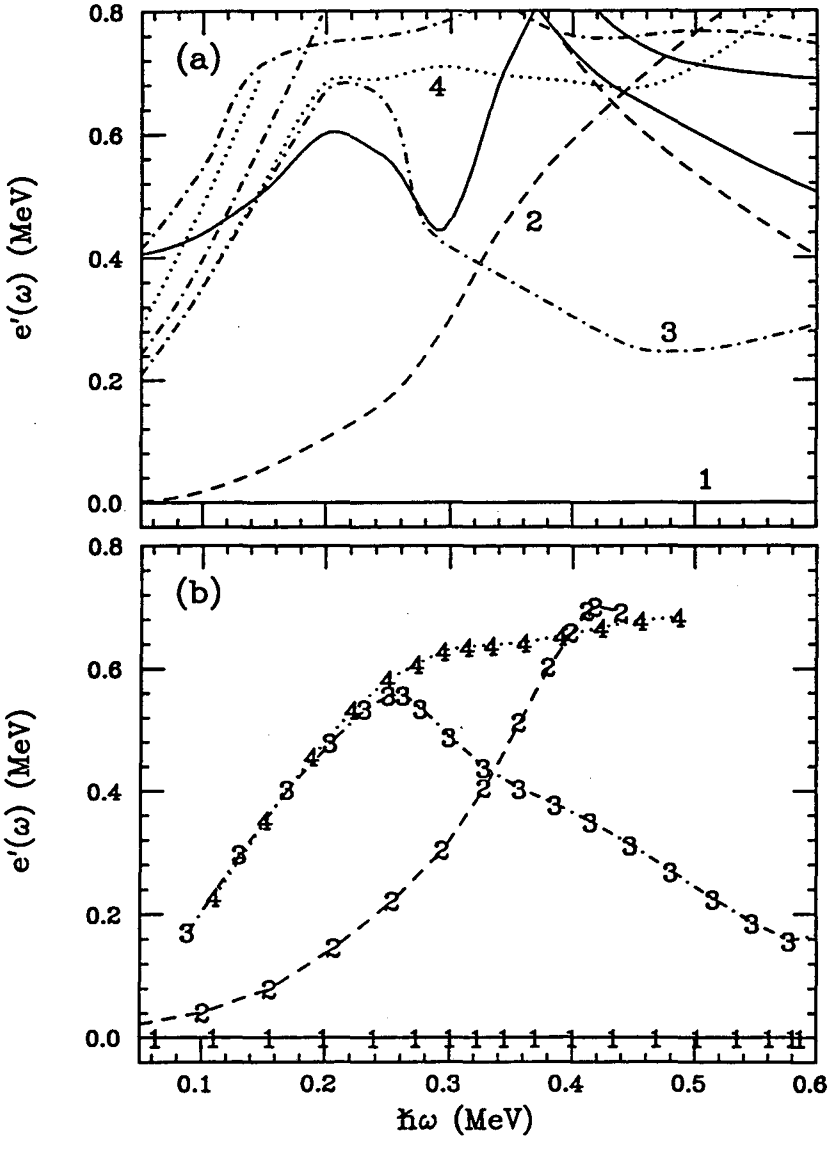

FIG. 4.

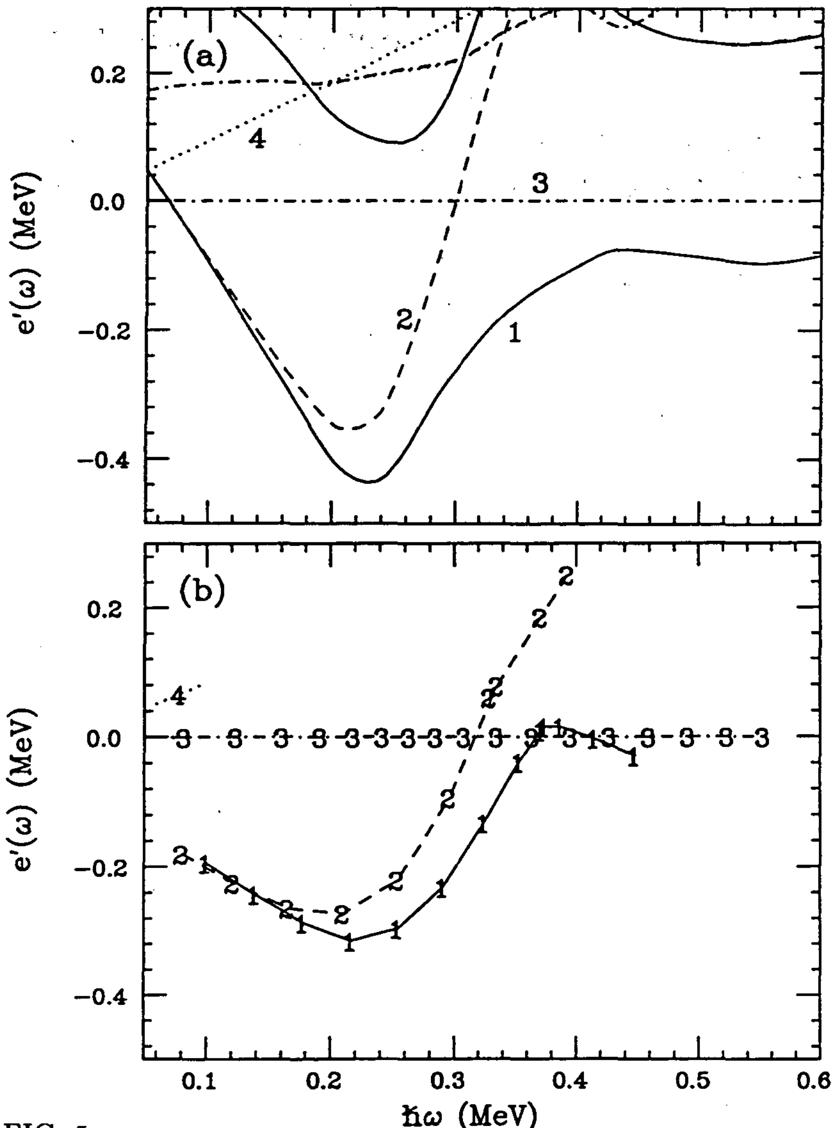

FIG. 5.

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
TECHNICAL INFORMATION DEPARTMENT
BERKELEY, CALIFORNIA 94720