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Interior probing capability in kaon-nucleus inelastic scattering

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Results from a nuclear structure form factor study are presented to investigate the extent of surface localization and volume sensitivity in K^+-nucleus inelastic scattering. Using wave functions from a macroscopic collective model and the microscopic particle-hole model of Gillet and Vinh Mau, form factors (transition densities) and cross sections are independently calculated and then compared for low-lying excited states in ^{12}C. Unlike strongly absorbed projectiles (including the pion), which have dominant surface localized reaction mechanisms, the interior differences between model form factors are clearly reflected (measurably distinct) at *all* scattering angles.

[NUCLEAR REACTIONS kaon-nucleus inelastic scattering. DWIA, KMT, and RPA. Calculated $\sigma(\theta,E)$ for ^{12}C. Comparative form factor study.]

One of the conclusions reached in an earlier study[1] of K^+-nucleus inelastic scattering was that the inelastic process was localized ($\pm\frac{1}{2}$ fm) near the nuclear surface. This study[1] also confirmed that the K^+ meson was, as previously noted by Dover,[2] quite weakly absorbed. These developments would appear "anomalous" as surface dominating processes are normally associated with strongly absorbed particles. Because of the potential ramifications from a growing interest in kaon-nucleus phenomena,[3-10] it is important at this time to fully understand this surface localization behavior and to determine the extent of volume probing sensitivity of the K^+ meson. In particular, it is essential to further document the improved and new nuclear structure information which can be uniquely obtained through kaon induced reactions. The purpose of the present communication is to address these issues by reporting results from a comparative form factor study for K^+-nucleus inelastic scattering. The comparison is between inelastic form factors obtained using a macroscopic collective model and the microscopic particle-hole model of Gillet and Vinh Mau.[11] The results indicate that the surface localization is directly attributable to the surface peaking of the collective form factor and that the kaon is indeed sensitive to details of the nuclear interior.

This theoretical study, which parallels a previous pion investigation,[12] compares microscopic and macroscopic form factors (transition densities) for the $J^\pi = 2^+$ ($E_x = 4.43$ MeV) and 3^- ($E_x = 9.64$ MeV) states in ^{12}C. The calculations are based on the distorted-wave impulse approximation (DWIA) to the exact multiple scattering transition amplitude and are further detailed in Refs. 1, 8, and 13. The necessary information entering the analysis are the phenomenological kaon-nucleon amplitudes and nuclear structure (model) wave functions. All calculations reported in this work use Martin[14] kaon-nucleon amplitudes and Fermi motion effects are neglected (no Fermi averaging). These amplitudes are used to construct the elastic (distorting) and inelastic kaon-nucleus interactions as a function of bombarding energy (see Ref. 8). To study surface localization two different wave functions were used to generate form factors: a macroscopic collective rotational model, in which the density is deformed, and the microscopic particle-hole model of Gillet and Vinh Mau (GV).[11]

The GV model, which used the random phase approximation (RPA), includes all 1 particle–1 hole excitations involving 1*s*, 2*s*, 1*p*, 2*p*, 1*d*, and 1*f* single-particle orbitals. Since two particle–two hole contributions are important for the low-lying collective states in ^{12}C, the GV wave functions fail to provide sufficient collectivity. However, because the phenomenological effective nucleon-nucleon interaction entering the RPA calculation was determined in part by properties of the first 2^+ state in ^{12}C, the results presented below, while perhaps not completely physically correct, should remain representative. For the collective model the ground state density, as determined by electron scattering, was deformed with deformation parameter β_J. To ensure consistent, meaningful form factor comparisons the collective model was constrained[12] to provide electric transition rates ($BE2$ and $BE3$ values) identical to those obtained using the GV wave functions. This yielded $\beta_2 \simeq \beta_3 = 0.56$. Finally, consistency also required the omission of all spin-flip inelastic amplitudes (magnetic transitions) in the microscopic form factor. The latter effect was found small for pions[12] involving natural parity excitations and should be even smaller for kaons since the kaon-nucleon amplitude is predominantly *s* wave for the energies used in the present calculation.

The microscopic and macroscopic ($BE2$ normalized) radial transition densities (inelastic form factors) for the ground to 2^+ (4.43 MeV) transition in ^{12}C are plotted in Fig. 1. The form factors differ appreciably in the interior but are similar near the nuclear surface (about 2.3 fm for ^{12}C). Accordingly, strongly absorbed particles, which predominantly probe the nuclear surface, should not provide sensitive means for distinguishing between these two different radial shapes. This is particularly true for the pion at energies near the (3,3) resonance and has been discussed in Ref. 12 where calculations demonstrate that only at back angles (large momentum transfer) can theoretical pion inelastic cross sections predict measurable differences.

Of central importance in this work is the interior probing capability of the weakly absorbed kaon. Figure 2 compares the predicted angular distributions for K^+ inelastic scattering at 100 MeV lab kinetic energy. There is a clear, measurable distinction between the particle-hole and collective models. The cross section difference is as much as 50% at forward angles, including a 10° maxima shift, and grows to an order of magnitude at back angles. Figure 3 demonstrates a similar sensitivity at 300 MeV where the minimum predicted by the collective model near 40° is completely missing in the particle-hole picture. Form factor and cross section calculations were also performed for the 3^- (9.64 MeV) state and similar differences were found (not shown).

A cursory examination of Fig. 1 immediately suggests that in the collective model the dominant inelastic contributions should come from the nuclear surface. The particle-hole model, however, peaks somewhat inside the surface (about 1.6 fm). To further determine the extent to which the kaon can resolve this difference, radial cutoff calculations, identical to the study in Ref. 1, were performed. The results are shown in Fig. 4 where the total inelastic cross section is plotted as a function of the cutoff radius R_c. For comparison, both the collective and particle-hole DWIA cross sections are presented along with corresponding plane-wave impulse approximation (PWIA) calculations. To effectively illustrate the differences, the curves have been renormalized to produce identical cross sections at $R_c = 0$. Notice that the kaon is indeed sensitive to the interior tail of both model form factors (see Fig. 1) and clearly reflects the radial peak shift of the GV form factor relative to the collective form factor.[15] Further-

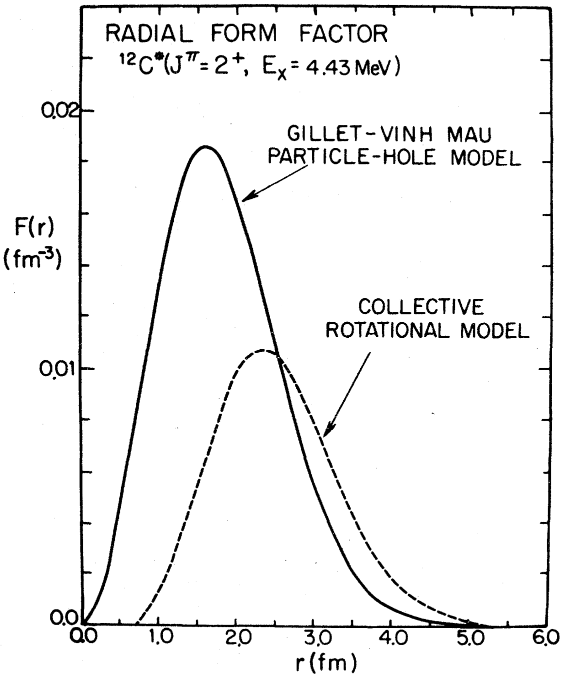

FIG. 1. Radial transition densities, $F(r)$ (form factors), computed for ground state to 2^+, 4.43 MeV state transition using microscopic particle-hole (solid curve) and collective macroscopic (dashed curve) models.

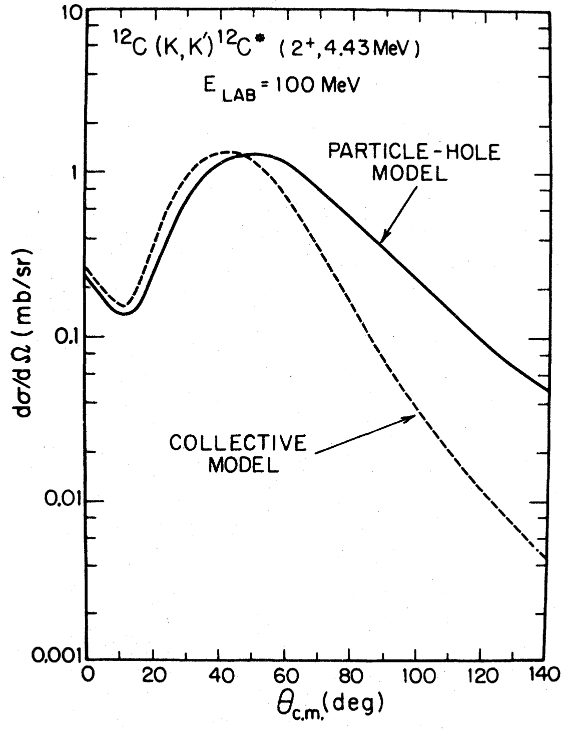

FIG. 2. Differential inelastic cross section for kaon inelastic scattering using the particle-hole (solid curve) and collective (dashed curve) form factors plotted in Fig. 1.

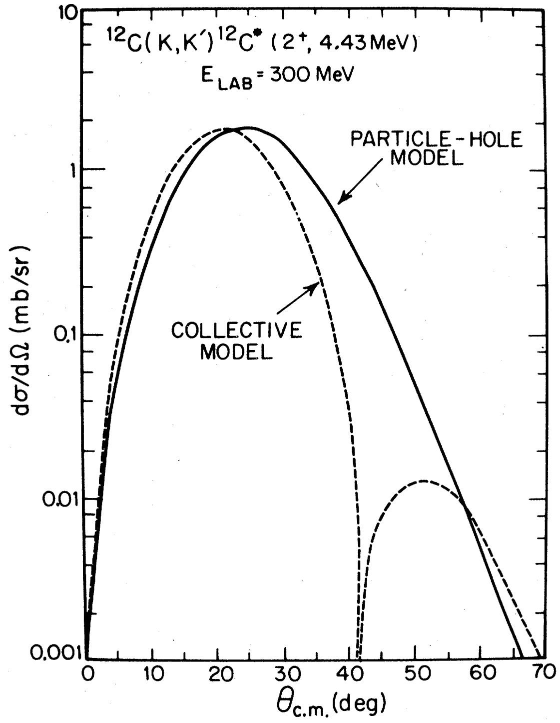

FIG. 3. Same as Fig. 2 for $E_{LAB} = 300$ MeV.

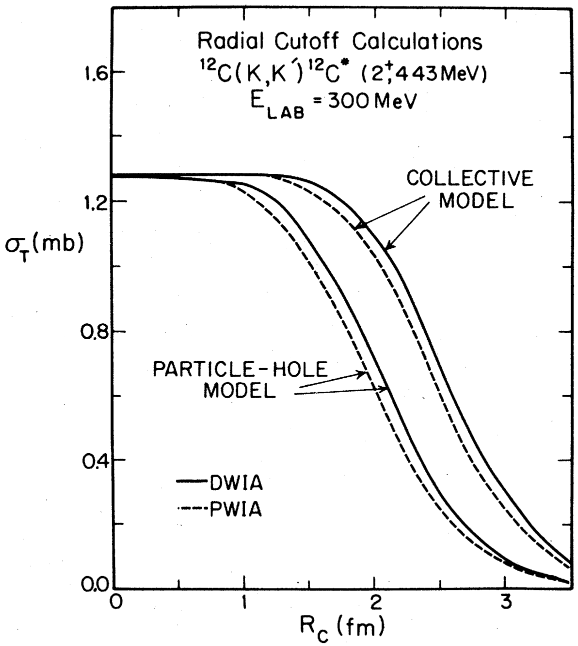

FIG. 4. Microscopic and macroscopic total inelastic cross section as a function of cutoff radius R_c. Solid curves represent DWIA, dashed curves PWIA. For visual comparison the curves have been renormalized to give equal cross sections at $R_c = 0$.

more, the small radial difference between DWIA and PWIA (no absorption) convincingly demonstrates that kaon distortion effects are small and do not significantly affect the probing sensitivity. In essence, the kaon appears to "see" whatever is available to be seen.

In summary, the weakly absorbed K^+ meson is predicted to be sensitive to details concerning the interior structure of the nucleus. Further, the kaon appears to have the rare capability of distinguishing between microscopic and macroscopic structure models. Although the microscopic particle-hole model used in this work may be incomplete for the low-lying collective states in ^{12}C, these conclusions should be valid for studies involving improved models. In particular, for high spin (stretched configuration) natural and unnatural parity states, the kaon should provide a powerful tool for probing particle-hole excitations.[3,7] Likewise for giant resonance studies, the kaon should prove invaluable in assessing the 1 particle–1 hole $T_<$ component of the resonance.[2,3,7,9] Finally, in the active area of kaon-nucleus elastic scattering, where experiments have recently been performed,[16,17] the kaon should provide a unique means for determining the ground state neutron distribution as well as neutron-proton density differences using neighboring isotope measurements (e.g., ^{40}Ca–^{48}Ca). These studies focus on both volume (interior) and surface structure and are now in progress.[18]

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