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MEASUREMENTS OF KAONIC X-RAY SPECTRA AND THE CAPTURE OF KAONS ON NUCLEAR SURFACES

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K^--mesons, when stopped in matter, are captured by nuclei into hydrogen-like systems that we call kaonic atoms. When kaonic atoms undergo de-excitation they emit characteristic x rays in the same manner as do muonic and pionic atoms. We have studied the x-ray emission of 29 elements ranging from $Z = 3$ to $Z = 92$(1) and conclude from the preliminary measurements on the medium and heavy elements that nuclear matter -- very probably neutrons -- extends to larger radii than the radii of the charge distributions given by the classic electron scattering experiments of Hofstadter(2) and the Stanford group.

That neutrons should dominate nuclear surfaces is not a new idea:
Johnson and Teller(3) (1954) and Wilets(3) (1956) suggested that neutrons should populate the nuclear surface. Since then several authors have proposed that the nuclear surface should be rich in neutrons.(4)

Muonic and pionic atoms(5) have also been studied for many years and have presented us with a wealth of information on the internal structure of the nuclei, but as Wilkinson(6) pointed out, kaons should be sensitive probes of the nuclear surface. Kaons are sensitive to the low-density regions of nuclei because they strongly interact with single protons or single neutrons. A cursory analysis of the kaonic x-ray measurements suggests that the neutrons are distributed in a low-density tail. The parameters of the tail are relatively insensitive to the radii at half the central matter density.

To study the kaonic x rays of medium and heavy elements we used an experimental arrangement similar to that of Wiegand and Mack.(7) The external proton beam of the Bevatron was used to generate a secondary beam of negative kaons that were brought to rest in our targets. In fixed positions a few centimeters on either side of the targets we placed two lithium-drifted germanium detectors. Goulding, Landis, and Pehl(8) of the Chemistry Nuclear Instrumentation Group of our laboratory supplied us with the solid state detectors and their associated amplifiers. When a kaon stopped in the target, digital numbers proportional to the energies deposited in the detectors were stored on magnetic tape. A computer processed the data into spectra.

Figure 1 shows three examples of the kaonic x-ray spectra. No backgrounds have been subtracted and no corrections for detector efficiency or target absorption have been applied. Consider the lead spectrum. It is the result of stopping about a million kaons. The detector was lithium-drifted germanium in the planar configuration with an effective volume of 13 cm^3. The lines at about 80 keV are the $_{82}Pb$ K alpha and K beta x rays from the emptying of the atomic electron K-shell. The next peak at 117 keV represents the kaonic transition from n = 12 to n = 11. Transitions to successively lower n values continue to the last observable peak at 427 keV, which corresponds to the n = 8 to 7 transition.

The kaons must be absorbed from orbits of maximum angular momentum (circular orbits) for our assumption that the kaons are absorbed on the nuclear surface to be valid.(6) Absorption from elliptical orbits would involve a nuclear volume effect and spoil the whole argument. To appreciate the argument for capture from circular orbits, consider the schematic energy level diagram of kaonic lead atoms shown in Fig. 2. Kaons are preferentially captured into atomic states of high angular momentum approximately in proportion to the statistical weight $2\ell+1$. Once a kaon enters a circular orbit it is trapped; there is no escape mechanism before capture. The existence of such a spectrum as the Pb series is strong evidence that the kaons are absorbed from circular orbits, because kaons in a given n level but with $\ell < n - 1$ are much more strongly absorbed than those with $\ell = n - 1$. Thus kaons in elliptical orbits cannot contribute at the end of a series. Therefore, we believe that if a kaon survives down to the eighth or ninth level of a kaonic Pb atom, it is surely in a circular orbit. Also the observed intensities of the lines are in approximate agreement with the calculations of Eisenberg and Kessler,(9) except where the kaons are strongly absorbed.

Figure 3 presents a chart of the principal kaonic lines that we measured in this survey of the medium and heavy elements. Along the abscissa are the atomic numbers. The ordinate consists of

12 lanes: each represents a transition from one circular orbit to the next. Heights of the bars are proportional to the observed intensities, which have been corrected for detector efficiency and target absorption. Shaded areas represent estimates of the errors in the intensities. The distance between the horizontal lines corresponds to 1 x ray per stopped kaon. The main point of the chart is to indicate where the various transitions are cut off. Consider the band that contains 5g to 4f transitions: we see intense lines from $_{17}$Cl, $_{19}$K, $_{20}$Ca, and $_{22}$Ti, but at $_{28}$Ni the transition is overwhelmed by nuclear capture. In $_{29}$Cu the line is unobservable. In this first experiment we did not find the cutoff of the 6h → 5g lines, but it lies somewhere between $_{42}$Mo and $_{53}$I. The 7i → 6h series ends at $_{64}$Gd (or $_{65}$Tb, which we did not measure). The transition was unobservable in $_{66}$Dy. We interpret the diminished intensity of the Gd 7i → 6h line to indicate that the nuclear capture rate is equal to or greater than the radiation rate from the state $n = 7$, $l = 6$ to $n = 6$, $l = 5$.

The radiation rates of the circular orbit transitions serve as built-in calibrations of the capture rates. When the kaon is about to be absorbed, the kaonic atom is very nearly hydrogenic and we have no hesitation in applying the hydrogen atom formulas. In the kaonic Gd atom, the radiation rate from $n = 7$, $l = 6$, to $n = 6$, $l = 5$ amounts to 1.2×10^{16} sec^{-1}. Therefore, the capture rate must be about 10^{16} sec^{-1}.

To relate the kaon absorption rate to nuclear size, we choose as a model of nuclei the Saxon-Woods distribution of nuclear matter

$$\rho_p(r) = \frac{\rho_p(0)}{1 + \exp[(r-C)/z]} ,$$

where the radius at half the central density is $C = 1.07\, A^{1/3}$ F and the skin thickness parameter is $z = 0.55$ F. According to the Stanford data these parameters of the charge distribution apply with good accuracy over the range of medium and heavy elements.

The capture rate can be approximated by the overlap integral

$$P_{cap} = \frac{2W}{\hbar} \int \frac{\rho(0)}{1 + \exp[(r-C)/z]} R^2_{n,n-1}\, r^2 dr ,$$

where $\rho(0)$ is the nuclear matter density at the center of the nucleus in units of particles per F^3, $R_{n,n-1}$ is the normalized hydrogenic radial eigenfunction for K$^-$, and W is the imaginary part of the kaon-nucleus potential. By invoking such an overlap integral we have made W independent of r and have reduced the kaon to a point with no interaction radius. However, these simplifications are probably not as serious as the assumption we must make for the value of W. To calculate our overlap integrals we rather arbitrarily set 2W equal to 100 MeV. Using the standard central density of 0.14 nucleons per F^3, 2W = 100 MeV, $C = 1.07\ A^{1/3}F$, $z = 0.55$ F, R_7^2 ($n = 7$, $_{64}$Gd), the above overlap integral gives a capture rate of $2.5\times10^{14}\ \text{sec}^{-1}$. This is a factor of 50 less than the experimentally calibrated capture rate of $1.2\times10^{16}\ \text{sec}^{-1}$. It is unlikely that W can account for the entire discrepancy. Because kaons react about equally on neutrons and protons through the reactions $K^- + N \rightarrow$ hyperon + pion, we have strong evidence that the kaons are absorbed by nucleons above the conventional nuclear surface.

We can bring the capture rate into agreement with the experiment by introducing a distribution of neutrons with different parameters than the proton parameters. Figure 4 shows one such distribution for $^{157}_{64}$Gd. We show the conventional proton distribution ρ_p and a neutron distribution ρ_n with the same radius but with a neutron skin thickness twice that of the proton skin thickness. The proton distribution requires $\int \rho_p dV = Z$ and the neutron distribution $\int \rho_n dV = A - Z$. The curve on the right-hand side of the illustration is the kaon distribution for $n = 7$, $\ell = 6$. The heavy solid curve in the center portion of the picture is the capture rate. The integral of the capture rate expression equals that of the radiation rate: $1.2\times10^{16}\ \text{sec}^{-1}$. In this nucleon distribution practically all the contribution to the overlap integral comes from the neutrons.

Figure 5 shows neutron and proton distributions made with conventional parameters and some modified distributions. The kaon-nucleus interaction energy is 2W = 100 MeV for all the curves. The curves with the skin thickness parameters increased to 2.3 times the conventional value give the experimentally determined capture rate. Bethe(4) has suggested that the neutrons outside a nucleus ($r \gtrsim C$) should be distributed by

$$\rho_n(r) = (1/2)\,\rho_n(0)\,\exp\left[-(8M\epsilon)^{1/2}\,(r - C)/\hbar\right],$$

where M is the neutron mass and ϵ is the neutron binding energy. Bethe's proposed exponential tail appears to give too small a contribution to the capture-rate overlap integral, if we keep 2W = 100 MeV. However, there is apparently no reason to believe that W cannot be as high as 500 MeV. An increase in 2W by a factor of 10 would bring Bethe's theory into agreement with the experiment at $Z \approx 64$. Bethe's exponential falloff has a solid theoretical foundation based on the neutron binding energy, whereas our Saxon-Woods distribution is only a convenient model that is similar to the measured charge distribution.

When we mention $P_{cap} = P_{rad}$ we refer to kaonic transitions that generate x-ray lines whose intensity is reduced to one-half the intensity they would have if there were no competition to radiation: $I \propto P_{rad}/(P_{rad} + P_{cap})$. The capture rate is probably larger than the radiation rate for the last transition observed in a series. In the next phase of the experiment we will try to determine how the intensities of the lines diminish as the series approach cutoff.

Another part of the next experiment will be to stop kaons in targets composed of single pure isotopes. There should be an observable effect on the intensities of lines that are nearly cut off. For example, the 5g to 4f transition in $_{28}$Ni can have measurable differences in intensity, depending upon whether the targets are ^{58}Ni, ^{60}Ni, or ^{62}Ni. Any observable change in the intensities of the lines, as we add neutrons, will be valuable information. We also expect to try to observe differences in the isotopes of Eu and Gd, where nuclear deformation might be a contributing factor.

The energies of the lines were measured by comparing them with the calibrated emissions of selected radioactive isotopes. We found the energies of the x-ray lines to be the energies given by the Klein-Gordon equation plus corrections for the vacuum polarization. The present accuracy of the experimental calibration is insufficient to establish differences due to strong interactions or other effects.

An interesting byproduct of the energy measurements of the kaonic x rays is an independent check on the mass of the kaons.

Our present energy calibration establishes the kaonic mass at 493.97 ± 0.22 MeV,(10) only 0.05 MeV higher and well within the accepted value, 493.82 ± 0.11 MeV.(11)

Now let us focus our attention on the potassium spectrum in Fig. 1. An interesting feature is the series of lines 6h → 5g, 7h → 5g, and 8h → 5g. These transitions of $\Delta n = 1, 2,$ and 3 have relative intensities in fair agreement with the predictions of Eisenberg and Kessler.(9)

At 186 keV there is a peak that corresponds to the pionic transition 3d → 2p. Several pionic lines have been seen among the kaonic lines. This is not surprising, because hyperons are generated when kaons react with nucleons. The subsequent decay of the hyperons is a source of pions that can lead to pionic x rays.

Some of the Σ^--hyperons that were generated in the targets through the reactions $K^- + n \rightarrow \Sigma^- + \pi^0$ and $K^- + p \rightarrow \Sigma^- + \pi^+$, were captured by target nuclei into hyperonic atoms. As the Σ^- particles cascaded toward the nuclei, x rays should have been emitted in the same manner as the kaonic x rays. We looked for the hyperonic transitions and found one line in the spectrum taken with a $_{19}$K target. In the spectrum resulting from one million kaons stopped in $_{19}$K there is a peak at 136 keV that corresponds to the Σ^--hyperonic transition 6h → 5g. Its intensity is about 0.015 x rays per stopped kaon whereas the kaonic transition 5g → 4f has an intensity about 40 times greater. This is a reasonable intensity based upon the European K^- Collaboration(12) experiment which reports that 0.08 K^- stopped in nuclear emulsion lead to the generation of Σ^--hyperons. X rays from the hyperonic transition $n = 7$ to 6 are expected at 82.2 keV, but the line is not observed. The $n = 5$ to 4 transition is probably eliminated by nuclear absorption. We hope to confirm the hyperonic atoms in the next experiment and to find hyperonic lines in the spectra of heavy elements. Σ^--hyperonic lines of the heavy elements are especially interesting because they should show a fine structure due to the magnetic moment of Σ^-. For example, in U the splitting of the $n = 11$ to 10 hyperonic transition at 467 keV should amount to 0.64 keV according to SU_3 theory. With more intense kaon beams and larger germanium detectors of improved resolution, we may be able to measure the Σ^- magnetic moment.

In summation we have a new tool for the investigation of the nuclear surface, and we may be able to make a significant and independent measurement of the kaonic mass. Study of Σ^--hyperonic atoms should eventually result in the measurement of the Σ^- magnetic moment. The study of antiprotonic atoms is another possibility.

I wish to thank the many persons who made the experiment possible, especially: Frederick Goulding and Richard Pehl for the detector system, Rory Van Tuyl and Jack Walton for the electronics, and the Bevatron crews for the kaon beam. Raymond Kunselman, with the help of Donald Brandshaft, made the computer programs for the overlap integrals. Professors Emilio Segrè and Lincoln Wolfenstein contributed many valuable ideas to the interpretation of the data.

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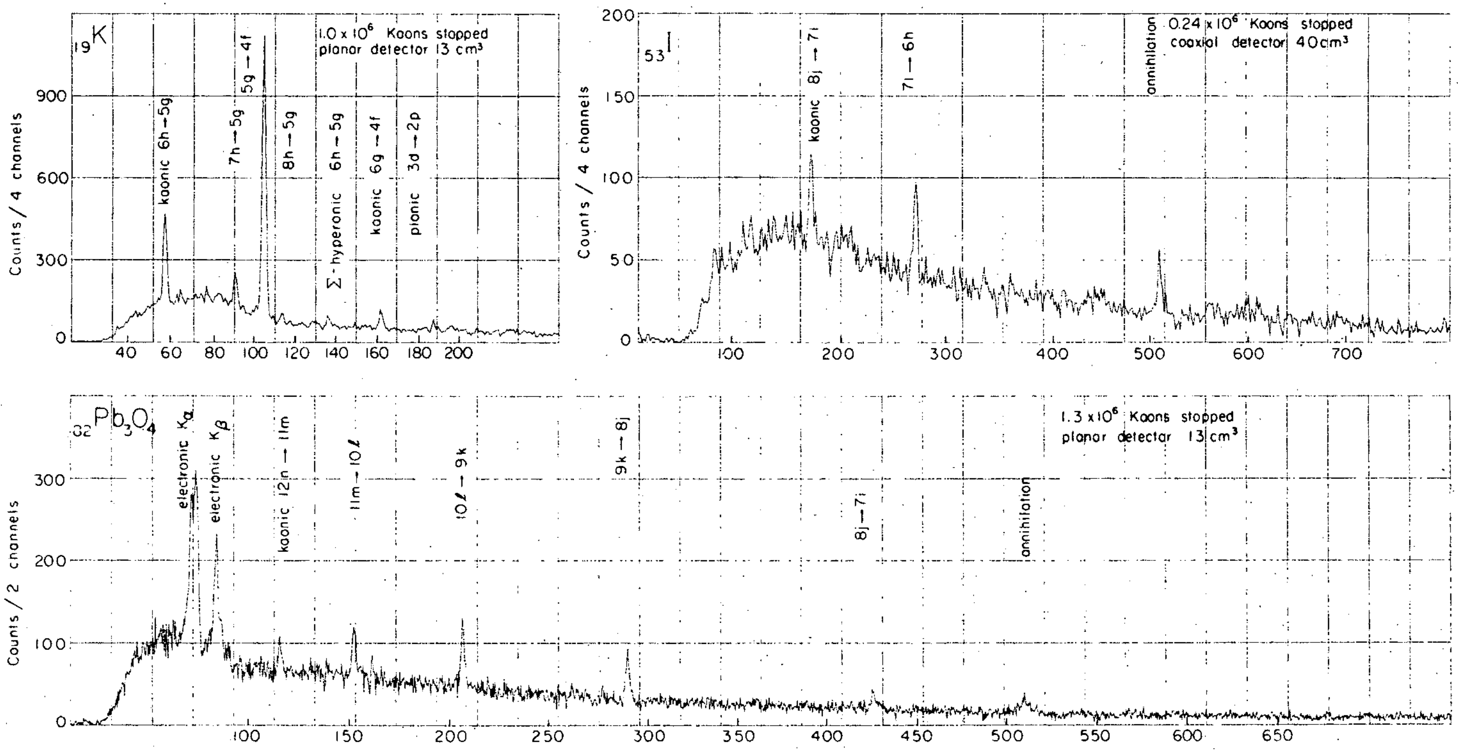

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Fig. 1. Examples of kaonic x-ray spectra.

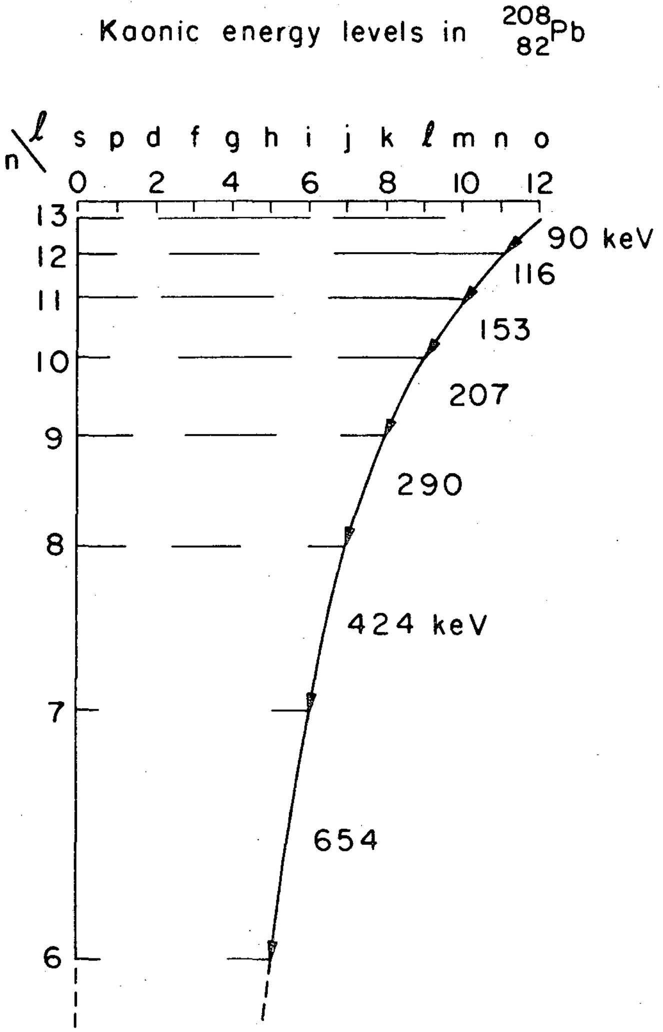

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Fig. 2. Schematic diagram of the energy levels of kaonic lead atoms.

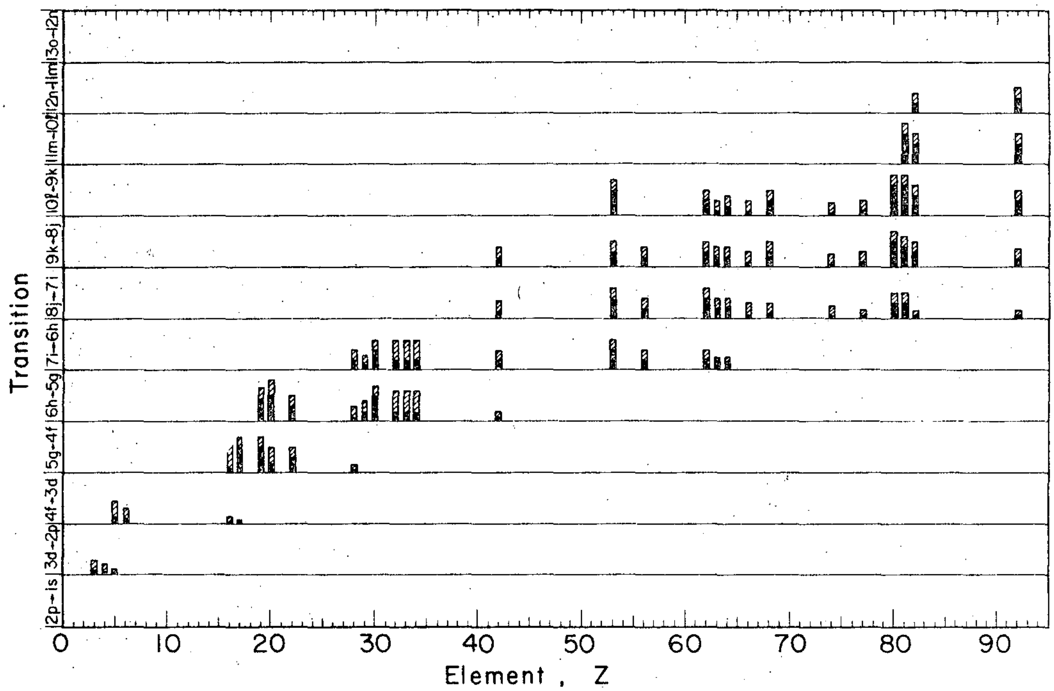

Fig. 3. Chart of the principal kaonic x-ray lines measured. The heights of the bars are proportional to the observed intensities with the shaded areas representing estimates of the errors. The distance between the horizontal lines corresponds to 1 x ray per stopped kaon.

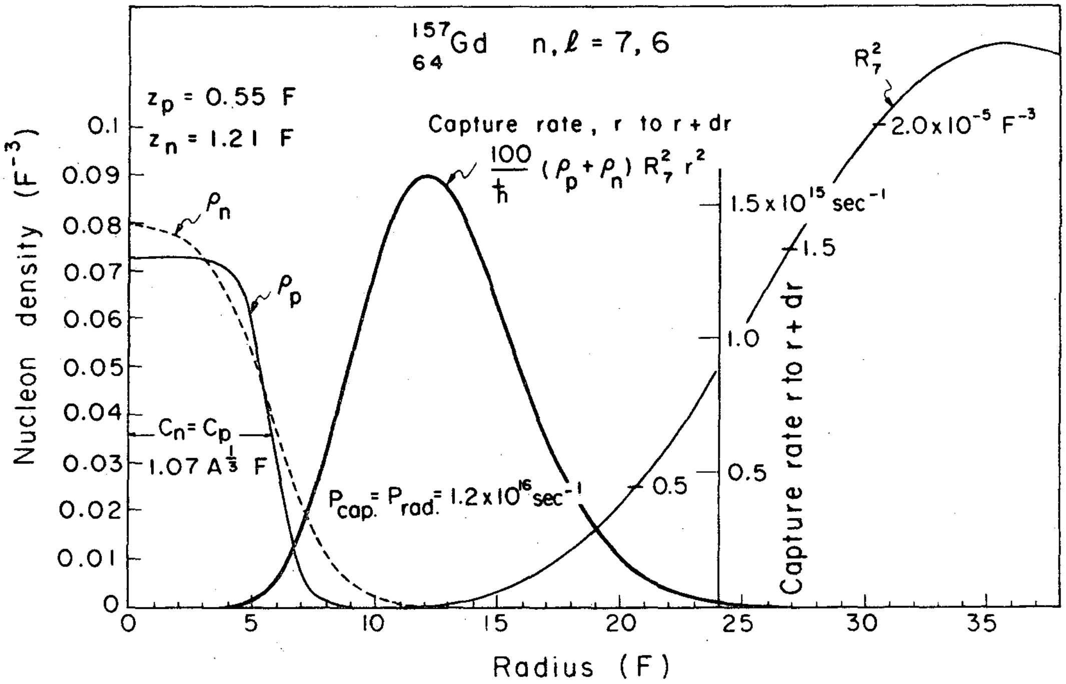

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Fig. 4. Example of a distribution of nucleons in $^{157}_{64}$Gd that agrees with the experimental kaon capture rate. The proton distribution is that of Saxon-Woods with Stanford parameters. The neutron distribution has the same radius but a larger skin-thickness parameter. Also shown are the kaon distribution for $n = 7$, $\ell = 6$, and the overlap function.

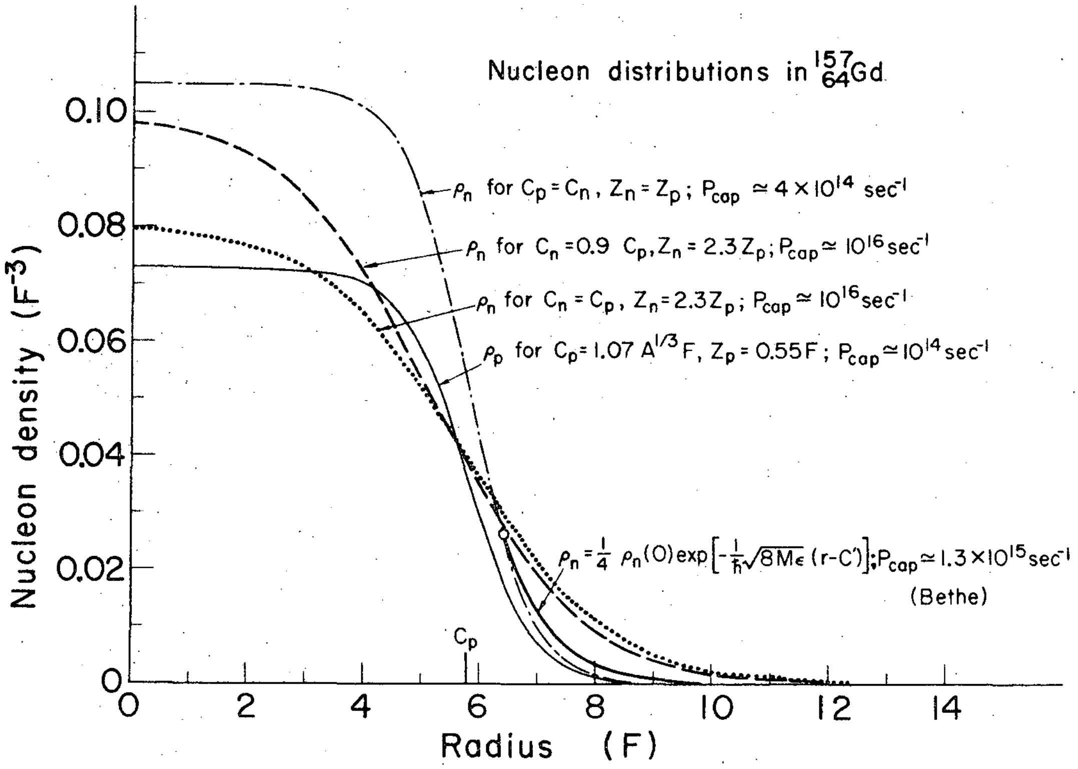

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Fig. 5. Several examples of nucleon distributions for $^{157}_{64}$Gd that are based on the Saxon-Woods model and fit the experimental kaon capture rates. Also shown is an exponential distribution suggested by Bethe which gives the required capture rate if W is increased to about 500 MeV. After the illustration was prepared, we learned that Bethe prefers the exponential falloff to be attached at $\rho_n = 1/2\ \rho_n(0)$.

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