from one detector into the other for which an attenuation factor of 5 is expected than with two-photon decay for which a factor of 3 is expected. Possible sources of γ-ray scattering from one detector into the other are (1) Doppler-shifted 0.511-MeV γ rays due to positron annihilation in flight,[3] (2) multiple Compton scattering, and (3) the summing in one detector of a positron-annihilation photon and a Compton-backscattered annihilation photon originating in the other detector. Calculations of these effects[4] indicate that the coincidences observed in the geometry of Fig. 2 and in the previous experiment[1] are mainly due to positron annihilation in flight. Those observed in the geometry of Fig. 1 without the heavy-metal shielding are similarly found to result from multiple Compton scattering and positron annihilation in flight.

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Note added.—Further measurements made in the configuration illustrated in Fig. 2 have provided an improved value of 4.8± 1.6 for the attenuation due to the Pb screens.

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Shell Structure of the ^{58}Ni Charge Density

I. Sick*
Department of Physics, University of Basel, Basel, Switzerland
and
J. B. Bellicard, M. Bernheim, B. Frois, M. Huet, Ph. Leconte, J. Mougey, Phan Xuan-Ho, D. Royer, and S. Turck
Département de Physique Nucléaire, Centre d'Etudes Nucléaires de Saclay, 91190 Gif-sur-Yvette, France
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A very-high momentum-transfer ($q = 780$ MeV/c), elastic electron-scattering experiment on ^{58}Ni has been performed using the 600-MeV linac of Saclay. The charge density, extracted from (e,e) and muonic–x-ray data, exhibits considerably less structure than predicted by Hartree-Fock calculations.

Elastic electron scattering is the most powerful probe for the charge density $\rho(r)$ of the nuclear ground state, and recent experiments have yielded very detailed information on $\rho(r)$. The central question is then: What can one learn from these experiments about microscopic theories for the nuclear ground state?

The fluctuations in the density measured by these experiments[1-5] are very sensitive to the microscopic structure of the ground state. Qualitatively, the oscillations superimposed on the average density are understood. However, their amplitude seemed to be much smaller than predicted by shell-model calculations. This effect was assumed to provide information on the short-range nucleon-nucleon correlations[6-8] which lead to a general reduction in the amount of structure of $\rho(r)$.

But, for two reasons, the densities deduced from these experiments are not well suited for a conclusive comparison with theory. First, for nuclei with incompletely closed shells like calcium, the effects of short-range correlations cannot be isolated in the presence of 2p-2h (two-particle, two-hole) excitations.[9,10] Secondly, model densities prevent an unbiased investigation of the fine details of $\rho(r)$. One therefore has to use the much less model-dependent densities provided by recent analyses[11,12] of the same data. These new analyses of closed-shell nuclei show that, except for ^{48}Ca, the fluctuations of the densities determined by experiment are compatible with theory within experimental uncertainties. This is a consequence of the maximum momentum transfer

q_{max} that is too small (the smallest form factor measured is too large).

In order to allow a conclusive comparison with theory, we have performed a high-momentum-transfer experiment on ^{58}Ni with a $q_{max} = 3.9$ fm^{-1}. This nucleus has well-closed proton shells and its density is predicted to exhibit a pronounced structure with two peaks, one at zero radius and a smaller one near 2.5 fm. The available experimental spectroscopic factors[13,14] indicate that in ^{58}Ni only about 0.25 proton is outside the closed core. The systematics of the two-proton separation energies[15] confirm that $Z = 28$ is a good shell closure, clearly better than $Z = 20$. The predicted oscillation of $\rho(r)$ has a wavelength $\lambda = 2$ fm and its measurement requires a q_{max} significantly larger than $2\pi/\lambda = 3.2$ fm^{-1}. We believe the experiment presented below to give the first unambiguous evidence for reduced fluctuations in $\rho(r)$ of a well-closed shell nucleus.

The linear accelerator of Saclay (ALS) was used. The high-resolution setup of the new HE1 end-station allows us to extend considerably the q range covered by previous experiments. The intense beam, together with the new detectors[16] that provide the necessary background rejection, makes feasible the measurement of the extremely small cross sections (down to 10^{-10} mb/sr) occurring at large q. The electron beam of 449.5-MeV energy and 0.5-MeV energy spread was incident on a 400-mg/cm^2 ^{58}Ni target isotopically enriched[17] to 99.9%. The beam current (at maximum 30 μA because of heat dissipation in the oscillating target) was integrated by a Faraday cup. The scattered electrons, energy analyzed by the new 900-MeV/c spectrometer ($\Omega = 5$ msr), were detected by two multiwire proportional chambers (MWPC), two rows of plastics, and a Lucite Cherenkov counter. The fast coincidences between the plastic scintillators and the 30-cm-thick Cherenkov counter identified detected particles as electrons. The electron energy was obtained from the first 512-channel MWPC located in the focal plane. The second 160-channel MWPC, placed 40 cm behind the focal plane, measured the direction of the electrons and allowed the system to reject the ones originating from the large flux of lower-energy electrons scattered by the spectrometer yoke. This setup has been found to have an unmeasurably small background rate, smaller than 10^{-39} cm^2/MeV. The overall efficiency was 0.92 ± 0.03, determined by measuring well-known (e,e) cross sections.[3,18] A more detailed description of this experiment will be published elsewhere.

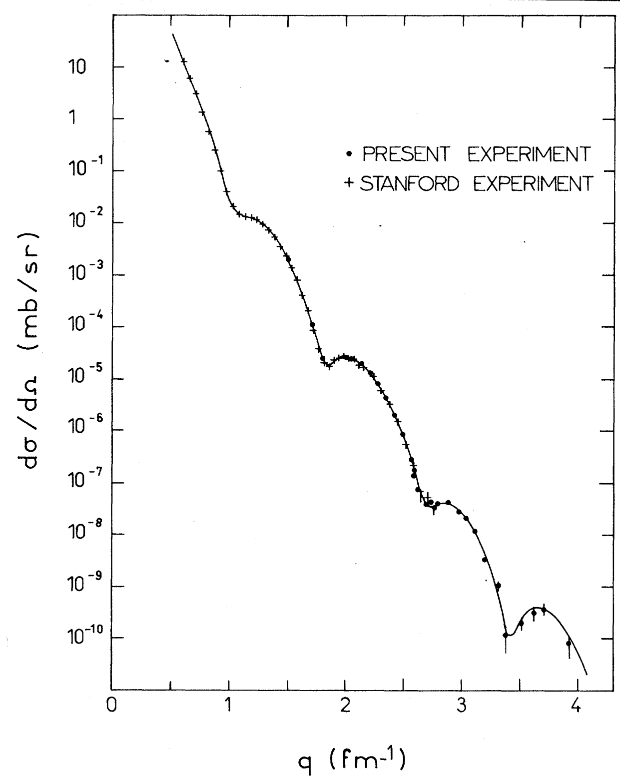

FIG. 1. Experimental cross sections for elastic electron scattering on ^{58}Ni as a function of momentum transfer. The Stanford data have been transformed to 449.5 MeV (see Ref. 19). The curve corresponds to the best-fit densities.

The experimental results are shown in Fig. 1; together with previous medium-q Stanford data,[3] these cross sections span about twelve decades. The limitation to a maximum momentum transfer of 3.9 fm^{-1} lies in the small counting rates for cross sections below 8×10^{-38} cm^2. These data, combined with the muonic-x-ray data,[20] have been used to determine the charge density shown in Fig. 2. The procedure used to extract $\rho(r)$ is described in detail in Ref. 19. For this analysis, the experimental information, necessarily incomplete because of the finite q_{max}, is complemented by a very general physical argument concerning the maximum amount of structure in single-particle wave functions of the occupied proton shells. Guided by a number of different Hartree-Fock (HF) calculations, we have limited the maximum amount of structure in the charge distribution by expanding $\rho(r)$ as a sum of Gaussian functions with rms widths of 1.45 fm. The resulting charge density is practically model independent and its

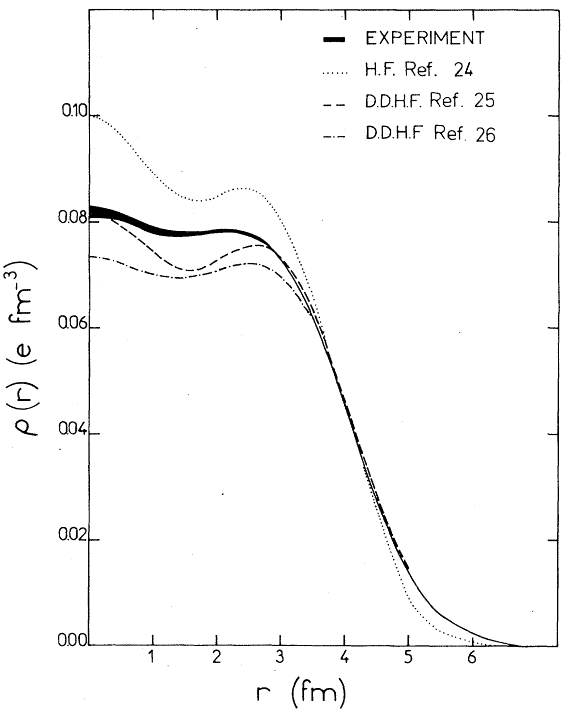

FIG. 2. The full curve represents the error band for the experimental ^{58}Ni charge density, the dashed and dotted curves correspond to the theoretical HF densities. The density-dependent HF calculations of Ref. 21 include pairing for the neutrons above the $1f_{7/2}$ shell.

error bars cover the statistical uncertainties of the data as well as the lack of higher-q data. The systematic uncertainties, basically a ± 3% normalization uncertainty of all cross sections, are not included in Fig. 2. A 3% normalization change leads to a 0.8% shift of $\rho(r)$ for radii $r < 3$ fm, without change of the structure of $\rho(r)$.

The data have also been analyzed by using a conventional model density.[22] A parabolic Gaussian shape [Eq. (1) of Ref. 4 with $c = 2.964$ fm, $z = 2.622$ fm, $w = 0.822$, and $n = 2.213$] has been used together with a Gaussian centered at zero radius (amplitude 0.222, full width at half-maximum 2.426 fm). This additional Gaussian was used to account for the central peak of $\rho(r)$. This density is in good agreement with the one described above.

From Fig. 2 it is immediately apparent that we do observe the type of structure expected from shell-model calculations. In spite of its surprisingly small amplitude, it is well determined by this experiment as a consequence of the very large q_{max}. Before discussing these rather fine details of $\rho(r)$, we also have to consider processes neglected in the above determination of $\rho(r)$. The virtual excitation of the target nucleus, probably the most important effect, gives corrections to $d\sigma/d\Omega$ which generally increase with q; for medium q and the present level of accuracy these corrections[23,24] are larger than the statistical uncertainties of some of the data points. For a very similar case, the ^{40}Ca data,[1] the effect on $\rho(r)$ of several very different theoretical predictions of dispersion corrections has been studied.[19] The change of $\rho(r)$ has been found to be more than a factor of 2 smaller than the error bars on $\rho(r)$ in Fig. 2. The meson-exchange effects, which also could become important at large q, are known for the very lightest nuclei only. For the deuteron, for instance, they lead[25] to a flattening out of the charge form factor at very large momentum transfer ($q > 7$ fm^{-1}). The regular diffraction pattern of Fig. 1 shows no evidence for such an effect, and the cross sections can be well explained by a static charge density.

In Fig. 2 we compare the experimental result to various HF densities. For these recent, very refined calculations the comparison with electron-scattering results represents the most stringent test. The HF density of Tarbutton and Davies[26] has been calculated with a velocity-dependent NN potential. This density exhibits a very pronounced structure in $\rho(r)$, similar to what is obtained when using the familiar Woods-Saxon single-particle potentials. The more sophisticated density-dependent effective interaction G-0, used in the density-dependent HF calculation of Ref. 21, has been derived from the Reid soft-core potential. The Skyrme II force used in the density-dependent calculation of Flocart[27] is a phenomenological interaction fitted to nuclear masses and rms radii. The force G-0 would be expected to give the most trustworthy prediction for the structure of $\rho(r)$. The Skyrme force is believed to yield too small density fluctuations for $N \simeq Z$ nuclei, partly as consequence of its unrealistic long-range behavior.[21]

As is evident from Fig. 2, both calculations[21,27] predict too much structure, and it remains to be verified whether stronger short-range correlations, appearing through the density dependence of the effective force, can explain the present data.

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