excite In^{115} and Cd. X-rays were employed more extensively by the Notre Dame group[10] to excite a whole series of nuclei. The theoretical basis for this method was given by the author.[11]

(*c*) The general idea of this method is that charged particles are scattered elastically (Rutherford) mainly in the forward direction; *inelastically* scattered particles will tend to a spherically symmetrical angular distribution, however. This difference may enable the detection of *inelastically* scattered (through 90° and backward) particles, although for medium and heavy nuclei the cross section for inelastic scattering may be by orders of magnitude smaller than that of the elastic scattering. *Protons* scattered by a few *light* nuclei were used by Wilkins and Kuerti[12] (Mg, Al) and by Powell, May, Chadwick, and Pickavance[13] (Ne^{20}, Al) employing a photographic method. A counter method was employed by R. H. Dicke and J. Marshall, Jr.[13] (Al^{27}, Cr^{52}, Mg, S^{32}). The protons penetrate the Coulomb barrier and are captured by the nuclei. The resulting compound nucleus re-emits the protons with spherically symmetrical angular distribution. Their number is (for such light nuclei) of the same order (about $\frac{1}{2}$) as that of the elastically scattered protons. Powell, *et al.*[14] point out that the probability of this (p,p) process decreases rapidly with increasing nuclear charge. The same holds for excitation by (d,d) and—*a fortiori*—by an (α,α) nuclear reaction. Cl and A gave too few inelastically scattered particles to observe.

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Nuclear Spectroscopy and Energy Distribution of Charged Particles Inelastically Scattered by Nuclei

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In the foregoing note various methods of detecting nuclear excitation caused by inelastic scattering of charged particles were discussed. Method (*c*), *viz.* measurement of the energy distribution of the inelastically scattered particles will now be discussed for the cases in which the scattered particles are (1) protons or alphas, (2) deuterons, and (3) electrons.

1. *Protons or alphas.* Besides the (p,p), (α,α) and (d,d) nuclear reactions, excitation of a nucleus may be brought about by the Coulomb field of the approaching charged particle. In the excitation of In^{115} by protons this process may play some role, and in the excitation of this nucleus by alphas it may make the main contribution. The cross section for the excitation of a nucleus of charge Ze by the Coulomb field of a charge ze has the form,

$$\sigma = f(v)\exp\left[\frac{-2\pi e^2 zZ}{\hbar}\left(\frac{1}{v'}-\frac{1}{v}\right)\right],$$

where v and v' are the velocities of the particle before and after the collision. The form of $f(v)$ depends upon the multipole-character of the transition involved, while the exponential factor (which varies much faster than $f(v)$), probably does not.[1] Because of this exponential factor, transfer of energy from a charged particle to the nucleus can happen with appreciable probability only if $v \gg v'$. Even then methods (e.g., using counters) more sensitive than the photographic method will be necessary for the detection of inelastically scattered particles.

2. *Deuterons.* The use of deuterons yields a somewhat different picture. Because of its low binding energy the deuteron may be polarized by the nuclear field. In this way the neutron may come close enough to the nucleus to enable an energy transfer from the deuteron to the nucleus without the necessity of a (d,d) reaction or even excitation by the Coulomb field of the deuteron. The new process ("polarization scattering") is somewhat similar to the well-known Oppenheimer-Phillips process, but differs from it essentially in that the outgoing particle is not a proton but a deuteron. This difference makes it possible to distinguish between the two processes,[2] even when the conditions for the O-P process are fulfilled (kinetic energy of the deuteron larger than its binding energy, medium, and heavy nuclei). In^{115} for instance should be excitable by deuteron with an energy less than its binding energy. The threshold for the process is just slightly higher than that for excitation by x-rays, because of the recoil of the nucleus.[3] Observation of the inelastically scattered deuterons seems to be a promising method for studying nuclear spectroscopy. Polarization scattering may be used, among other things, to liberate neutrons from Be^9 and D, etc.

3. *Electrons.* Inelastically scattered electrons will not be easy to detect, even in the case in which the scattering angle approaches 180°, because of the background of the elastic scattering. Still a suitable β-ray spectrograph employing sensitive counters should make detection possible. Once established, the use of electrons for nuclear spectroscopy may very well be preferable even to the use of deuterons. For in contrast to the case with deuterons only electrons with comparatively high energies (namely, energies greater than the threshold for photo-disintegration) can disintegrate nuclei.

[1] A rigorous derivation of this formula (including the exact form of $f(v)$) was given by V. F. Weisskopf and the author (unpublished). An earlier derivation of the exponential factor by L. Landau, Physik. Zeits. U.S.S.R. **1**, 88 (1932) is not very clear and does not give the value of $f(v)$. The author is indebted to Dr. S. N. Dancoff for pointing out that in the formula giving the cross section for nuclear excitation, followed by re-emission, the same exponential factor enters while the factor $f(v)$ is replaced by another $g(v)$ which in general is much smaller than $f(v)$.

[2] The same holds for excitation of the nucleus by the deuterons disintegrated by the Coulomb field of the nucleus, and for the ordinary (d,d) reaction, mentioned before.

[3] This process has actually been observed for In^{115} by M. L. Wiedenbeck (private communication).