New method of investigating the electronic and ion-atomic mechanisms of stopping heavy ions in matter

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It is shown that the use of a semithick target in experiments on Coulomb excitation of nuclei makes it possible to investigate the stopping of the recoil nuclei in matter, by analyzing the shape of the γ line that is Doppler broadened by deexcitation of the excited recoil nuclei emitted into vacuum.

The Lindhard, Scharff, and Schiott (LSS) theory of stopping[1] describes the stopping losses in terms of universal dimensionless units of energy (ϵ) and range (ρ):

$$-\frac{d\epsilon}{d\rho}=\left(\frac{d\epsilon}{d\rho}\right)_e+\left(\frac{d\epsilon}{d\rho}\right)_n .$$

The first term here is the electronic component of the loss, the second is the nuclear component connected with the elastic ion-atom collisions. If $v/c < Z_1^{2/3}/137$ we have $(d\epsilon/d\rho)_e = K\epsilon^{1/2}$.

The following approximation holds at $\epsilon > 0.01$:

$$\left(\frac{d\epsilon}{d\rho}\right)_n=\frac{\Delta\epsilon^{1/2}}{0.67\Delta+\epsilon} .$$

The parameter K of the electronic losses is calculated in the theory on the basis of the values of Z and A of the moving ion and the target, while the nuclear-loss parameter corresponding to the LSS theory is equal to 0.483.

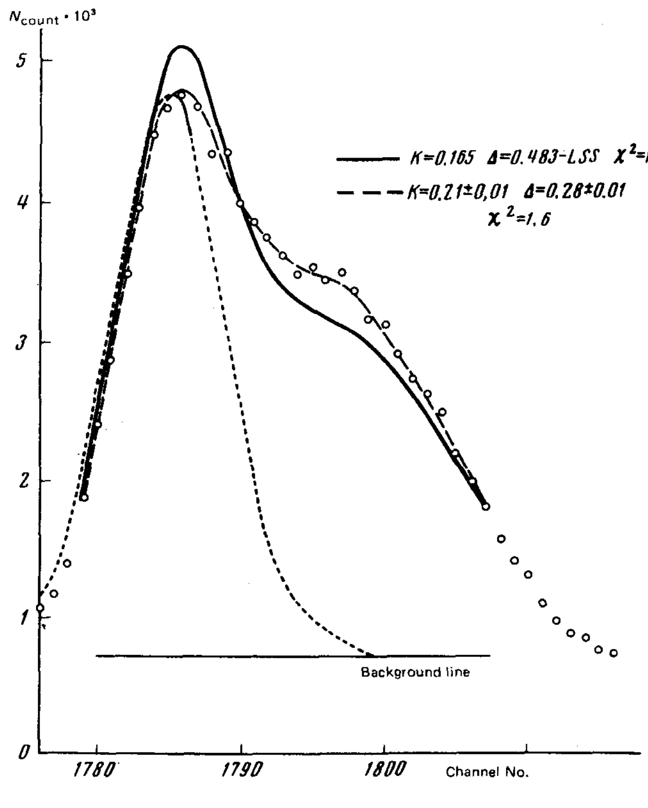
Recently reported experiments point to considerable deviations of $(d\epsilon/d\rho)_e$ from the theoretical values, by as much as 50% and more.[2] The scanty indirect data on $(d\epsilon/d\sigma)_n$[3] indicate that as a rule the latter deviate from the LSS theory values by a factor 0.4 to 1.

On the whole, especially in the region $Z_1 > 40$, the experimental information on the stopping losses are very scanty. Yet the corresponding data are very important, especially in connection with the extensive work beding done on measurements of the lifetimes (τ) of short-lived bound states of unclei by the method of the Doppler shift attenuation (DSA) of γ-ray energy (see the review[4]).

The difficulties of obtaining experimental data on $d\epsilon/d\rho$ in traditional experiments are due to the need for having accelerated beams of the investigated stopped ions in a wide range of v and Z_1, and the need for producing thin and uniform films of the investigated substance. Another method of obtaining information on the stopping process is to solve the inverse problem of the DSA method (determine $d\epsilon/d\rho$ with the value of τ known) also encounters appreciable difficulties, principal among which are the almost complete lack of sufficiently accurate (<10%) information on τ obtained by other methods, and the practical impossibility of separating the contributions of the electronic and nuclear components to the total stopping ability.

We propose a principally new method of investigating the process of stopping heavy ions in matter, which makes it possible to determine both $(d\epsilon/d\rho)_e$ and $(d\epsilon/d\rho)_n$. The idea of the method is the following:

Assume that Coulomb excitation results from bombardment by an accelerated beam of heavy ions, and that the γ quanta emitted by the excited recoil nuclei are registered by a detector located on the beam axis. If the value of τ of the excited state is much longer than the characteristic stopping time (α) of the recoil nuclei in the solid ($\alpha \approx 1$ psec) and if the target thickness L is comparable with the range (R) of the recoil nuclei, projected on the direction of the initial velocity, then, owing to the broad distributions of the excited recoil nuclei with respect to the magnitudes and directions of the initial velocity, distributions typical of Coulomb excitation, the shape of the observed γ line, first, will include a contribution from the unshifted γ peak due to the recoil nuclei stopped in the target, and second, will reflect the distribution of the recoil nuclei with respect to the velocity projections at the instant of emission from the target, a distribution that depends on the stop-



ping losses and on the multiple scattering in the material of the semithick target.

Since 1) the differential cross section and the angular correlation functions can be calculated exactly in the case of Coulomb excitation; 2) the stopping of relatively light (^{12}C, ^{14}N) bombarding particles in a semithick target has a purely electronic character and can be exactly calculated with the aid of available tables; and 3) the shape of the γ line is practically independent of τ ($\tau \gg \alpha$), it is possible, after accurately measuring L, to investigate the stopping of recoil nuclei in the target material by analyzing the shape of the Doppler γ line.

We have previously calculated the shape of the γ line for the DSA case with $L \gg R$ and with τ comparable with α. [5] Unlike in that case, a calculation of the line shape at $\tau \gg \alpha$ and $L \approx R$ called for a more accurate and more detailed account of the multiple scattering of therecoil nuclei. In addition, it was necessary to take into account the Coulomb excitation perturbation due to random hyperfine fields that a nucleus emitted into vacuum experiences under the action of the excited and ionized electron shell.

In first-order approximation, the deviation of the values of $d\epsilon/d\rho$ from those given by the LSS theory can be described by retaining the same form of the functions $(d\epsilon/d\rho)_e$ and $(d\epsilon/d\rho)_n$, but by regarding K and Δ as parameters that must be determined.

A program developed for the BÉSM-4 computer makes it possible to calculate the γ-line shapes at different parameters, compare them with experimental histograms, and determine the optimal values of the K and Δ.

Using the described technique, we investigated the stopping of Cd in Cd and of Ni in Ni. The thickness of the employed semithick targets was determined with accuracy better than 5% by measuring the energy losses of the α particles emitted by a ^{226}Ra source. The bombarding particles were $^{12}C^{+4}$ with energy 36 MeV (for the Cd isotopes) and $^{14}N^{+4}$ with energy 30 MeV (^{61}Ni). We analyzed the γ-line shapes corresponding to transitions from the 558, 617, and 656 MeV levels of ^{114}Cd, ^{112}Cd, and ^{61}Ni, respectively, to the ground states of these nuclei.

An analysis of the shape of the cadmium-isotope γ lines was carried out in four experiments, in which two ^{112}Cd and two ^{114}Cd targets of different thicknesses were bombarded.

The obtained mean values of K and Δ were respectively 0.211 ± 0.017 and 0.30 ∓ 0.03 (LSS—$K = 0.165$, $\Delta = 0.483$). In the case of ^{61}Ni we obtained $K = 0.145 \pm 0.015$ and $\Delta = 0.25 \mp 0.07$ (LSS—$K = 0.155$, $\Delta = 0.483$).

The figure shows the experimental (circles) and calculated shapes of the γ lines for the ^{112}Cd target ($L = 655\ \mu g/cm^2$). The solid curve corresponds to the LSS theory, and the dashed one to the optimal values of K and Δ. The points represent the shape of the unshifted γ line.

Our result for K, in the case of stopping of Cd in Cd, can be compared with the result $K = 0.212 \pm 0.017$ for the sufficiently close case of stopping of I ions in Ag. [6] Accordingly, our value of Δ agrees with the value (≈ 0.3) obtained by measuring the projected range of Ag in Ag. [3] To check on our results in the case of Ni, we specially investigated the DSA of the energies of the γ rays emitted as a result of Coulomb excitations of the first 2^+ levels of the isotopes ^{58}Ni, ^{60}Ni, and ^{62}Ni. Using the measured values of K and Δ we found that the values of τ of these nuclei are respectively 1.0 ± 0.1, 1.1 ± 0.1, and 2.9 ± 0.4 psec, which agrees with results of independent measurements of τ (0.95 ± 0.03, 1.08 ± 0.03, and 2.5 ± 0.1 psec, respectively). The described procedure can be developed for the case of stopping of a heavy recoil nucleus in a semithick substrate of foreign matter, and to study the stopping of heavy ions in media with different Z. We propose to carry out systematic investigations of the stopping parameters on the basis of the procedure described above, for the purpose of correcting the conclusions of the LSS theory and refining the values of τ obtained as a result of DSA studies.

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