STOPPING RELATIVISTIC Xe, Ho, Au AND U NUCLEI IN NUCLEAR EMULSIONS

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Abstract. Nuclei of $_{54}$Xe, $_{67}$Ho, $_{79}$Au and $_{92}$U accelerated at the Bevalac to energies between 1200 and 900 MeV/n have been stopped in nuclear emulsions. The observed residual ranges have been compared with those calculated from various models of energy loss and shown to be most consistent with a calculation that includes those higher order correction terms proposed previously to describe the energy loss of highly charged particles, for which the first Born approximation is not valid.

1. Introduction. We have previously reported, Waddington et al. (1983), on the stopping of 200 GeV gold nuclei in nuclear emulsions. Here we describe a new study of the residual ranges of energetic Xe, Ho, Au and U nuclei in nuclear emulsions.

2. Measurements. A single small stack of Ilford G5 nuclear emulsion pellicles, placed so that the pellicles were parallel to the beam, was exposed at the Lawrence Berkeley Laboratory Bevalac to beams of krypton ($^{84}_{36}$Kr), xenon ($^{132}_{54}$Xe), holmium ($^{165}_{67}$Ho), gold ($^{197}_{79}$Au) and uranium ($^{238}_{92}$U) nuclei. These exposures were made over a period of less than a week to nuclei accelerated at maximum rigidity of 5.6 GV and incident on the same edge of the pellicles. Those nuclei which did not interact in the emulsions were, apart from Kr-nuclei, brought to rest in the emulsions by energy loss, thus permitting their residual ranges to be measured. In order to determine the mean ranges of each nuclei species, individual tracks were not followed from the top edge of the emulsions,

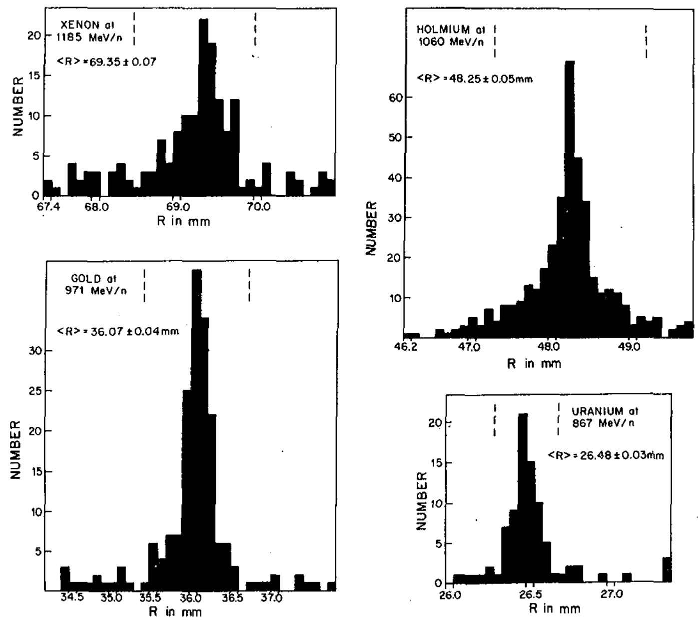

Fig. 1. The residual ranges, R, in mms of nuclear emulsions, measured for each beam. The mean values of range, <R>, are the arithmetic means taken between the values indicated by the dashed lines and the errors are the formal errors in the mean, not those in the width of the distribution.

but were detected by a line scan made a few mms above the estimated depth of stopping for each species. Each track recorded was then followed for a distance that at most would be a few mms beyond the expected stopping point for that species. Tracks of different primary nuclei than the one being studied could be readily eliminated by visual inspection. Hence each sample consisted of a group of primary nuclei with an admixture of fragments produced from interactions occurring above. The resulting range distributions, Fig. 1, show clearly defined peaks, superimposed on a background of secondary fragments. The peaks observed define the mean residual ranges of each species with adequate accuracy, given the uncertainties in the energies.

3. Discussion. Our previous study of Au-nuclei and that of Ahlen and Tarle (1983) on U-nuclei, both showed that there are large deviations in the residual ranges of highly charged nuclei from those calculated using the standard Bethe-Born formalism of energy loss. In order to fit the observations it is necessary to consider terms which are of higher order in Z than the Z^2 terms that result from assuming the validity of the first Born approximation. Instead, it is necessary to include additional terms that take account of the finite size of the projectile nucleus and the electron binding to the target nucleus. Ahlen (1980, 1982) has modified the energy loss expression by including the terms M, B and B_R as follows:

$$\frac{dE}{dx} = \frac{4\pi N Z_m e^4}{mc^2} \frac{Z_p^2}{\beta^2} \cdot J \left[\ln \frac{2mc^2}{I_m} \cdot \frac{\beta^2}{(1-\beta^2)} - \beta^2 - S - D + M - B + B_R \right]$$

Here the effective charge on the projectile, Z_p, is corrected for the effects of energy dependent electron pickup and D is a density correction that is ≈ 0 at these moderate energies. J is a correction for distant collision polarization effects. Energy losses calculated only using terms up to and including D we consider as the classical Bethe formalism, Fano (1963), denoted as Bethe + and will compare with the earlier calculation of Barkas (1963, 1973). Successive inclusion of the Mott correction for the finite size of the projectile, M; the Bloch correction for electron binding, B; and the relativistic Bloch corrections for relativistic terms of the electron binding, B_R, lead to a series of further estimates of dE/dx and hence to calculated residual ranges. Ahlen and Tarle (1983) showed that their observations on the range of U nuclei in a mostly copper medium were consistent with the calculated value using all the terms of the modified dE/dx expression. Our results on Au nuclei in nuclear emulsions were slightly more consistent with an expression that disregarded the relativistic Bloch term, unless the parameters assumed to be valid in that term were modified from those used to fit the U data. Whether there was a significant discrepancy between these two results was not clear, and as a consequence we decided to take advantage of the opportunity to study several different nuclei under as uniform conditions as possible.

The energy of each beam was measured by determining the magnetic field needed to guide the beam in a transport line. Similar measurements have been made many times before and checked by time of flight determinations. Provided that the beam is well focused these measurements should be reliable to ±3 MeV/n. In this case these exposures were made during a calibration of the HEAO C3 UH-nuclei satellite detector, Binns et al. (1981), and an image of the beam spot was available in real time as output from a thin multi-wire proportional counter. Except for the U-beam a well-focused spot was obtained in every case and the energies should be reliable. For Uranium there were clearly multiple charge states present in the beam and the energy estimate is based on the assumption that the state with both K-shell electrons attached was dominant in the beam transport line. The Table shows the assigned energies for each beam.

Table of Energies and Ranges

Nuclei	$E_{measured}$	ΔE	E_{enter}	$R_{measured}$
	Mev per nucleon			mms
$^{132}_{54}Xe$	1239 ± 4	54	1185	69.35 ± 0.30
$^{165}_{67}Ho$	1128 ± 3	68	1060	48.25 ± 0.17
$^{197}_{79}Au$	999 ± 3	27.5	971.5	36.07 ± 0.17
$^{238}_{92}U$	899.4 ± 3	32.4	867	26.48 ± 0.08

The emulsions were exposed to particles after they had traversed the vacuum window, an air path and the light tight window in front of the emulsions. The MWPC counter used to examine the footprint of the beam was removed after defocusing to ensure a uniform exposure, but for the Xe and Ho exposures a scintillation counter was also present in the beam. The energy loss in these materials, ΔE, has been calculated from the full expressions for dE/dx, using all terms, for each Z and initial energy.

The charge or energy dependencies of these higher correction terms, M, B, and B_R are not obvious by inspection and indeed are not simple. We have calculated dE/dx and hence residual ranges, R, using the same assumptions as in our previous report. It is found that in every case the Bethe + terms lead to the lowest value of dE/dx, which would imply the largest range, and that the Mott correction alone leads to the highest dE/dx. Application of the Bloch and rel Bloch corrections gives intermediate values of dE/dx but reverse in magnitude as Z increases.

Integration of these dE/dx curves allow us to calculate the residual ranges. In practice these integrations have only been carried down to a residual energy of 10 MeV/n and a very small correction made for the additional range. These calculated ranges have been compared with those predicted from the proton ranges in nuclear emulsions determined by Barkas, scaled by A/Z^2. The ratios of R_i/R(Barkas) are shown in Fig. 2 for each beam at the appropriate energy, Table. This figure shows that as Z increases the Bethe + expression deviates from the scaled proton range, being some 3% too high at U. All three of the higher order correction terms give ranges less than those predicted from Barkas, and, as suggested by the behavior of dE/dx, the Bloch and relativistic Bloch corrections interchange between Au and U. The experimental observations are in all four cases in good agreement with those predicted by including all terms, including the relativistic Bloch term. This result is not entirely consistent with our previous Au result, which was more consistent with the predictions that did not include the relativistic Bloch term. The magnitude of the correction

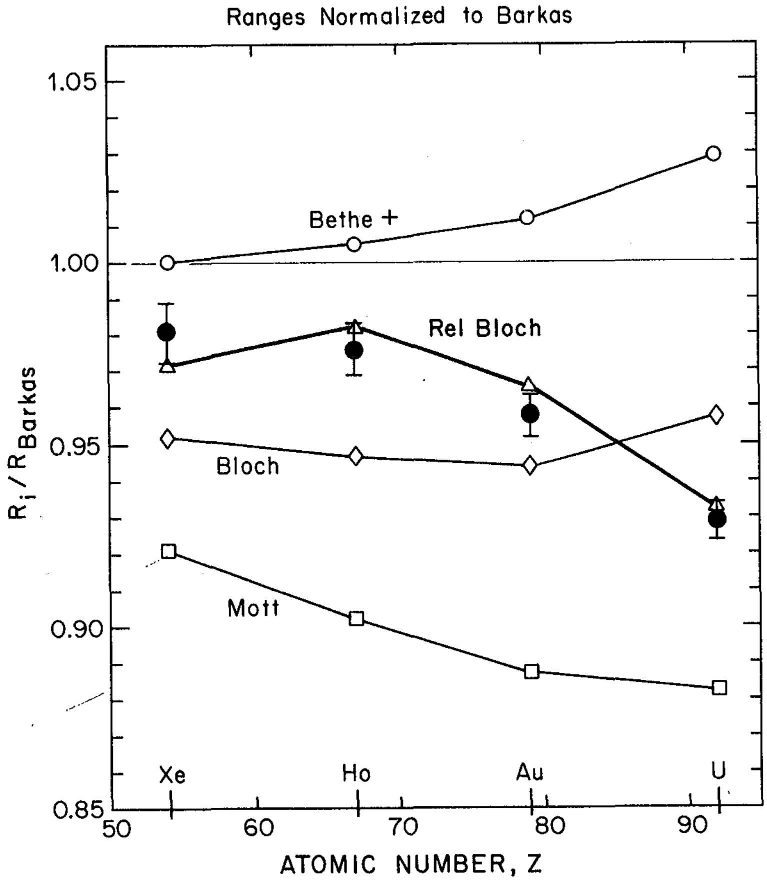

Fig. 2. Ranges normalized to those of Barkas (1973). Values calculated from the dE/dx equation are shown as open symbols, those from the measured ranges as solid with error bars.

that it is necessary to apply to the Barkas ranges steadily increases with increasing Z, reaching some 7% for U. However, it should be remembered that these four measurements are all at different energies and the corrections suggested by Fig. 2 do not truly represent solely the Z dependence of the corrections.

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