Stopping of 200-GeV gold nuclei in nuclear emulsions

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The residual ranges of $^{197}_{79}$Au nuclei stopping in nuclear emulsions has been measured for nuclei with an incident energy of 991 MeV/amu. The mean ranges observed are appreciably less than those predicted from measurements made on energetic particles of lower charge. However, by the consideration of higher-order correction terms to the rate of energy loss, good agreement can be obtained between the predicted and observed ranges.

Two small and identical stacks of Ilford G5 nuclear emulsion pellicles have been exposed to a beam of gold nuclei, $^{197}_{79}$Au, accelerated by the Lawrence Berkeley Laboratory (LBL) Bevalac. This Brief Report describes a determination of the residual ranges of these nuclei as they are brought to rest in these stacks, and relates the residual range observed for those nuclei that come to rest without making a visible interaction to that predicted from measurements made on particles of lower charge. In particular, we are interested in whether there is evidence for non-Z^2 terms in the energy loss similar to those reported for Fe nuclei.[1,2] These results should also be comparable with those that will be available shortly from similar exposures to beams of relativistic uranium nuclei.

The emulsions were exposed during a calibration of the HEAO-3 ultraheavy-nuclei – cosmic-ray detector[3] to a beam of Au nuclei having a nominal energy of 1063.8 MeV/amu and an intensity of about 1000 nuclei per dump, spread over an area of some 100 cm^2. The energy of the beam was measured by a bending magnet after extraction from the Bevalac and after passage through a thin foil to ensure that the nuclei were fully stripped, since they were accelerated to a rigidity of about 5.7 GV as $Z=61$ particles, i.e., with 18 electrons still attached. This measurement of the energy is stated[4] to be accurate to 1 MeV/amu. The beam then passed through a thin scintillator before leaving the vacuum through a sailcloth window, traversing a gas-filled multiwire proportional chamber, air, and the light-tight paper wrapping of the emulsions. A proton with an initial energy of 1063.8 MeV would have lost 2.077 MeV while traversing these various materials. Hence a $^{197}_{79}$Au nucleus, if its energy loss were purely Z^2 dependent, would have lost 65.8 ± 2.0 MeV/amu and the energy on entry into the emulsions would have been (998 ± 2) MeV/amu.

The tracks of Au nuclei were found by scanning 1 mm below the top edges of the pellicles and then traced back to the top edge and down into the emulsions until the nuclei either interacted or came to rest. Residual ranges R were measured on only those tracks that remained in a single pellicle. Figure 1 shows the distribution in R observed in the two stacks, and indicates a significant difference between the two mean values, as well as wide tails on the distributions. This latter "straggling" we attribute mainly to unobserved interactions causing relatively small changes in Z and/or A. Proton and/or neutron stripping of Au nuclei could lead to quite large range differences without necessarily producing an observable interaction. As an extreme example, $^{197}_{79}\mathrm{Au} \rightarrow {}^{174}_{78}\mathrm{Pt} + p + 22n$ would result in a fragment with a range as much as 9% less than that of the incident nucleus.

The observed full width at half maximum of the two distributions of 0.4 mm of emulsion gives standard deviations of 0.17 mm, corresponding to an energy spread of ± 3 MeV/amu (assuming only Z^2 effects), which is thus an upper limit to the energy dispersion in the beam. However, the difference between the two exposures, which is about 0.5 mm, i.e., some 10 MeV/amu, is too small to be due to the imposition of additional detector elements in the beam, since it represents an imposition of only about 0.16 g cm^{-2} of low-Z absorber. It is possible, but not verifiable, that this difference represents a slow drift in the beam energy over the six hours between the energy determination, which was closely followed by the initial exposure, and the second exposure. We will therefore take the lower value of R, which is from the initial exposure, as the value appropriate to the measured energy.

If we combine the various forms of energy loss that have been described in the literature, we can write the rate of en-

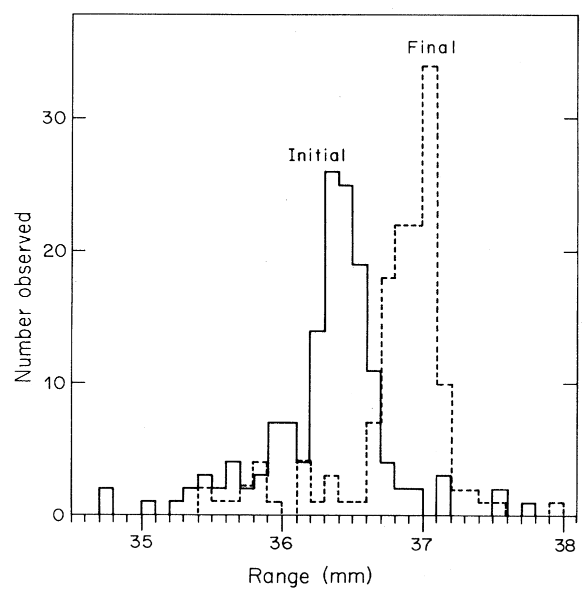

FIG. 1. Distribution of range in emulsion for ending Au nuclei, as observed in the initial exposure made shortly after the beam energy determination and in the final exposure made at the end of the run.

ergy loss, following Ahlen,[5] as

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

where N is the number of atoms per unit volume in the medium with mean atomic number Z_m and adjusted ionization potential I_m. Z_p is the effective charge of the projectile of velocity βc and m is the mass of the electron.

Z_p differs from the true atomic number of the projectile Z_0 due to the effects of electron pickup and stripping. We have used the semiempirical expression of Pierce and Blauer[6] to estimate Z_p from

$$Z_p=Z_0[1-\exp(-130\beta/Z_0^{2/3})]\ .$$

This expression has been found to be a reasonable fit to a wide range of experimental results.[5] In this experiment changing the exponential constant to 150 alters Z_p by 10% at a β where $Z_p=Z_0/2$ and changes the residual range of a 1000-MeV/amu Au nucleus by 0.3 mm (see Fig. 2).

We now discuss each term in Eq. (1):

$S=C(\beta,I)/Z_m$ is the correction for shell effects introduced by Barkas and Berger[7] to account for the finite velocities of atomic electrons. It is only significant when the velocity of the projectile is comparable to that of the electrons.

$D=(\delta/2)(Z_m,\rho_m,\beta)$ is the relativistic density correction and is not significant for the $\beta\leq 0.88$ case that we are considering here.

$M=(G/2)(Z_p,\beta,I_m)$ is the correction for Mott scattering which accounts for the finite size of the charge distribution on the projectile. It has been approximated by Ahlen[5] who included terms in Z_p and β up to Z_p^5 and β^{-3}. Consequently, this approximation is invalid at low velocity. Conventionally it has been customary to "turn off" this correction at a velocity where the uncertainties equal the magnitude of the correction.[1] This approach introduces a somewhat arbitrary discontinuity into the calculation, which, however, does not sensitively affect the range. Thus varying the turn-off energy by 10% only changes R by 0.06 mm. In our

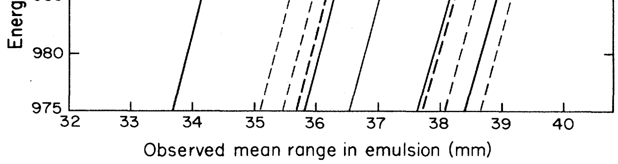

FIG. 2. Observed mean ranges as a function of energy of the incident nuclei. Also shown are the predictions from successive terms of Eq. (1) (see text).

calculations we have chosen to set the Mott correction to a constant when the energy fell to a value where the estimated error in the approximation equals the correction itself, $E\simeq 200$ MeV/amu. Since the Mott correction term varies slowly with energy, ~3%/(100 MeV/amu), fixing its value at the turn-off point seems more physically plausible than turning it off. The reduction in calculated range from this approach compared with turning off the correction is 0.33 mm.

$B=f(Z_p\alpha/\beta)$ is a correction derived by Bloch[8] for the electron binding during close collisions. The validity of this correction in the relativistic limit is not clear, and Ahlen[9] has introduced a further term:

$R_B=C(Z_p,\beta,\theta,\lambda)$, the relativistic Bloch correction, where θ and λ are adjustable parameters of the theory, and λ is of the order of unity and has been set equal to 1 in what follows.

$J=F(\beta,Z_m)$ is the so-called low-velocity correction introduced by Jackson and McCarthy.[10]

The residual range $R(E)$ is then given by

$$R_i(E)=\int\frac{dE}{dE/dx}\ ,$$

where dE/dx is evaluated including each of the above terms, in turn. Values of $R_i(E)$ between 975 and 1000 MeV/amu for ${}^{197}_{79}$Au nuclei are shown in Fig. 2, under the following assumptions.

The Bethe terms are straightforward apart from the selection of the correct value for I_m in the nuclear emulsion. A range of values appear in the literature. The majority of these have been calculated from the adjusted ionization potentials derived for each element and the assumed composition of nuclear emulsions. Depending on the quantities selected, values of I_m between 286 and 323 eV can be obtained.[11,12] However, Barkas *et al.*[13] have used direct range measurements of pions and protons with $E\lesssim 800$ MeV to derive a value for I_m of 323 eV. We have used this value in what follows, but it may be noted that the effect on the range of a 1000-MeV/amu Au nucleus is quite small, making R change by 0.62 from 38.99 to 38.37 mm as I_m is varied from 323 to 286 eV. A further small source of uncertainty comes from the precise value of the relative humidity, and thus the density, appropriate to this particular exposure. In this case the emulsions were allowed to equilibrate with a 50% relative humidity atmosphere before being sealed. The effect on the density is to increase it from the nominal 3.828 g/cm^3 by 0.45%, thus decreasing the range by 0.3%, or ~0.11 mm on the 1000-MeV/amu Au nucleus. Since the standard deviation of batch density variations is of the order of 0.5%,[14] we have neglected this effect, but note that density uncertainties could produce an error similar to the statistical spread.

Figure 2 shows that the Bethe range is significantly greater than the measured range, and that the addition of the shell and Z corrections merely reduce the rate of energy loss, dE/dx, over at least some part of the trajectory, and hence extend the range, increasing the discrepancy. However, including the Mott correction greatly increases dE/dx and leads to a range significantly less than that measured. Adding the Bloch correction and the minor multiplication of the Jackson term leads to a range in good agreement with the value from the initial exposure.

The remaining correction is the relativistic Bloch correction. The form suggested by Ahlen[9] leads to too high a range. However, the parameter θ has a major influence on the result. Some plausible values even change the sign of the correction. The values of θ must lie between $\alpha\gamma/\beta$ and 1, where α is the fine-structure constant and $\gamma=(1-\beta^2)^{-1/2}$. Ahlen selects the energy-independent value of 0.1 as it is the geometric mean of $\alpha\gamma/\beta$ and 1 over the energy interval 100 to 750 MeV/amu. In our initial calculation θ was taken to be the energy-dependent geometric mean of $\alpha\gamma/\beta$ and 1. The difference between these two approaches is only 0.16 mm s of range. If θ is arbitrarily increased or decreased from this geometric mean value by a factor of $\sqrt{e}$ or e, the resulting calculated ranges cover a wide band of values which includes both of the measurements (see Fig. 2).

If the energy loss experienced by the beam before entering the emulsion in now reevaluated using the dE/dX expression up to and including the J term, but neglecting R_B, the primary energy of the Au nuclei is reduced by a further 7.1 to 990.9 ± 3.0 MeV/amu, where the error includes allowance for uncertainties in the thickness of the matter. Both experimental mean-range values are then in reasonable agreement with the predictions of this energy-loss expression. It appears unnecessary to invoke any relativistic Bloch correction, although such a term, with θ reduced by approximately $\sqrt{e}$, could be included.

We conclude that the range-energy relation of highly charged nuclei with $\beta\lesssim 0.9$ can be adequately derived from Eq. (1), neglecting the R_B term.

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[1]G. Tarlé and M. Solary, Phys. Rev. Lett. 41, 483 (1978).
[2]M. H. Salamon, S. P. Ahlen, G. Tarlé, and K. C. Crebbin, Phys. Rev. A 23, 73 (1981).
[3]W. R. Binns, M. H. Israel, J. Klarmann, W. R. Scarlett, E. C. Stone, and C. J. Waddington, Nucl. Instrum. Methods 185, 415 (1981).
[4]H. Crawford (private communication).
[5]S. P. Ahlen, Rev. Mod. Phys. 52, 121 (1980).
[6]T. E. Pierce and M. Blann, Phys. Rev. 173, 390 (1968).
[7]W. H. Barkas and M. J. Berger, Natl. Acad. Sci. N.R.C. Publ. No. 1133 (1964).
[8]F. Bloch, Ann. Phys. (Leipzig) 16, 285 (1933).
[9]S. P. Ahlen, Phys. Rev. A 125, 1856 (1982).
[10]J. D. Jackson and R. L. McCarthy, Phys. Rev. B 6, 4131 (1972).
[11]J. F. Janni, U.S. Air Force Tech. Report No. AFWL-TR-65-150 (unpublished).
[12]V. Fans, Annu. Rev. Nucl. Sci. 13, 1 (1963).
[13]W. H. Barkas and S. von Friesen, Nuovo Cimento 19, 41 (1960).
[14]M. M. Shapiro, in *Nuclear Instrumentation II,* Encyclopedia of Physics, edited by S. Flügge (Springer, Berlin, 1958), Vol. 45, p. 342.