DETERMINATION OF PRIMARY ENERGY IN NUCLEUS–NUCLEUS COLLISIONS
AND THE HIGH $p_T$ TAIL OF $\alpha$-PARTICLES

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Abstract. A determination of primary energy is required in order to
study the energy dependence of meson multiplicity in A–A collisions in
cosmic rays. Various procedures which estimate the energy of a primary
nucleus from its interaction have been investigated. We have used an
average of two methods, one using the pions and wounded protons and the
other using spectator protons and $\alpha$-particles. The high $p_T$ tail
observed for $Z = 2$ fragments requires a modification of the latter
method.

1. Introduction. From accelerator studies of 1.7 and 3.7 GeV/amu of A-
emulsion inelastic collisions, the distribution in $p_T$ for projectile
fragments has been measured for $^{12}$C, $^{16}$O, $^{16}$O and $^{56}$Fe beams.\(^1\)-\(^4\)
Although the distribution in $p_T$ for $Z = 1$ fragments is consistent with a
Gaussian–like distribution

$$\frac{dN}{dp_T} = \frac{p_T}{\sigma^2} \exp\left(-\frac{p_T^2}{2\sigma^2}\right) \quad (1)$$

with $\sigma = 100$ MeV/c ($<p_T> = 125$ MeV/c),\(^3\) for fragments of $Z \geq 2$ there is
a marked deviation from this shape due to the presence of a tail of
large momentum transfers. This high $p_T$ tail results in $<p_T>$ being
significantly larger than the $<p_T>$ expected from eq. (1). For $Z = 2$
fragments from $^{12}$C, $<p_T> = 241\pm 8$ MeV/c,\(^1\) and from $^{56}$Fe, $<p_T> = 370\pm 10$
MeV/c.\(^3\) $<p_T>$ seems to depend only weakly on target $A$, ($<p_T>$\(^{56}$Fe) but the
dependence on projectile $A$ is more pronounced ($<p_T>$\(^{12}$C).\(^3\) This increase
in $<p_T>$ is mainly due to the enhancement of the high $p_T$ tail with $A$ of
the projectile. We shall show that the high $p_T$ tail is also enhanced as
the energy of the projectile is increased.

2. Measurements on Beam Projectiles. We have analyzed 105 $^{55}$Mn-emulsion
interactions at $<E> = 1.69\pm 0.3$ GeV/amu, measuring the emission angles of
fragments, $\alpha$-particles, protons, and mesons. The angular distribution
of $\alpha$-particles is shown in Fig. 1. The transverse momentum, $p_T$, is
calculated from the angle assuming $^4$He is emitted at the same momentum
per nucleon, $p_0$, as the projectile had at the interaction:

$$p_T = 4 \ p_0 \ \sin \theta \quad (2)$$

The peak in the angular distribution corresponds to $p_T$ (peak) = 240
MeV/c, while $<p_T> = 356\pm 20$ MeV/c. This $<p_T>$ value agrees very well with
the value 370\pm 10 MeV/c measured by Chernov et al.\(^3\) for $\alpha$-particles from
$^{56}$Fe at 1.7 GeV/amu.

The emission angles of $\alpha$-particles from $^{179}$Au-emulsion interactions
at 0.5 – 1.0 GeV/amu are also shown in Fig. 1. (The energy at each
interaction was calculated by correcting for ionization loss of the
Fig. 1. Angular distributions of $\alpha$-particles from A-emulsion interactions. ..... Mn at 1.7 GeV/amu; --- Au at 0.5-1.0 GeV/amu; --- cosmic rays, $Z = 6-26$ at $E = 7.5$, $E_1/2 = 11.8$ GeV/amu. The arrows show the angles corresponding to the measured $p_T(\text{peak})$ for Mn and Au and to $p_T(\text{peak}) = 240$ MeV/c at the median energy for cosmic rays. 

There is a marked shift of the angular distribution to larger angles due both to the lower primary energy but also to an increase in $p_T(\text{peak})$ and an enhanced tail of high momentum transfers. The peak corresponds to $p_T = 350$ MeV/c but $\langle p_T \rangle = 520$ MeV/c.

We have used the angles of emitted mesons, protons, and $\alpha$-particles from $^{55}$Mn-emulsion interactions to calculate the energy of the Mn projectile using two different methods: one uses the participant protons (WP) and produced mesons (M), and the second uses the spectator protons (SP) and $\alpha$-particles. Paper HE 1.4-10 of these proceedings discusses the first method and the separation of spectator and participant protons. This paper discusses the second method and what adjustments are required in applying it to higher energy cosmic ray projectiles.

Providing $p_T$ is approximately independent of energy, we can estimate the primary energy from

$$P_{\text{primary}} = \frac{\sum p_{T,SP}^{\text{eff}} N_{SP} \frac{1}{\sin \theta_i} + \frac{1}{4} \sum p_{T,\alpha}^{\text{eff}} N_{\alpha} \frac{1}{\sin \theta_i}}{N_{SP} + N_{\alpha}}$$

where $P_{\text{primary}}$ is the momentum per nucleon and the $p_T$ are effective values of spectator and $\alpha$-particle transverse momentum given in the
Table. This estimate of energy (eq. 3) will be dominated by spectator protons since $<N_{sp}> \approx 4 <N>$. The Table shows the peak values of $p_T$ for $\alpha$-particles and spectator protons measured in the interactions of the $^{55}$Mn beam. The $p_T$ used for wounded protons and mesons (discussed in Paper HE 1.4-10) are also shown in the Table. The "beam" average and median energies are shown in columns 2 and 3 of the Table and can be compared to the calculated energies in columns 8 and 9. The calculated energies are simply averaged from the spectator and participant energy determinations. Figure 2 shows this average energy for the Mn beam. Some 70% of the particles have measured energies within $E \pm E/2$.

Fig. 2. The distribution in measured energy, $1/2[E(\text{participant}) + E(\text{spectator})]$, for a 1.69 GeV/amu Mn beam.

<table>
<thead>
<tr>
<th>Beam</th>
<th>$&lt;E&gt;$</th>
<th>$E_{1/2}$</th>
<th>$p_T^{eff}$ (MeV/c)</th>
<th>Energy (GeV/amu)</th>
<th>Tail/Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z</td>
<td></td>
<td></td>
<td>SP $\alpha$ WP M</td>
<td>$&lt;E&gt;$ $E_{1/2}$</td>
<td></td>
</tr>
<tr>
<td>25.0</td>
<td>1.69</td>
<td>1.68</td>
<td>101 232 575 175</td>
<td>2.03 1.51</td>
<td>0.020</td>
</tr>
<tr>
<td>13.0</td>
<td>5.50</td>
<td>3.00</td>
<td>106 232 438 179</td>
<td>5.67 2.82</td>
<td>0.084</td>
</tr>
<tr>
<td>14.5</td>
<td>19.60</td>
<td>11.80</td>
<td>255 680 691 384</td>
<td>19.90 12.40</td>
<td>0.218</td>
</tr>
</tbody>
</table>

3. Energy Measurements on Cosmic Ray Nuclei. Using the same techniques as used for Mn, we determined the energy of each cosmic ray primary from its interaction. For the 1000 nuclei measured over Texas where $E \geq 1.7$ GeV/amu, the $p_T$ values determined from the Mn beam gave reasonable measurement of energy (see Table). However, for the 500 nuclei measured over India where $E \geq 7.5$ GeV/amu, the energies determined from the spectators using the same values of $p_T$ were far too low. A remeasurement of many of the angles showed they were correct to within ± 0.1°. The observed peak in the $\alpha$-particle angular distribution is consistent with the beam value $p_T(\text{peak}) = 240$ MeV/c and the median cosmic ray energy, $E_{1/2} = 11.8$ GeV/amu (see Fig. 1). However, the tail to peak ratio, where the cut is defined as six times the peak angle, is much larger in India (see Table). The result is too many low energy events. (For a higher angle cut there were no particles in the Mn tail; the tail to peak ratio for Au is 0.005.)

The effective $p_T$ for the cosmic rays given in the Table were determined by the requirement that the calculated energies fit the cosmic ray energy spectrum as closely as possible. Figure 3 shows the resulting energy spectrum of the 500 particles measured in India compared to a power law in total energy of $E^{-1.7}$. The energy measured from 1000 particles at Texas ($E > 1.7$ GeV/amu) fits equally well.
4. Conclusions. Calculation of energies of primary cosmic rays using a method assuming constant p_T of fragments fits the known energy spectrum for a low energy data set (E > 1.7 GeV/amu). The required effective p_T for cosmic rays > 7.5 GeV/amu are high. The high p_T eff for α-particles can be attributed to the high p_T tail. Since p_T eff for protons must be increased by about the same factor to fit the cosmic ray spectrum, it appears that a high p_T tail must also be present for spectator protons. The high p_T tail increases with energy.

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References
5Atwater, T. W., et al. (1985), this conf., Paper HE 1.4-10.