Detecting and Identifying Heavy Nuclei and Antinuclei with Standard Detectors

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Abstract

Most data gathered from high energy experiments at colliders are analyzed assuming that particles stable enough to not decay in the detector volume, and able to interact strongly or electromagnetically, must be electrons, muons, protons, neutrons, photons, kaons, and charged pions, or their antiparticles. While light nuclei and antinuclei such as (anti)deuterons have been detected, we argue that it is experimentally interesting to look for even heavier nuclei in high energy collisions. To this end, we point out that using only tracking and calorimetry information it is, in principle, possible to also search for high energy nuclei and antinuclei and determine, with errors, their charge $Z$ and atomic weight $A$. 
INTRODUCTION

Given the observation of antideuterons by the ARGUS\cite{1, 2} and CLEO\cite{3} collaborations in $e^+e^-$ collisions around center-of-mass energies around 10 GeV, the LEP collaborations OPAL\cite{4} and ALEPH\cite{5} in $e^+e^-$ collisions around 90 GeV, as well as by the ZEUS\cite{7} and H1\cite{6} at HERA in DIS scattering events with center-of-mass energies around 300-318 GeV.

The production of antideuterons is perhaps somewhat puzzling. Unlike deuterons, they certainly cannot be produced by beam-gas or beam-wall collisions by simply ejecting deuterons from nuclei. In whatever model one chooses for baryon production it might seem somehow unlikely to produce 6 antiquarks close enough in x-space to bind and form a proton and a neutron while not breaking up any fragile deuteron produced – its binding energy being a mere 2.2 MeV which is far lower than the energies flying about in 10 GeV or 90 GeV $e^+e^-$ collisions!

In fact, the standard LUND fragmentation models\cite{8} while quite successfully reproducing ratios of pseudoscalar and vector mesons from string fragmentation ideas, require some degree of tuning to produce the correct number of baryons such as protons and neutrons, let alone producing the correct numbers of (anti)deuterons. There is a coalescence model\cite{9} developed for heavy ion collisions which has been used with some success in modelling (anti)deuteron production, but the point of view we take here is that it would be both interesting and possible to look for much heavier (anti)nuclei. Certainly the fact that one sees $\alpha$ decay from nuclei (and indeed this was one of the first nuclear processes observed, with the $\alpha$ particle being much more stable than a deuteron) is encouraging.

Higher baryon number bound states have also been produced. Notably, the antihypertriton (an antineutron-antiproton-antilambda bound state) has been seen by the STAR collaboration\cite{10} at RHIC in collisions Au+Au collisions at $\sqrt{s} = 200$ GeV. The Phenix\cite{11} collaboration at RHIC has also reported antideuteron production. ALICE has reported the production of antideuterons, antitritons and antialpha particles in $pp$ collisions at $\sqrt{s} = 7$ TeV and in Pb-Pb collision at $\sqrt{s} = 2.76$ TeV.

It has been pointed out\cite{13} that the $e^+e^-$ production of baryon-antibaryon pairs, including $b\bar{p}$, $\Lambda_c\bar{\Lambda}_c$, and $\Lambda_c\bar{\Lambda}_c$ at threshold at BaBar\cite{14, 15} is consistent with a form factor of unity – that is, despite being rather complex objects made of many quarks and antiquarks, they
are produced as if they were point particles. This remarkable experimental fact might well
give one pause before dismissing complex heavy objects such as nuclei as being intrinsically
hard to make due to some putatively tiny form factor.

The suggestion has recently been made[16] that there is possibly interesting Higgs physics
involving the production of heavy nuclei and anti-nuclei with charges and masses far in excess
of those carried by the usual particles assumed to be produced.

Distinguishing an antideuteron from an antiproton is quite a challenging task, but, as
we shall see, heavier (anti)nuclei, if perhaps less likely to be produced, may well be more
amenable to experimental detection.

DETECTING NUCLEI AND ANTINUCLEI

We will assume a detector with tracking that involves at least some determination of
the charge deposited per unit length, a magnetic field to allow the quotient of momentum and charge to be determined. Measurements of ionization give information on charge. Calorimetry gives a measure of kinetic energy, and, possibly in the case of annihilation of an antinucleus, total mass[17].

Detecting and identifying a nucleus or antinucleus involves determining its charge $Z$ and mass $M$. We briefly examine now how this might be done.

Determining $Z$

The first simple observation is that for minimum ionizing particles of charge $Z$, the most probable energy loss along a path is proportional to $Z^2$. Responses from detectors typically have long tails as represented by distributions such as the ones due to Landau or Vavilov[17], so there is always a possibility of misidentification of $Z^2$, but for any given experimental setup it is possible (though not often done) to construct a likelihood function $L_{\text{tracker}}(Z)$ for the charge. Simple approximations can be derived from a measured distribution for the signal read out for a charge $Z$ based on the fact that the most likely energy deposited scales as $Z^2$.

Often detectors may be essentially blind to $Z^2$ by simply not having the dynamic range to read out large signals which would otherwise be taken to be fluctuations in the long tails of
energy loss distributions due to charge $|Z| = 1$ particles, but there is no problem in principle in determining the likelihood $L_{\text{tracker}}(Z)$, and even allowing it to depend on the particle speed $\beta$ to allow for the rapid increase in energy deposited at lower speeds which scales as $1/\beta^2$. A determination of $\beta$ is typically more difficult and involves additional detector components such as time-of-flight systems or Cerenkov or transition radiation detectors. Here we simply note that if information on $\beta$ is available it can be included into a likelihood function.

For this short note we will restrict attention to highly relativistic nuclei and assume that they are minimum-ionizing, but the general case is clearly tractable. In the unhappy situation that the detector cannot determine energy deposited beyond some maximum corresponding to the most likely, a likelihood function would still be constructible but having little information about higher charge values.

The point is that it is, in principle, possible to determine the likelihood distribution of $|Z|$ for a particle such as a nucleus or antinucleus, in principle being strongly peaked at a given value of $|Z|$.

The sign of $Z$ can be determined as is routinely done from the curvature of the track that a particle makes in a magnetic field.

This means that $Z$ itself can be determined, or at least a likelihood distribution for it obtained. Indeed, there is no intrinsic problem in determining an inclusive “charge spectrum” for particles produced in high energy collisions.

**Determining $M$**

The curvature $R$ of a track is related to its momentum $p_T$ transverse to the magnetic field $B$ by

$$\left[\frac{p_T}{\text{GeV}/c}\right] = 0.2998\left[\frac{B}{\text{Tesla}}\right]\left[\frac{R}{\text{meters}}\right].$$  \hspace{1cm} (1)

For a charge $Z$ measured in units of the proton charge, this has to be corrected to

$$\left[\frac{p_T}{\text{GeV}/c}\right] = 0.2998\left[\frac{B}{\text{Tesla}}\right]\left[\frac{R}{\text{meters}}\right][Z],$$  \hspace{1cm} (2)

since tracks of particles carrying larger charges are bent more by a magnetic field. The full momentum $\vec{p}$ is determined as usual from the direction of the track and the transverse momentum.
The energy $E$ of a particle is given by $E^2 = p^2 + m^2$. For particles of mass of a GeV/c$^2$ or less, and calorimetric errors typically greater than a GeV/c$^2$, one can obtain little information about $M$.

For particles such as nuclei with masses much greater, the mass can be determined by an apparent mismatch between energy calculated from $E \approx p$ and what is actually measured in the calorimeter.

The cases for nuclei and antinuclei are quite different. Let us consider masses $M$ well over 1 GeV. For nuclei, the rest mass of the nucleus will not be deposited as measurable energy in the calorimeter, so one would find an energy seemingly too low by $M$. For antinuclei, one expects complete annihilation (mainly into $\pi^0$'s which decay into photons) and an apparent excess in energy.

For any specific experiment, a likelihood $L_{\text{calorimeter}}(Z, M)$ that the track was caused by a nucleus or antinucleus of charge $Z$ and mass $M$ is clearly constructible. For a (anti)nucleus such as carbon-12, say, a mismatch of 12 GeV could well be detectable with existing calorimeters.

**Putting it together**

Multiplying likelihood distributions $L_{\text{tracker}}$ and $L_{\text{calorimeter}}$ gives a 2-dimensional likelihood distribution $L_{\text{total}}(Z, M)$, constructed using existing techniques, for $Z$ and $M$ of a track being due to a nucleus or antinucleus. Under the assumption of the particle indeed being a nucleus and (neglecting binding energies as small), the number of neutrons can be approximated as $M - Z$ so a rather complete characterization is possible. $L_{\text{total}}(Z, M)$ can be searched for peaks corresponding to nuclei or antinuclei either inclusively or in any given analysis. It can also be multiplied by whatever prior distribution one favours and integrated in order to set confidence levels on nuclei or antinuclei not being produced.

Of course in a practice one does not expect simple closed form expressions for the relevant likelihoods. Generalizing the usual analyses to allow for the possibility that tracks are produced by heavy nuclei or antinuclei would be a major undertaking, but one we feel would be an interesting and worthwhile one.

While the main point of this note is to show how nuclei and antinuclei can be detected in
high energy collider experiments, the ideas are clearly applicable with little change to direct 
searches for fractionally charged particles which may or may not decay in the calorimeter 
system.

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