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May 1994

**LPCC 94-05**

*To be published in Physics Letters B*

INSTITUT NATIONAL
DE PHYSIQUE NUCLEAIRE ET DE PHYSIQUE DES PARTICULES

CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

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# From in-plane to out-of-plane enhancement of the directed flow in $^{64}$Zn on $^{58}$Ni collisions between 35 and 79 MeV/u*

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(April 12, 1994)

## Abstract

The azimuthal distributions of light particles relative to the reaction plane have been measured for several bins of experimentally estimated impact parameter in the reactions of $^{64}$Zn + $^{58}$Ni at energies between 35 and 79 MeV/u. An in-plane enhancement for mid-rapidity Z=1,2,3 particles is observed at low incident energy but gradually evolves to out-of-plane enhancement (squeeze-out effect) with increasing energy. This evolution depends on the impact parameter in a way similar to the flow parameter. The energies for this system at which the azimuthal distribution is uniform are lower than the corresponding balance energies.

Pacs number 25.70

Nucleus-nucleus reaction mechanisms at incident energies below 10 MeV/u are governed by mean field effects. Nucleon-nucleon collisions begin to become important as the energy increases above the Fermi energy and finally dominate above 100 MeV/u. This evolution manifests itself experimentally in the modification of the directed flow of the emitted participant nucleons. The directed flow in the reaction plane is expressed by the flow angle which is obtained from the kinetic energy tensor or by the flow parameter obtained using the global transverse momentum analysis [1]. Flow was first studied at relativistic energies where nucleon-nucleon interactions are repulsive and lead to positive flow parameters because the nucleons emitted in the projectile direction are deflected, on the average, on the initial side of the projectile [2–4]. The mean field attraction leads to deflection on the opposite side around the Fermi energy which results in negative flow parameter values [5–7]. These flow values are sensitive to both the nucleon-nucleon cross section in medium and to the equation of state.

The in-plane flow parameter describes only one aspect of the directed collective flow. Another aspect lies in the azimuthal distribution of particles relative to the reaction plane. Only results relative to mid-rapidity particles are presented in this paper. Observed effects at high energies are opposite to those observed at low energies. In the systems Ne + NaF, Ne + Nb and Ne + Pb at 800 MeV/u [2,3], Nb + Nb and Au + Au from 150 to 1050 MeV/u and Ca + Ca at 400 and 800 MeV/u, a maximum in the direction perpendicular to the reaction plane on both sides was named the squeeze-out effect [4] since it appears that the compressed matter in the interaction region can preferentially escape in directions unhindered by the presence of the projectile and target spectators. Below 100 Mev/u, maxima in the reaction plane have been observed for the rather light systems of Ar + V [8] and Ar + Al [9,10]. Since such an in-plane enhancement is also produced in the de-excitation emission of a nucleus with a large angular momentum, this effect was called a rotation-like effect [8]. It was studied as a function of energy, impact parameter and emitted particle mass in the collisions of $^{40}$Ar on $^{27}$Al at energies from 36 to 65 MeV/u [9] and $^{36}$Ar + $^{27}$Al from 55 to 95 MeV/u [10]. We report in this letter the first observation of the transition with energy from *rotation like* in-plane enhancement to *squeeze-out* out-of-plane enhancement in the $^{64}$Zn + $^{58}$Ni system at energies between 35 and 79 MeV/u.

The experiments were performed at the GANIL facility in the NAUTILUS reaction chamber. Charged products were detected in a nearly $4\pi$ geometry using two complementary multidetector systems measuring the velocities of charged products and identifying their charge up to Z=8. The forward angles between 3.2° and 30° were covered by the MUR [11] which is a wall of 96 plastic scintillators arranged in 7 concentric rings located 210 cm from the target. Angles between 30° and 150° were covered by the TONNEAU [12] which is a spherical barrel located 80 cm from the target. Seven large solid angle silicon telescopes installed 60 cm from the target covered polar angles between 3° and 30° and allowed to measure the energy and charges of products from Z=3 to Z=30. They made a shadow on the MUR on an azimuthal width of 22°.

The selection of well characterized events was accomplished by using the sum of the parallel momenta of all detected particles. A distribution of this parameter shows two peaks. One peak at 20% of the projectile momentum corresponds to peripheral events in which the projectile like fragment carrying around 80 % of the projectile momentum escaped through the 3.2° hole and the other located around 80% of the projectile momentum includes central, mid central and semi-peripheral events [13], and accounts for around 75% of the reaction cross section. As in our previous analyses [7,10], all analyzed events were in the high momentum peak. This is a strong criterion which is almost never satisfied in nucleus-nucleus collision studies below 100MeV/u.

These well characterized events were sorted as a function of the violence of the collision using the total transverse momentum, $p_\perp = \sum_i p^i_\perp$, to estimate the impact parameter $b_{exp}$ [13,14]. This method uses a large part of the information gained for each event and hence gives a more realistic estimate of the impact parameter than the multiplicity. In simulation calculations including the response of the detectors, the correlation between $b_{exp}$ and the real impact parameter $b$ was found to have a FWHM around 1.5-2 fm.

A meaningful determination of the reaction plane requires a detection array with an azimuthally uniform response , a sufficient granularity and well characterized events. The later requirement has been discussed above. The MUR and TONNEAU multi-detectors satisfied the first two requirements, but for shadow of the telescopes discussed below. The accuracy of the reaction plane determination with this set-up was studied in [9,22]. For a given system, this accuracy depends only on the percentage of the total mass of the system which is detected. The selection of well characterized events ensures that this percentage is the same at the different beam energies.

We adopted the convention defined in transverse momentum analysis [1] and used by other authors that the $0^o$ azimuth is in the reaction plane on the side of the high rapidity products. Two different methods have been used to define the anisotropy ratio in previous studies. The azimuthal distribution in references [2,3] and [9] was fit by a polynomial

$$dN/d\phi = 1 + a_1 \cos\phi + a_2 \cos 2\phi \tag{1}$$

where $a_1$ is related to the in-plane flow and has a value of zero at mid-rapidity. The anisotropy factor, $a_2$, is negative for out-of-plane enhancement, zero for a uniform distribution and positive for in-plane enhancement. In reference [15] the ratio of the numbers of particles emitted out-of-plane to in-plane, $R_N$=(N(90$^o$)+N(-90$^o$))/(N((0$^o$)+N(180$^o$)) , was used. It is equal to $(1 - a_2)/(1 + a_2)$.

The main difference between these papers is the polar axis used to build the azimuthal distribution. In reference [9] it was simply the beam direction. The disadvantage of using the beam direction is that the measured azimuthal anisotropy of mid-rapidity particles is partly due to the in-plane flow angle, $\theta_F$, as seen in figure 1 which uses the same labels as figure 1 in reference [4]. N(90$^o$) is independent of the polar axis chosen in the reaction plane since Y'=Y", but N(0$^o$) is not. When the polar axis is the flow axis, N(0$^o$) is the number of particles which lie along the X" axis which is the axis in the reaction plane ($\phi = 0^o$) perpendicular to the flow axis. When the polar axis is the beam , N(0$^o$) is the number of particles which lie along the X' axis; it increases with $\theta_F$. To avoid this coupling of in-plane flow to the azimuthal anisotropy, Gutbrod *et al.*used the flow axis as polar axis. At the bombarding energies and systems we have studied, the determination of $\theta_F$ via the kinetic energy tensor analysis has very large fluctuations due to the small number of emitted participants and to particles emitted by the bounce-off spectators. This is why the transverse momentum method and the flow parameter have been introduced. We evaluated the sensitivity of the average transverse momentum in the reaction plane, $< p_t > (\theta)$, by rotating all events of the same impact parameter by the same angle, $\theta$. We expected a minimum of $< p_t > (\theta)$ when $\theta = \theta_F$. $< p_t > (\theta)$ decreases by around 10 % when $\theta = 10^o - 15^o$ at all beam energies and $\theta_F$ could not be determined. We attribute that to the fact that the participant ellipsoid is closer to a sphere than to a cigar at these energies and in addition that $< p_t > (\theta)$ has a large contribution from spectator particles with increasing $\theta$ . We therefore used the beam axis as the polar axis for the azimuthal distribution. Note that at the beam energy where the flow vanishes (the balance energy, $E_{bal}(b_{exp})$), $\theta_F = 0$ and the anisotropy is measured relative to the flow axis. At other energies, the value of N(90$^o$)/N(0$^o$) decreases and the value of $a_2$ increases relative to the values they have when the polar axis is the flow axis.

We define mid-rapidity particles as those having rapidities Y in the interval of $.35 < Y/Ybeam < .65$. Azimuthal distributions were found to display symmetry relative to the reaction plane as in reference [4,10,15]. Therefore, they were plotted from 0$^o$ to 180$^0$ only. Examples for Z=2 particles (mostly $\alpha$-particles) are shown in figure 2 for two estimated impact parameter bins at energies of 35 and 69 MeV/u. Z=1,2 and 3 particles were neither detected in the telescopes, nor in the part of MUR shadowed by the telescopes ($\theta$ = 3-30$^o$, azimuthal width = 22$^o$). Therefore, the azimuthal range - in each event - was reduced to the 180$^o$ half which does not contain this shadow. However when the reaction plane direction was within the shadowed range , both halves were shadowed near 0$^o$ or 180$^o$. We choosed the half with the narrowest perturbed range, i.e. at most 22$^o$/2 = 11$^o$. The distortion is therefore limited to 0-11$^o$ and 169-180$^o$. In fig. 2, the dips near 0$^o$ and 180$^o$ extend on a broader range : about 25$^o$ at all energies . This could be partially due to *nuclear* shadowing by the adjacent projectile and target spectators, but this point is not established in the present analysis and will be studied with a set-up having a fully uniform azimuthal response

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In-plane enhancement increases from central to semi-peripheral collisions as was already observed in the Ar + Al system [9,10]. The solid curves in figure 2 show the result of a fit of equation (1) to the data in the unperturbed part ($25^o < \phi < 155^o$). The dashed curves show the $a_1 \cos\phi$ terms (shifted up for clarity). At $5 < b_{exp} < 7$fm, horizontal lines mean $a_1 = 0$, as it should be at mid-rapidity. At $0 < b_{exp} < 3$fm, weak slopes mean $a_1$ is very small, but not 0 because of slight asymmetries in the detector geometry and/or calibration. The dotted curves show the anisotropy term $a_2 \cos 2\phi$ (shifted up).

The same in-plane enhancement is observed in the azimuthal dependence of the average transverse momentum per nucleon, $< p_t > (\phi)$, revealing not only an in-plane enhancement in the density of particles, but also that these particles are emitted with a higher average transverse velocity. The in-plane energy flow is therefore significantly larger than the out-of-plane energy flow. Such a simultaneous variation of $dN/d\phi$ and $< p_t > (\phi)$ was also observed in the case of squeeze-out [4,15]

The 69 MeV/u data, however, exhibit the opposite trend. The right panel of figure 2 shows an out-of-plane enhancement in the azimuthal distribution. The corresponding $< p_t > (\phi)$ distribution is, however, rather constant within experimental uncertainties.

The evolution from in-plane enhancement to squeeze-out as a function of incident energy is shown in figure 3 for 4 impact parameter bins and for Z=1,2,3 particles. Due to very low statistics, $a_2$ values could not be obtained for Z=3 in peripheral collisisons and for $Z > 3$ at all impact parameters . To facilitate comparison with previously published data, the left ordinate is $a_2$ [9,10] and the right ordinate is $R_N$ [15]. As noted above, at $E_{bal}$, $\theta_F = 0$, the flow axis lies in the beam direction and $a_2$ has the same value as it does when the polar axis is the flow axis . The balance energies, $E_{bal}(b_{exp})$, are indicated by the thick bars [16]. Above and below, $\theta_F$ increases and contributes to increase N(0°). Had the flow axis been used, the slopes in figure 3 would be gentler below $E_{bal}(b_{exp})$ and steeper above $E_{bal}(b_{exp})$, but the general behavior would not be modified.

BUU calculations on the Ar + Al system have shown that mean field effects produce an in-plane enhancement [17]. The Zn + Ni system is being studied with the LVUU equation and preliminary results showed an in-plane enhancement which increases with impact parameter at 49 MeV/u [18]. Conversely QMD calculations indicate compression in the interaction zone to be responsible for squeeze-out, in addition to nuclear shadowing [19–21]. Compression increases with beam energy and the corresponding in-plane enhancement decreases until the mean field and compression effects equal at $E_{uni}(b_{exp})$, the energy at which the azimuthal distribution is uniform. Out of plane enhancement then begins to dominate with further increases of compressional energy.

One similarity between the behavior of the anisotropy factor $a_2$ and the flow parameter is seen in figure 3 where $a_2$ increases from central to semi-peripheral collisions having impact parameters between 5 and 7 fm and decreases in the more peripheral collisions having impact parameters between 7 and 9 fm. The flow parameter also reaches its maximum value for such semi-peripheral collisions [7,10,16]

Another similarity is that $a_2$ increases with the charge Z of the emitted particle, like the flow parameter [10]. The values of $E_{uni}(b_{exp})$ seem to be independent of Z, like the values of $E_{bal}(b_{exp})$ .

The behaviors of $a_2$ and the flow parameter are also similar in that $E_{uni}(b_{exp})$ increases with impact parameter as $E_{bal}(b_{exp})$. This is in agreement with the decrease of $R_N$ with increasing impact parameter observed at higher incident energies [15]. For fixed incident energy, compression is weaker in peripheral collisions whereas the rotation-like effect is larger . This variation of $E_{uni}$ with $b_{exp}$ is similar to the variation of $E_{bal}(b_{exp})$ since both are related to the competition between mean field and two body friction.

A difference in the behavior of the anisotropy ratio and flow parameter is that the values of $E_{uni}(b_{exp})$ are not equal to the values of $E_{bal}(b_{exp})$. This is not due to the choice of the beam axis as polar axis. Indeed, as noted above, the values of $a_2$ would be lower with the flow axis at energies below $E_{bal}$. $a_2 = 0$ would therefore be attained at lower energies than those observed in figure 3 (by an amount estimated to be less than 10 MeV/u) and the difference between $E_{uni}(b_{exp})$ and $E_{bal}(b_{exp})$ would increase. This difference varies with the mass of the system and may change sign. Uniform distributions were indeed observed at energies higher than or equal to $E_{bal}(b_{exp})$ in the $^{36}$Ar + $^{27}$Al system [10]. This is not surprising because the squeeze-out effect was observed to decrease with decreasing mass of the system [15].

In conclusion, the use of a high efficiency $4\pi$ detector array and the good characterization of each analyzed event made it possible to study the azimuthal distribution of mid-rapidity particles relative to the beam axis for the $^{64}$Zn + $^{58}$Ni system. At the lowest energies of 35 and 49 MeV/u, the azimuthal distribution exhibits an in-plane enhancement in the average transverse momentum value as well as in the number of particles. The distribution becomes uniform at an energy $E_{uni}(b_{exp})$ which is about 50 MeV/u in central collisions and increases with impact parameter. Values of $E_{uni}(b_{exp})$ in this system are lower than the corresponding balance energies. Out of plane enhancement is observed at the higher energies of 69 and 79 MeV/u. These data will be compared to dynamical calculations of the early moments of the nucleus-nucleus encounter.

* Experiment Performed at GANIL

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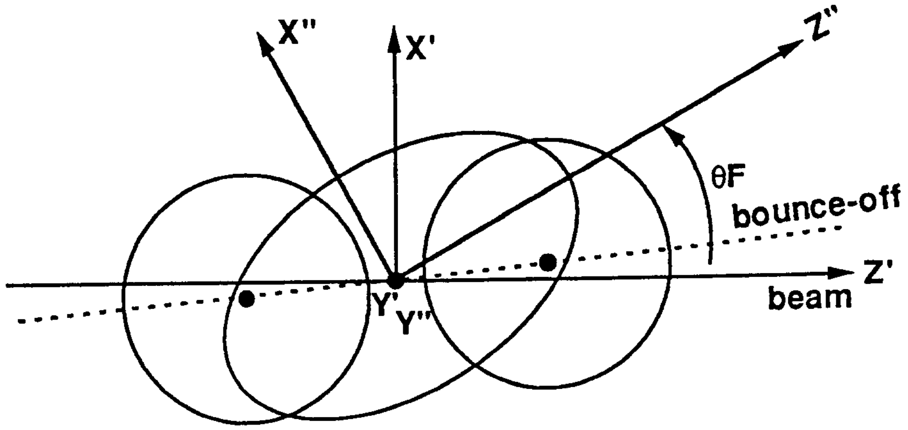
# FIGURES

FIG. 1. Coordinate axis applied to the data. The paper plane is the reaction plane and the axis Y'=Y" is perpendicular to this plane. The central ellipsoid shows the distribution of the momenta of pre-equilibrium participant particles. The circles show very schematically the contribution of particles evaporated in later stages by the target and projectile excited spectators (actually they have a Boltzmann distribution).

FIG. 2. Azimuthal distributions of mid-rapidity Z=2 particles (mostly $\alpha$-particles) emitted in central (top) and semi-peripheral (bottom) collisions at 35 and 69 MeV/u. $0^o$ is the reaction plane direction. The polar axis is the beam direction. The minima at $0^o$ and $180^o$ are due to the detector setup (see text). The solid curves represent fits of expression (1) to the data. The dashed and dotted curves represent the terms $a_1 \cos\phi$ and $a_2 \cos 2\phi$, respectively, shifted up for clarity.

FIG. 3. Excitation functions for the anisotropy factor, $a_2$, (left scale) and the number ratio, $R_N$ , (right scale) for Z=1,2,3 mid-rapidity particles , in four bins of the estimated impact parameter, $b_{exp}$. The thick horizontal bars show the location of the balance energies. The lines are just to guide the eye.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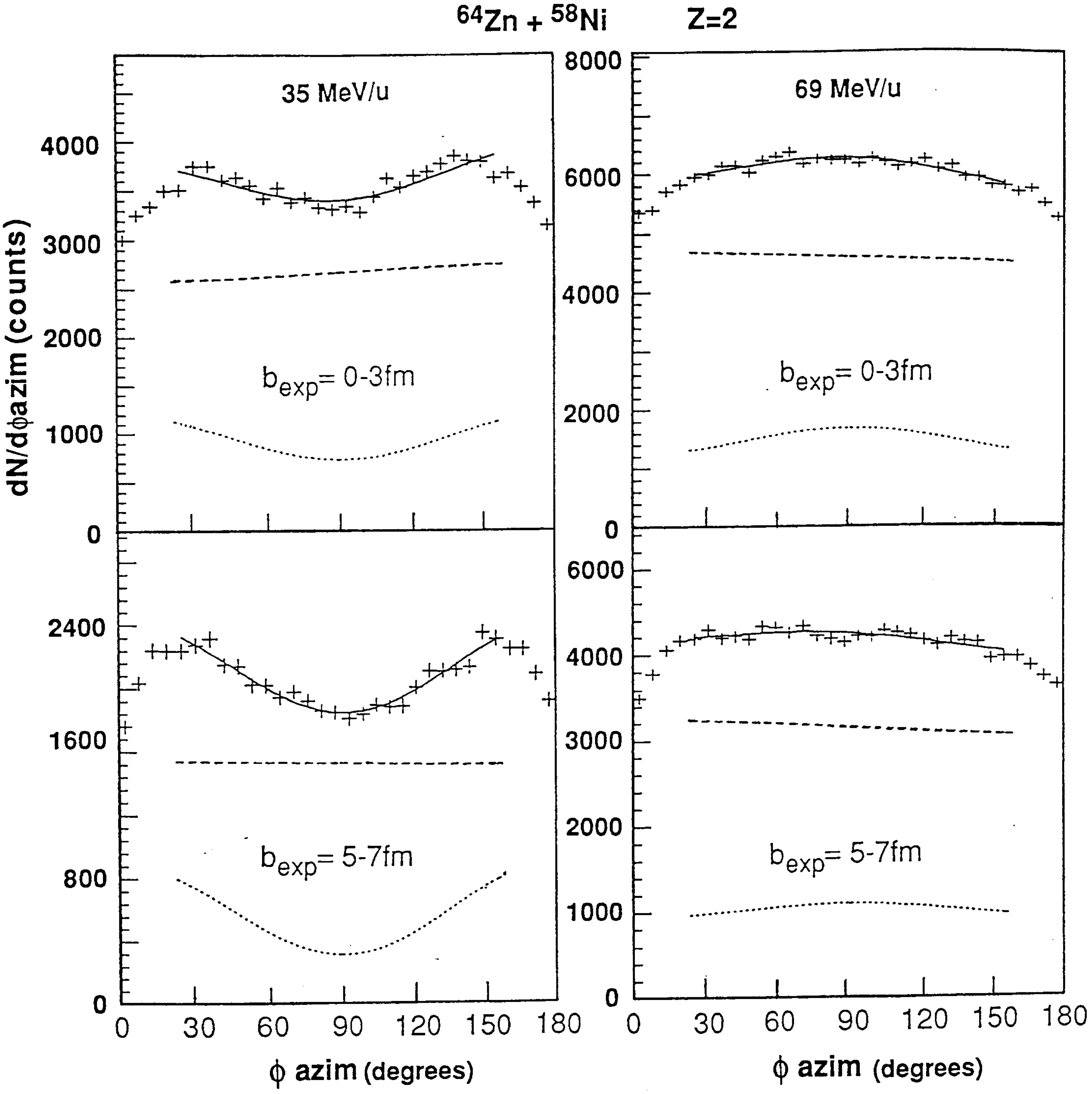
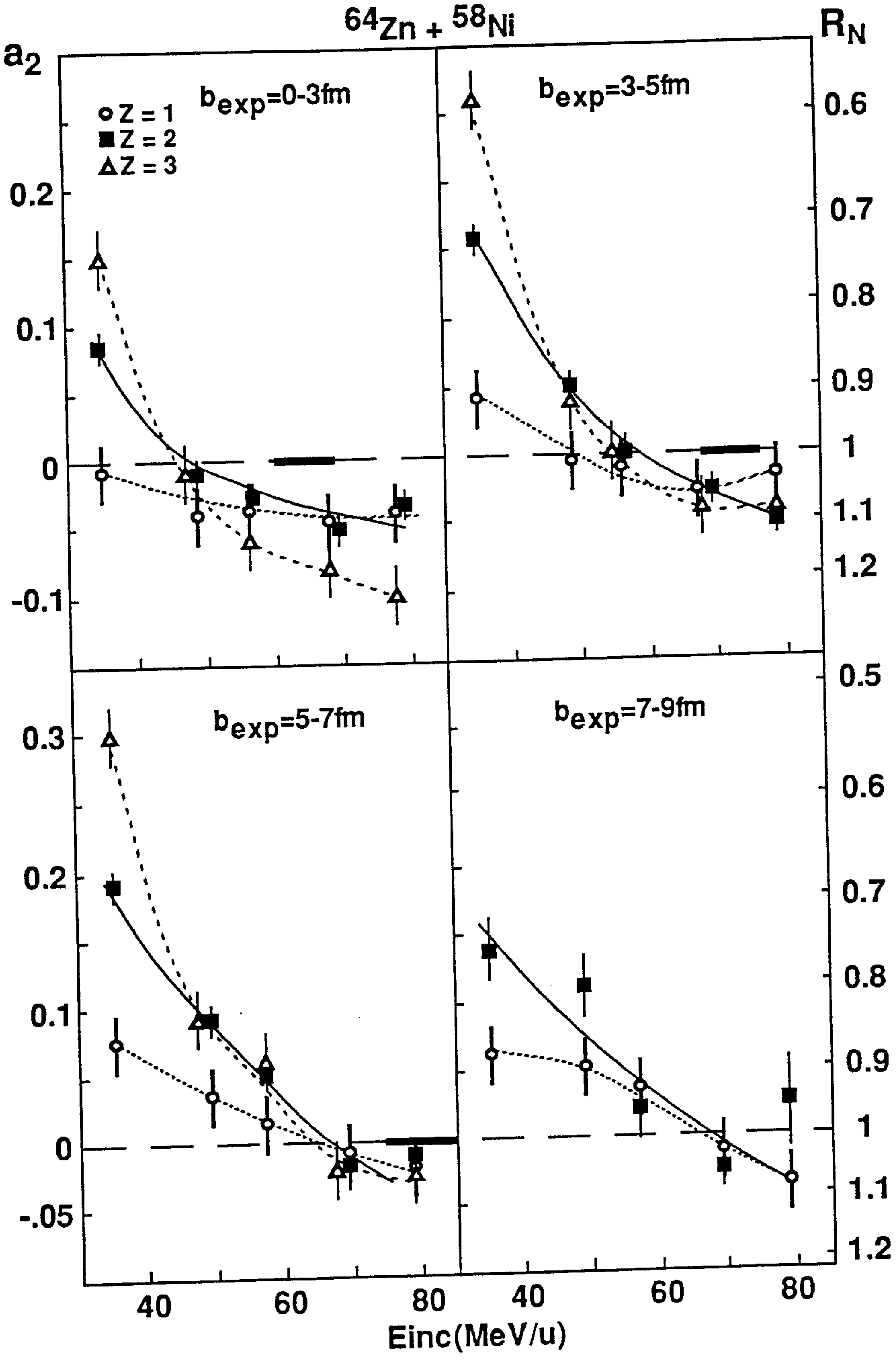

$^{64}$Zn + $^{58}$Ni
Z=2
35 MeV/u
69 MeV/u
dN/dφazim (counts)
4000
3000
2000
1000
0
8000
6000
4000
2000
0
$b_{exp}$= 0-3fm
$b_{exp}$= 0-3fm
2400
1600
800
0
6000
4000
3000
2000
1000
0
$b_{exp}$= 5-7fm
$b_{exp}$= 5-7fm
0
30
60
90
120
150
180
0
30
60
90
120
150
180
φ azim (degrees)
φ azim (degrees)


$^{64}$Zn + $^{58}$Ni
$a_2$
$R_N$
○ Z = 1
■ Z = 2
△ Z = 3
$b_{exp}$=0-3fm
$b_{exp}$=3-5fm
$b_{exp}$=5-7fm
$b_{exp}$=7-9fm
0.2
0.1
0
-0.1
0.3
0.2
0.1
0
-.05
0.6
0.7
0.8
0.9
1
1.1
1.2
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
40
60
80
40
60
80
Einc(MeV/u)