LPC CAEN

LABORATOIRE DE PHYSIQUE CORPUSCULAIRE
14050 CAEN CEDEX - FRANCE

Properties of very hot nuclei formed in $^{64}Zn + {}^{nat}Ti$ collisions at intermediate energies

J.C. Steckmeyer, A. Kerambrun, J.C. Angélique, G. Auger, G. Bizard, R. Brou, C. Cabot, E. Crema, D. Cussol, D. Durand, Y. El Masri, P. Eudes, M. Gonin, K. Hagel, Z. Y. He, S.C. Jeong, C. Lebrun, J.P. Patry, A. Péghaire, J. Péter, R. Régimbart, E. Rosato, F. Saint-Laurent, B. Tamain, E. Vient and R. Wada

September 1995

LPCC 95-13

Submitted to Physical Review Letters

INSTITUT NATIONAL
DE PHYSIQUE NUCLEAIRE ET DE PHYSIQUE DES PARTICULES

CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

INSTITUT DES SCIENCES
DE LA MATIERE ET DU RAYONNEMENT

UNIVERSITE DE CAEN

Téléphone : 31 45 25 00
Télécopie : 31 45 25 49

Properties of very hot nuclei formed in $^{64}Zn+^{nat}Ti$ collisions at intermediate energies*

J.C. Steckmeyer,[1] A. Kerambrun,[1] J.C. Angélique,[1] G. Auger,[2] G. Bizard,[1] R. Brou,[1] C. Cabot,[2,†] E. Crema,[2,‡] D. Cussol,[1] D. Durand,[1] Y. El Masri,[3] P. Eudes,[4] M. Gonin,[5,§] K. Hagel,[5] Z.Y. He,[1,**] S.C. Jeong,[1,††] C. Lebrun,[4] J.P. Patry,[1] A. Péghaire,[2] J. Péter,[1] R. Régimbart,[1] E. Rosato,[6] F. Saint-Laurent,[2] B. Tamain,[1] E. Vient[1] and R. Wada[5]

[1] *Laboratoire de Physique Corpusculaire, ISMRA et Université de Caen, IN2P3-CNRS, 14050 Caen Cedex, France*

[2] *GANIL, DSM-CEA, IN2P3-CNRS, BP 5027, 14021 Caen Cedex, France*

[3] *Institut de Physique Nucléaire, FNRS, Université Catholique de Louvain, 1348 Louvain-la-Neuve, Belgium*

[4] *SUBATECH, Université de Nantes, Ecole des Mines, IN2P3-CNRS, 44072 Nantes Cedex 03, France*

[5] *Cyclotron Institute, Texas A&M University, College Station, TX 77843, USA*

[6] *Dipartimento di Scienze Fisiche, Universita di Napoli, 80125 Napoli, Italy*

(August 7, 1995)

Abstract

The formation and de-excitation of hot nuclei have been studied in $^{64}Zn+^{nat}Ti$ collisions between 35 and 79 MeV/nucleon. The mass and excitation energy of excited quasi-projectiles are reconstructed from the kinematical characteristics of the decay products. In the most central collisions and for the highest bombarding energy, excitation energies larger than 10 MeV/nucleon are obtained. Comparisons with theoretical predictions indicate that a fraction of the excitation energy is associated with an isotropic

collective expansion.

PACS numbers : 25.70.-z, 25.70.Mn, 25.70.Pq

Typeset using REVTeX

One of the presently most debated questions in heavy-ion physics at intermediate energies focusses on the properties of hot nuclear matter, and in particular, on the so-called multifragmentation process as well as on the search for a liquid-gas phase transition. A very often invoked scenario is the occurrence of a compression-expansion phase at the very beginning of the interaction between projectile and target. In the course of such a process, after an initial compression, the hot nuclear matter expands towards low density regions where it can break up into fragments [1–3]. From the fragment kinetic energies, we expect to gain information about the magnitude of the radial collective flow resulting from the expansion phase. Indeed, some results begin to appear in the literature, showing evidence for a compression energy ranging from a few MeV/nucleon up to more than 10 MeV/nucleon [4–9], though other results obtained with similar systems and bombarding energies do not exhibit such an effect [10,11]. This letter reports on the properties of hot nuclei formed in the ^{64}Zn+$^{\rm nat}$Ti reaction at intermediate bombarding energies. Emphasis is put on the sorting of the events and on the careful reconstruction of initial mass and excitation energy of hot nuclei. Detailed comparisons of the data with various statistical and dynamical models are presented. They give support to a collective radial expansion occurring in the decay step.

The ^{64}Zn+$^{\rm nat}$Ti reaction was investigated at GANIL at several bombarding energies between 35 and 79 MeV/nucleon. The experimental procedure can be found elsewhere [12]. Light charged particles (LCP's, $Z = 1$ and 2) and intermediate mass fragments (IMF's, $3 \leq Z \leq 8$) were detected in two plastic multidetectors covering a total solid angle of 84% of 4π, between 3 and 150° [13,14]. Detection of LCP's and IMF's was achieved for energies above 2.5 MeV/nucleon. Identification of IMF's was possible only above 15-20 MeV/nucleon. Heavier fragments were detected and identified in an additional set of seven $\Delta E - E$ telescopes between 3 and 30°.

Comparisons of the data with theoretical calculations are more easily performed as a function of the impact parameter. Therefore, the events were sorted according to an experimental impact parameter b_{EXP} deduced from the total transverse momentum, taken as the sum of the moduli of transverse momenta of all particles detected in an event. For this purpose, it was assumed that the transverse momentum is maximum for head-on collisions and is a decreasing function of the impact parameter. In the various calculations which have been carried out, the calculated events have been filtered by the acceptance of the experimental setup and analyzed in the same way as the data. In particular, the impact parameter from the models was disregarded. Instead an experimental impact parameter was determined from the total transverse momentum as for the experiment [15].

Some of the material presented here has been given in previous reports [12,15]. The correlation between the total multiplicity of charged products detected in an event and the corresponding total parallel momentum displays two distinct regions. Low values of multiplicity and parallel momentum are associated with peripheral collisions in which both the projectile-like and target-like fragments were not detected, while high values of multiplicity and parallel momentum correspond to well characterized events, with a mean total detected charge equal to 70% of the total charge and a mean total parallel momentum equal to 80% of the incident momentum. Only these well characterized events are considered in the subsequent analysis.

From the invariant cross-sections $d^2\sigma/V_\perp dV_\perp dV_\parallel$ plotted in the velocity plane for LCP's, two sources are extracted : a fast source associated with the projectile-like and a slow one associated with the target-like. A third component centered at half the beam velocity appears essentially with $Z = 1$ particles and to a lesser extent with $Z = 2$ [12]. It has been interpreted as a pre-equilibrium emission originating at the beginning of the interaction between projectile and target. These features are observed at all energies and all impact parameters. These results suggest binary dissipative collisions accompanied by pre-equilibrium emission. This statement is reinforced by the disappearance of significant fusion-like cross-section above 50 MeV/nucleon [16] as well as by the results of theoretical predictions performed with the EUGENE [17] and QMD [18] codes, which both follow the entire evolution of the collision.

Once the emission sources have been clearly recognized, their characteristics can be searched for. In the following we will concentrate on the properties of the fast source, the primary quasi-projectile, since all its decay products are well detected by the experimental setup due to their high velocities. The charge and mass of the primary quasi-projectile are obtained from the characteristics of its decay products. The source velocity has been either deduced from the mean value of the experimental parallel velocity distribution of fragments with $Z \geq 6$, or calculated from the momenta of all products having velocities larger than the center of mass velocity. Both methods lead to similar results. The angular distributions of LCP's and IMF's in the frame of the quasi-projectile display an isotropic emission in the forward hemisphere [15], which is, however, less marked for the $Z = 1$ particles due to pre-equilibrium emission and to a bad identification below 10° in the laboratory system [19]. This isotropic emission pattern is seen whatever the impact parameter and the bombarding energy. Thus we assumed that all particles emitted in the forward hemisphere in the frame of the quasi-projectile originate from that nucleus. Its charge is constructed by adding to the largest detected fragment (quasi-projectile residue) twice the charge of the forward emitted particles, while its mass is deduced from its charge using the A/Z ratio of the projectile.

In Fig. 1(a) is shown the mass of the largest detected fragment as a function of b_{EXP} at different bombarding energies. The largest fragment mass strongly decreases when b_{EXP} decreases revealing that more energy is deposited in the primary nucleus when going from peripheral to central collisions. The reconstructed mass of the quasi-projectile, corrected for the geometrical inefficiency (mainly particles escaping through the beam hole), is shown in Fig. 1(b). Due to the assumptions used in the reconstruction procedure, pre-equilibrium particles have been accounted for in the primary mass leading to an overestimated value. The pre-equilibrium component is responsible for the slight rise of the primary mass in central collisions. Relying upon calculations performed with the EUGENE code [17], the mass overestimation is found to increase with the decrease of b_{EXP}, reaching $\approx 15\%$ for the most central collisions. Accounting for this correction, a nearly constant mass value slightly lower than the projectile mass is observed as a function of the impact parameter and the bombarding energy. This behaviour is an additional indication in favor of a binary reaction mechanism. Similar results were obtained in the ^{36}Ar+ ^{27}Al reaction [20].

Once the identity of the quasi-projectile has been accessed, its excitation energy can be determined from the kinetic energies of all its decay products [12,21]. It has been calculated on an event by event basis taking into account the contribution of the neutrons (not detected in the experiment) as well as the Q-value of the reaction. The mean value of excitation energy distributions is shown in Fig. 1(c) as a function of b_{EXP} at different bombarding energies. As expected for a given bombarding energy, the excitation energy increases when the impact parameter decreases, starting from less than 2 MeV/nucleon in peripheral collisions. In central collisions, the excitation energy increases with the bombarding energy, reaching 11-12 MeV/nucleon at the highest bombarding energy. As for the mass determination, the mean values of the excitation energy are upper limits due to the contribution of pre-equilibrium particles. Simulations performed with EUGENE [17] result in an overestimation of the excitation energy by $\approx 15\%$ in the most central collisions at 79 MeV/nucleon. Nevertheless, even if this correction is accounted for, the data clearly show that highly excited nuclei are formed with excitation energy larger than 10 MeV/nucleon. Similar results were obtained in the study of the close system ^{36}Ar+ ^{27}Al [22]. It is worth noting that studying the quasi-projectile on a large scale of impact parameters offers the opportunity to explore a large range of excitation energy.

In order to give an insight into the formation and decay mechanisms of these very hot nuclei, various calculations have been carried out and compared to the data. In Fig. 1(d) the excitation energy distribution measured at 79 MeV/nucleon is compared to simulations. An excellent agreement between the data and QMD calculations is ascertained, while the EUGENE code overpredicts the excitation energy by 2 MeV/nucleon in central collisions.

To go more deeply into the confrontation of the data with calculations, we will look at the multiplicity and charge distributions of particles emitted by the hot nuclei, as well as at their kinetic energy spectra. Hereafter, we will concentrate on the most central collisions measured at 79 MeV/nucleon, with $b_{EXP} \leq 2$ fm, corresponding to a measured cross-section of 125 mb and a mean excitation energy of 11-12 MeV/nucleon.

The experimental multiplicities of LCP's and IMF's are confronted to theoretical calculations in Fig. 2. The QMD calculations (using either a soft or a hard equation of state) overpredicts the yield of $Z = 1$, and underpredicts the number of $Z = 2$ particles and IMF's. The EUGENE calculations overestimate the yield of hydrogen nuclei by more than a factor of 2, give the right number of $Z = 2$ and underpredict the number of IMF's. The data are also compared with predictions performed with the statistical code WIX which simulates the multifragmentation of one single source [23]. This model is an improved version of the earlier FREESCO code [24] : The Coulomb interaction between the excited prefragments was introduced and a collective radial flow can be injected. As a consequence, less thermal energy is left for the decay process and more IMF's are produced. The calculations were carried out assuming a single nucleus of ^{59}Co with an excitation energy of 12 MeV/nucleon. This nucleus was given a velocity distribution taken from the experiment and the simulated events were filtered by the experimental setup. A standard value of the density at freeze-out of $\rho/\rho_o \approx 1/3$ was used. As seen in Fig. 2, the description of the data is improved when a part of the excitation energy is stored in an isotropic collective expansion. The switching off of the collective expansion changes the results in a more abundant emission of $Z = 1$ since more thermal energy becomes available [23].

In Fig. 3 the mean kinetic energy per nucleon of LCP's and IMF's is displayed as a function of the atomic number. A flat behaviour of the kinetic energy comes out from this figure for IMF's, as already observed [5]. All models which do not incorporate a radial flow fail in reproducing the data : The IMF's energy is underestimated by more than 2 MeV/nucleon. Using a hard equation of state in the QMD calculations (not shown in Fig. 3) only modifies the mean kinetic energy of $Z = 1$ and 2 particles, which is increased by 2-3 MeV/nucleon. The WIX calculations with incorporation of a collective radial flow reproduce in a qualitative way the experimental data. The extracted value of the isotropic radial flow is in betwen 1.8 and 2.7 MeV/nucleon and no significant evolution of the radial flow is observed as a function of the atomic number, at variance with Refs. [7,22].

The experimental charge distribution of events issued from central collisions is displayed in Fig. 4, together with the charge distribution calculated from WIX. The yield of LCP's and IMF's is reproduced in a very satisfactory way. However, for fragments with $8 \leq Z \leq 12$, the model deviates significantly from the experiment. This discrepancy is related to a too large predicted multiplicity of hydrogen isotopes, which seems to be a constant failure of all the models at high excitation energies.

From the above detailed comparisons, it comes out that the statistical WIX model reproduces the experiment. The charge, multiplicity and kinetic energy distributions are well accounted for altogether, as well as the shape of the kinetic energy spectra [15]. The fraction of energy released in the collective expansion is $\approx$ 10-15% of the total available kinetic energy, considerably lower than observed at higher bombarding energy in a much heavier system [5,7]. However as already mentioned, the compressional energy is much more efficient than thermal energy to desintegrate a nucleus [25,26]. As a result the IMF multiplicity is strongly enhanced. In view of the success of the description of the data by the WIX code, it is tempting to conclude that the hot nuclei have reached a statistical equilibrium. Nevertheless, further dynamical calculations have to be carried out before deciding about the validity of such a global thermodynamical concept.

To summarize, the formation and de-excitation of excited quasi-projectiles produced in the ^{64}Zn+ ^{nat}Ti reaction have been studied at intermediate energies. The initial mass and excitation energy of quasi-projectiles have been determined from the kinematical characteristics of the decay products. The primary mass is slightly lower than the projectile mass, nearly independent of the bombarding energy and impact parameter, whereas the excitation energy per nucleon increases with the bombarding energy and the decrease of the impact parameter. In the most central collisions, excitation energies larger than 10 MeV/nucleon are reached. The whole data are well reproduced by a statistical simulation of a hot source in which some part of the excitation energy is stored into an isotropic collective expansion whose magnitude is 2.3 ± 0.5 MeV/nucleon. The following scenario may be invoked : After an initial compression, the hot and thus compressed nucleus expands and emits isotropically LCP's and IMF's while boosting their radial velocities.

* Experiment performed at GANIL, Caen, France.

† Permanent address : Institut de Physique Nucléaire, Université Paris-Sud, IN2P3-

CNRS, 91406 Orsay Cedex, France.

‡ Permanent address : Instituto de Fisica, Universidade de Sao Paulo, CP 20516, 01498 Sao Paulo, Brazil.

§ Present address : LPHNE-X, Ecole Polytechnique, 91128 Palaiseau Cedex, France.

** Permanent address : Institute of Modern Physics, POB 31, 730000 Lanzhou, P.R. China.

†† Present address : Institute of Nuclear Studies, University of Tokyo, Tokyo, Japan.

REFERENCES

[1] J. Aichelin and H. Stöcker, Phys. Lett. **B176**, 14 (1986).

[2] B. Remaud *et al.*, Nucl. Phys. **A488**, 423c (1988).

[3] E. Suraud *et al.*, Phys. Lett. **B229**, 359 (1989).

[4] W. Bauer *et al.*, Phys. Rev. **C47**, 298 (1993).

[5] S.C. Jeong *et al.*, Phys. Rev. Lett. **72**, 3468 (1994).

[6] D. Heuer *et al.*, Phys. Rev. **C50**, 1943 (1994).

[7] W.C. Hsi *et al.*, Phys. Rev. Lett. **73**, 3367 (1994).

[8] F. Schussler *et al.*, Nucl. Phys. **A584**, 704 (1995).

[9] G. Poggi *et al.*, Nucl. Phys. **A586**, 755 (1995).

[10] O. Lopez *et al.*, Phys. Lett. **B315**, 34 (1993).

[11] K. Hagel *et al.*, Phys. Rev. **C50**, 2017 (1994).

[12] D. Cussol *et al.*, in Proceedings of the XXXIst International Winter Meeting on Nuclear Physics, Bormio, Italy, ed. I. Iori (Univ. di Milano, Milano,1993).

[13] G. Bizard *et al.*, Nucl. Instr. and Meth. **A244**, 483 (1986).

[14] A. Péghaire *et al.*, Nucl. Instr. and Meth. **A295**, 365 (1990).

[15] J.C. Steckmeyer *et al.*, in Proceedings of the XXXIIIrd International Winter Meeting on Nuclear Physics, Bormio, Italy, ed. I. Iori (Univ. di Milano, Milano, 1995).

[16] A. Kerambrun *et al.*, report LPCC 94-14 and in preparation.

[17] D. Durand, Nucl. Phys. **A541**, 266 (1992).

[18] J. Aichelin, Phys. Rep. **202**, 233 (1991).

[19] A. Kerambrun, Thesis, Université de Caen, 1993 (unpublished).

[20] J. Péter *et al.*, report LPCC 95-10, accepted by Nucl. Phys. **A**.

[21] D. Cussol *et al.*, Nucl. Phys. **A541**, 298 (1993).

[22] S.C. Jeong *et al.*, submitted to Phys. Lett. **B**.

[23] J. Randrup, Comput. Phys. Commun. **77**, 153 (1993).

[24] G. Fái and J. Randrup, Comput. Phys. Commun. **42**, 385 (1986).

[25] L. Vinet *et al.*, Nucl. Phys. **A468**, 321 (1987).

[26] W.A. Friedman, Phys. Rev. **C42**, 667 (1990).

FIGURES

FIG. 1. Shown as a function of b_{EXP} at different bombarding energies, the mean values of the distributions of the largest detected fragment in panel (a), of the mass of the reconstructed quasi-projectile in panel (b) and of the excitation energy of the quasi-projectile in panel (c). In panel (d) the excitation energy distribution measured at 79 MeV/nucleon is compared to results of calculations (see text). The vertical bars account for standard deviations.

FIG. 2. Experimental multiplicities of LCP's ($Z = 1$ and 2) and IMF's ($3 \leq Z \leq 8$) compared to results of calculations (see text).

FIG. 3. Mean value of kinetic energy spectra of LCP's and IMF's emitted at angles in between 30 and 60 degrees in the frame of the primary quasi-projectile. The data are compared to results of calculations (see text).

FIG. 4. Elemental charge distribution of quasi-projectiles compared to results from WIX calculations [23].

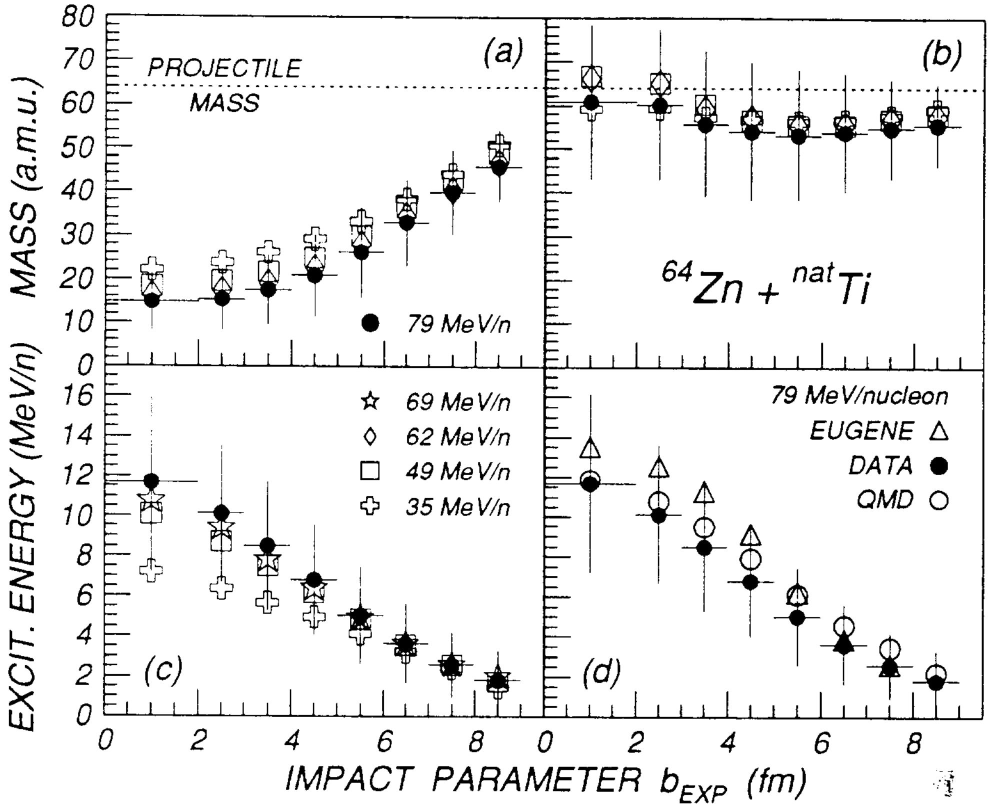
(a)
PROJECTILE
MASS
MASS (a.m.u.)
79 MeV/n
(b)
$^{64}Zn + ^{nat}Ti$
EXCIT. ENERGY (MeV/n)
69 MeV/n
62 MeV/n
49 MeV/n
35 MeV/n
(c)
79 MeV/nucleon
EUGENE
DATA
QMD
(d)
IMPACT PARAMETER b_{EXP} (fm)

Fig. 1

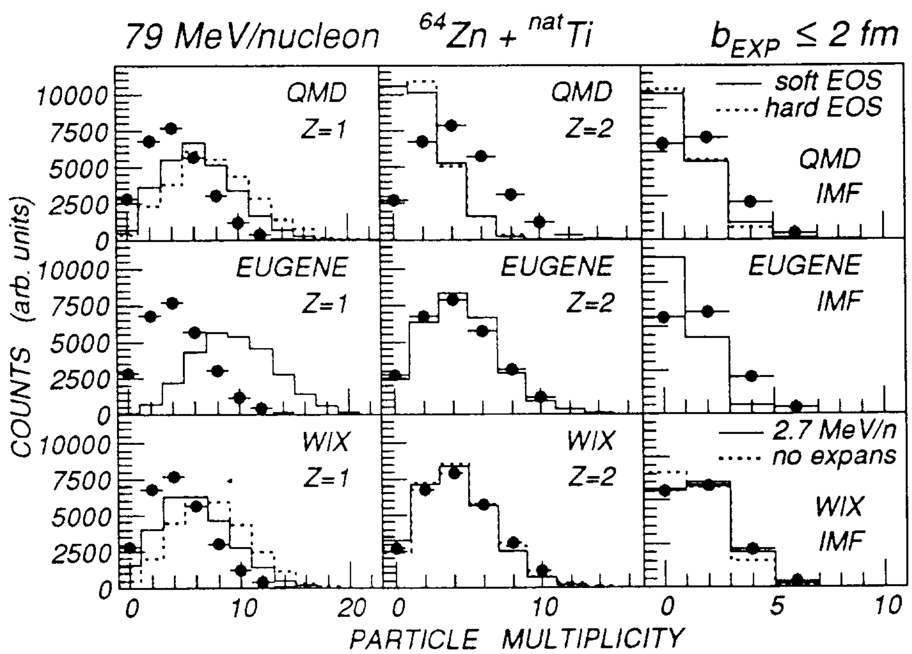
79 MeV/nucleon
$^{64}Zn + ^{nat}Ti$
$b_{EXP} \leq 2$ fm
QMD
Z=1
QMD
Z=2
soft EOS
hard EOS
QMD
IMF
EUGENE
Z=1
EUGENE
Z=2
EUGENE
IMF
WIX
Z=1
WIX
Z=2
2.7 MeV/n
no expans
WIX
IMF
COUNTS (arb. units)
10000
7500
5000
2500
0
PARTICLE MULTIPLICITY
10
20
5

Fig. 2

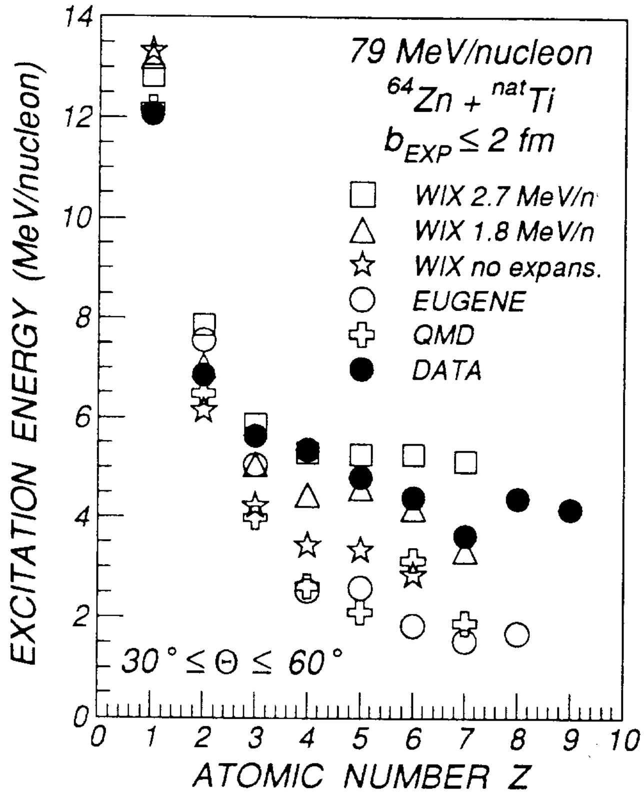
79 MeV/nucleon
$^{64}Zn + ^{nat}Ti$
$b_{EXP} \leq 2$ fm
WIX 2.7 MeV/n
WIX 1.8 MeV/n
WIX no expans.
EUGENE
QMD
DATA
$30° \leq \Theta \leq 60°$
EXCITATION ENERGY (MeV/nucleon)
ATOMIC NUMBER Z
0
1
2
3
4
5
6
7
8
9
10
12
14

Fig. 3

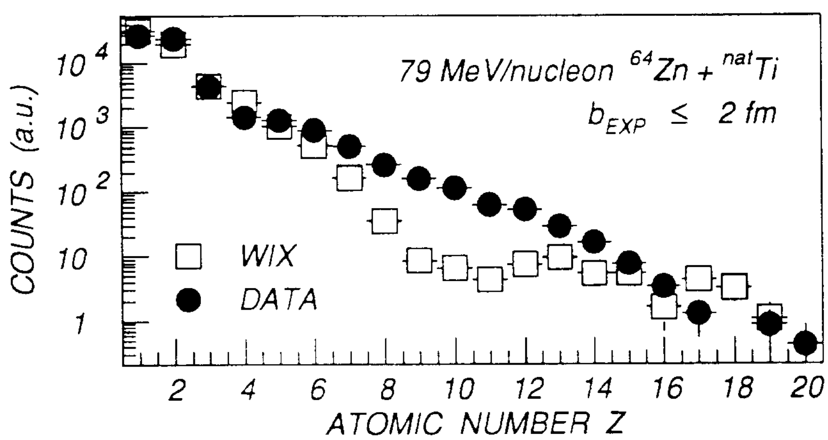
79 MeV/nucleon $^{64}Zn + {}^{nat}Ti$
$b_{EXP} \leq 2$ fm
WIX
DATA
COUNTS (a.u.)
ATOMIC NUMBER Z

Fig. 4