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Publication Date
1983-06-01

LBL-16373
Preprint c.2

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Submitted for publication

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June 1983

NUCLEAR SCIENCE DIVISION

LBL-16373 c.2

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

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LBL-16373

A Feedback Process Controlling Energy Partition and Mass Exchange Between Heavy Ions

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Abstract: The thermal energy partition between fragments and the lack of mass drift under the action of a driving force are explained in terms of a temperature-dependent particle exchange. A feedback mechanism driven by the relative motion minimizes the temperature gradient between the fragments at the expense of the light fragment mass.

PACS numbers: 25.70 Lm

*Alexander von Humboldt Senior Scientist Award.

**Fellowship Angelo della Riccia. On leave from Istituto di Fisica di Catania, Italy.

+This work was supported in part by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the US Department of Energy under contract DEAC03-76SF00098.

Two apparently unrelated features associated with heavy ion collisions have not received a satisfactory explanation as yet: the internuclear thermalization of the dissipated energy on one hand, and the lack of drift towards symmetry for systems where such a drift is expected from potential energy considerations on the other.[1] We intend to show here that these two features can be related to one another, and that they can be explained simultaneously in the framework of a particle exchange mechanism.

It is well established experimentally that the partition of the dissipated energy between the two fragments is approximately thermal (i.e. such that $T_1 = T_2$) in the Q-value range explored so far, namely from -50 MeV to full relaxation.[2-6] Furthermore the processes which are most likely involved in the energy dissipation, namely particle exchange and coherent or incoherent particle-hole excitation deposit approximately the same amount of energy in each fragment, while thermal equilibrium requires an energy partition proportional to the fragment masses. Thus for a rather asymmetric system a substantial lack of initial energy equilibration is expected. Yet, internuclear thermalization appears already at the smallest inelasticities, despite the very short interaction time associated with these collisions. Then, how can the expected low heat conductivity lead to such a quick thermalization?

Concerning the mass asymmetry, a somewhat opposite phenomenon is observed, namely a peculiar reluctance of the system to evolve in the direction of equilibrium when this implies moving towards symmetry. Rather, the masses seem to be more or less locked to their entrance channel values throughout most of the Q-value range spanned by the reaction. Only for the greatest inelasticities, when the relative motion of the fragments has died out, does one observe the expected drift, if at all. The question is of course "what" prevents the system from moving along with the driving force towards symmetry for such a long time.

The obvious coupling, if any, between the two problems is the particle exchange, as it is naturally involved in the evolution of the fragment masses on one hand, and it is thought to be the major, if not the entire cause of energy dissipation on the other.[7] For simplicity, in our explanation we shall assume that: 1) particle exchange is the only means of energy transfer; 2) intranuclear equilibration is immediate. We shall also assume that the particle fluxes are substantially temperature-dependent. This is clearly the case when a sufficiently high barrier is present between the two potential wells. Such a regime in fact prevails when the nuclear overlap is incomplete which is also when the energy is dissipated most rapidly.

As mentioned above, the particle transfer process deposits the same energy in both fragments since the two one-way fluxes are the same. If the system is asymmetric, the smaller fragment must then grow hotter due to its smaller heat capacity. The temperature gradient that ensues creates an imbalance in the particle fluxes, the large fragment receiving more particle than it gives away. The energy deposition on each fragment is proportional to the number of nucleons that land on it. Therefore more energy will now be deposited on the heavy fragment and this will tend to correct the temperature gradient. In other words we are observing a feedback effect that leads to a self-regulation in the energy partition. In different words, the initially generated thermal imbalance redirects the energy deposition towards the larger fragment and controls the thermal gradient, but at the expense of the light fragment mass!

This explanation is particularly satisfactory because: a) the energy thermalization does not arise from the heat conductivity which is quite small, but from the fast redirection of the energy being dissipated; b) it creates a drive towards increasing asymmetry that may resist an opposite conservative force; c) these effects rely on the presence of energy in the relative motion and disappear rapidly after the two fragments are at rest.

We can translate these ideas in quantitative terms. For the sake of simplicity let us consider two objects moving <u>tangentially</u> to one another (i.e. there is no radial component of the velocity during the interaction). A window is open between them which allows for a particle flow between the two objects. Let $\Phi(T)$ be the one-way particle flux and $\Phi_E(T)$ be the energy flux exclusive of the relative motion which is treated separately. Also let the temperature-energy relation be $E = Nf(T)$.

Particle conservation gives the first equation

$$\frac{dN_1}{dt} = \Phi(T_2) - \Phi(T_1) \quad . \tag{1}$$

Notice that $(dN_1/dt) < 0$ if $T_2 < T_1$.

From momentum conservation we have:

$$\frac{dP_1}{dt} = -V_1\Phi(T_1) - V_2\Phi(T_2) = N_1 \frac{dV_1}{dt} + V_1 \frac{dN_1}{dt}$$

$$N_1 \frac{dV_1}{dt} = -(V_1 + V_2)\Phi(T_2) \; ; \quad N_2 \frac{dV_2}{dt} = -(V_1 + V_2)\Phi(T_1) \quad .$$

Finally:

$$\frac{d\ln V}{dt} = -\left(\frac{\Phi(T_2)}{N_1} + \frac{\Phi(T_1)}{N_2}\right) \; ; \quad V = V_1 + V_2 \quad . \tag{2}$$

From energy conservation we have

$$\frac{dE_1}{dt} = \Phi_E(T_2) - \Phi_E(T_1) + \frac{1}{2}\,\Phi(T_2)V^2 \quad . \tag{3}$$

In order to obtain an equation for the temperature we can use

$$E = Nf(T) \;; \quad \frac{dE}{dt} = f(T)\frac{dN}{dt} + N\frac{df(T)}{dT}\frac{dT}{dt}$$

$$= f(T)\frac{dN}{dt} + c_v\frac{dT}{dt}$$

where c_v is the heat capacity.

Solving for dT/dt we have

$$\frac{dT_1}{dt} = \frac{1}{c_{v,1}}\left[\Phi_E(T_2) - \Phi_E(T_1) + f(T_1)\{\Phi(T_2) - \Phi(T_1)\} + \frac{1}{2}\Phi(T_2)V^2\right] \quad (4)$$

$$\frac{dT_2}{dt} = \frac{1}{c_{v,2}}\left[\Phi_E(T_1) - \Phi_E(T_2) + f(T_2)\{\Phi(T_1) - \Phi(T_2)\} + \frac{1}{2}\Phi(T_1)V^2\right] \; . \quad (5)$$

The last two equations show the feedback quite clearly. If for instance $T_1 > T_2$, the last term of eq. (5) will increase the value of dT_2/dt until there is a nonzero relative velocity.

In order to perform some relevant calculation, let us apply this model to two Fermi gases separated by a barrier. The one-way particle flux is given by:

$$\Phi(T) = K\left[\frac{\pi^2}{12}T^2 + T(\mu - B)\ln\left(1 + \exp\frac{\mu - B}{T}\right) + T^2\int_{(B-\mu)/T}^{0}\frac{z}{1 + e^z}\,dz\right] \; .$$

The corresponding energy flux, exclusive of the damped energy, is given by

$$\Phi_E(T) = K\left[\frac{3}{2}\zeta(3)T^3 + \frac{\pi^2}{12}T^2(2\mu - B) + T\mu(\mu - B)\ln\left(1 + \exp\frac{\mu - B}{T}\right)\right.$$

$$\left. + T^2(2\mu - B)\int_{(B-\mu)/T}^{0}\frac{z}{1 + e^z}\,dz + T^3\int_{(B-\mu)/T}^{0}\frac{z^2}{1 + e^z}\,dz\right]$$

where μ is the chemical potential, $\zeta(3)$ is the zeta function of argument 3, B is the barrier height and T is the temperature. Relevant limits for small and large values of the quantity $(\mu - B)/T$ are easily obtained.

A calculation performed for an asymmetric system ($A_1 = 50$, $A_2 = 150$) at 300 MeV center of mass energy is shown in Fig. 1 for the following values of $\mu - B$: 0.5 MeV, 10 MeV, 20 MeV, 30 MeV and 40 MeV. The temperature dependence of the one-sided flux goes from very great at the lower range of this interval, to minimal at the upper range. The upper part of Fig. 1 shows the temperature ratio T_1/T_2 as a function of kinetic energy. For very low barriers (e.g. $\mu - B = 40$ MeV) the temperature ratio goes rapidly up to $\sqrt{3}$ consistently with equal energy deposition, and weakly declines thereafter. The effect of thermal conductivity is visible in the very late decline associated with the largest energy losses. In this regime there is little self-regulation and a very slow thermalization. For a barrier very close to the Fermi surface, the result is dramatically different. The initial rise in temperature ratio is quickly controlled by the feedback effect and kept within a narrow range above unity throughout the Q-value range. In this case we see that the feedback effect is present and that it leads to a very nearly thermalized energy partition even at moderately low energy losses.

The lower part of Fig. 1 shows the dependence of the mass of the light fragment upon energy loss. For low barrier values the mass remains fixed near 50 for most of the Q-value range. Only very late in the collision does one observe a decrease in mass as a late and slow response of the system to a great temperature gradient. For barriers near the Fermi surface the fluxes become substantially imbalanced at once, and the light fragment loses mass steadily throughout the Q-value range. This calculation quantitatively verifies our expectation. When the barrier is close to the Fermi surface, the temperature dependence of the fluxes is sufficiently strong to set a strong feedback effect in motion leading to a fine control of the temperature gradient on one hand and to a steady mass loss suffered by the light fragment on the other.

In Fig. 2 the effect of a progressively greater driving force towards symmetry is studied. The curves shown represent the light fragment mass as a function of kinetic energy for the following driving forces: 0, 0.5, 1.0, 1.5, 2.0 MeV/A, the lower Fermi surface being 0.5 MeV above the barrier. For nonzero driving forces we observe an initial tendency of the system to move towards symmetry. This tendency is readily controlled and even inverted by the feedback process as soon as a temperature gradient is established. Only very late in the collision, when lack of energy in the relative motion prevents the feedback process from operating, can the system follow the driving force towards symmetry once again. As a whole, we see that the mass asymmetry can be readily stabilized near its initial value throughout the Q-value range, in agreement with experiment. The wiggly curve predicted by the theory suggests that a similar structure may be seen experimentally. In the inset of Fig. 2 the pre-evaporation light fragment mass vs Q-value for the reaction Kr + Er[8] shows a behavior that is not unlike that predicted by this theory.

The response of the system to a driving force depends rather strongly on the difference between average chemical potential and the barrier $\bar{\mu} - B$. Large values of $\bar{\mu} - B$ lead to a small mass drift when observed against energy loss. The reason is that the energy loss rate depends upon the sum of the one-way fluxes while the drift depends on their difference. In Fig. 3 such an effect is illustrated. The relation between energy loss and light fragment mass is shown for $\bar{\mu} - B$ = 50, 25, 10, 0.5 MeV with a driving force of 1.5 MeV. The systematic increase of the mobility with decreasing $\bar{\mu} - B$ is readily seen at small energy losses. However, at the smallest values of $\bar{\mu} - B$ the increased mobility is compensated by the feedback effect which, as was already seen in Fig. 2, stabilizes the mass near the entrance channel value. Consequently while a small mass drift could be consistent with either large or small $\bar{\mu} - B$, the near thermalization of the dissipated energy is consistent only with a small value of $\bar{\mu} - B$.

The theories available so far do assume both intra- and internuclear thermalization. We have been able to show that by removing the internuclear thermalization assumption it is possible to explain simultaneously both the near isothermicity of the fragments and the lack of mass drift towards symmetry.

Acknowledgements

We would like to thank Prof. H.A. Weidenmüller for his kind hospitality at the Max-Planck-Institut. We are also grateful to Dr. H. Feldmeier for many very stimulating discussions. This work was supported in part by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under contract DE-AC03-76SF00098.

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Figure Captions

Fig. 1. Top: Temperature ratio vs total kinetic energy loss for a set of values of $\mu - B$ (see text). Bottom: Light fragment mass vs kinetic energy for the same values of $\mu - B$ from right to left.

Fig. 2. Light fragment mass vs kinetic energy for different driving forces (see text). The inset shows the experimental pre-evaporation mass in the reaction $^{84}Kr + {}^{166}Er$.

Fig. 3. Light fragment mass vs kinetic energy for different values of $\mu - B$ and a fixed driving force.

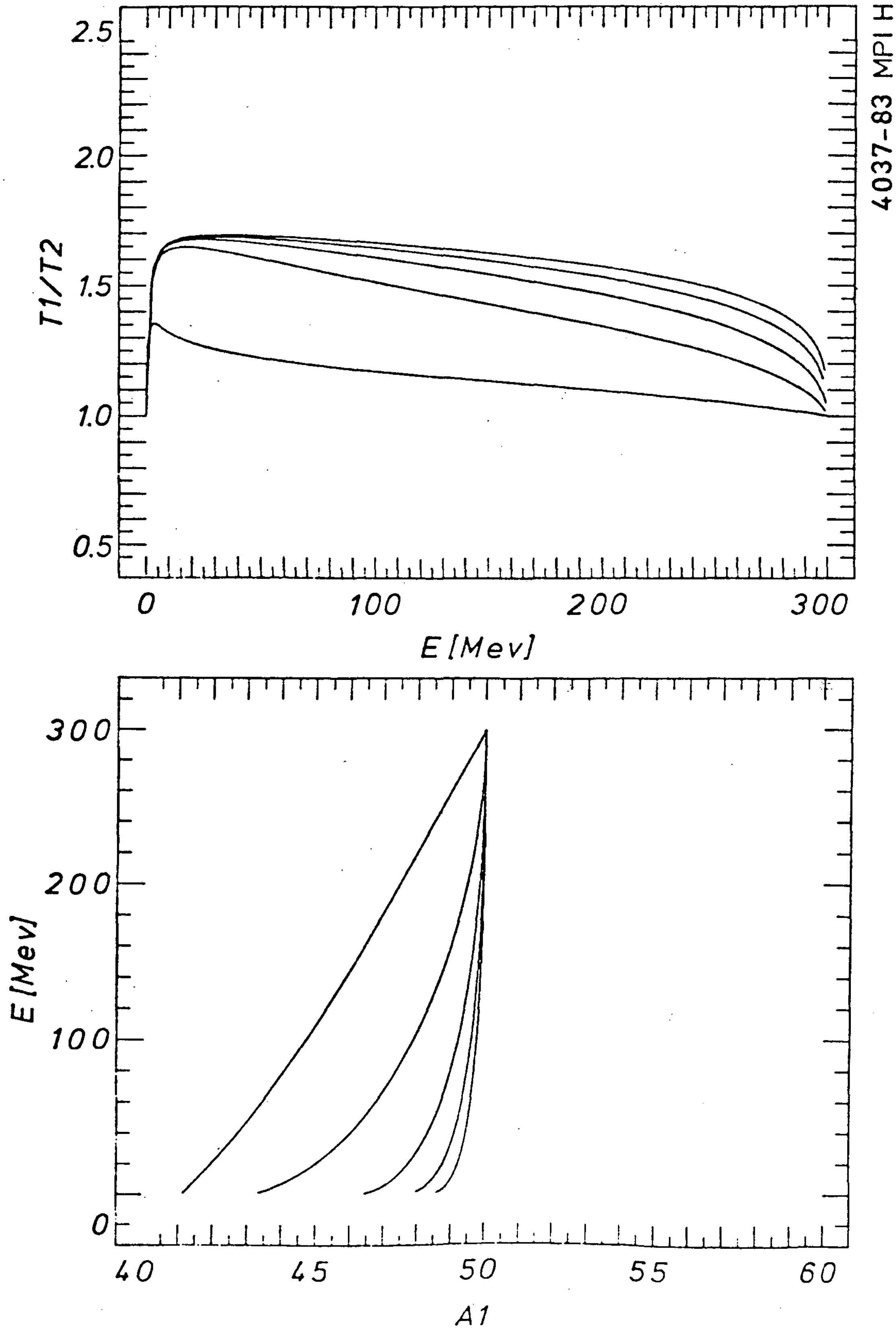
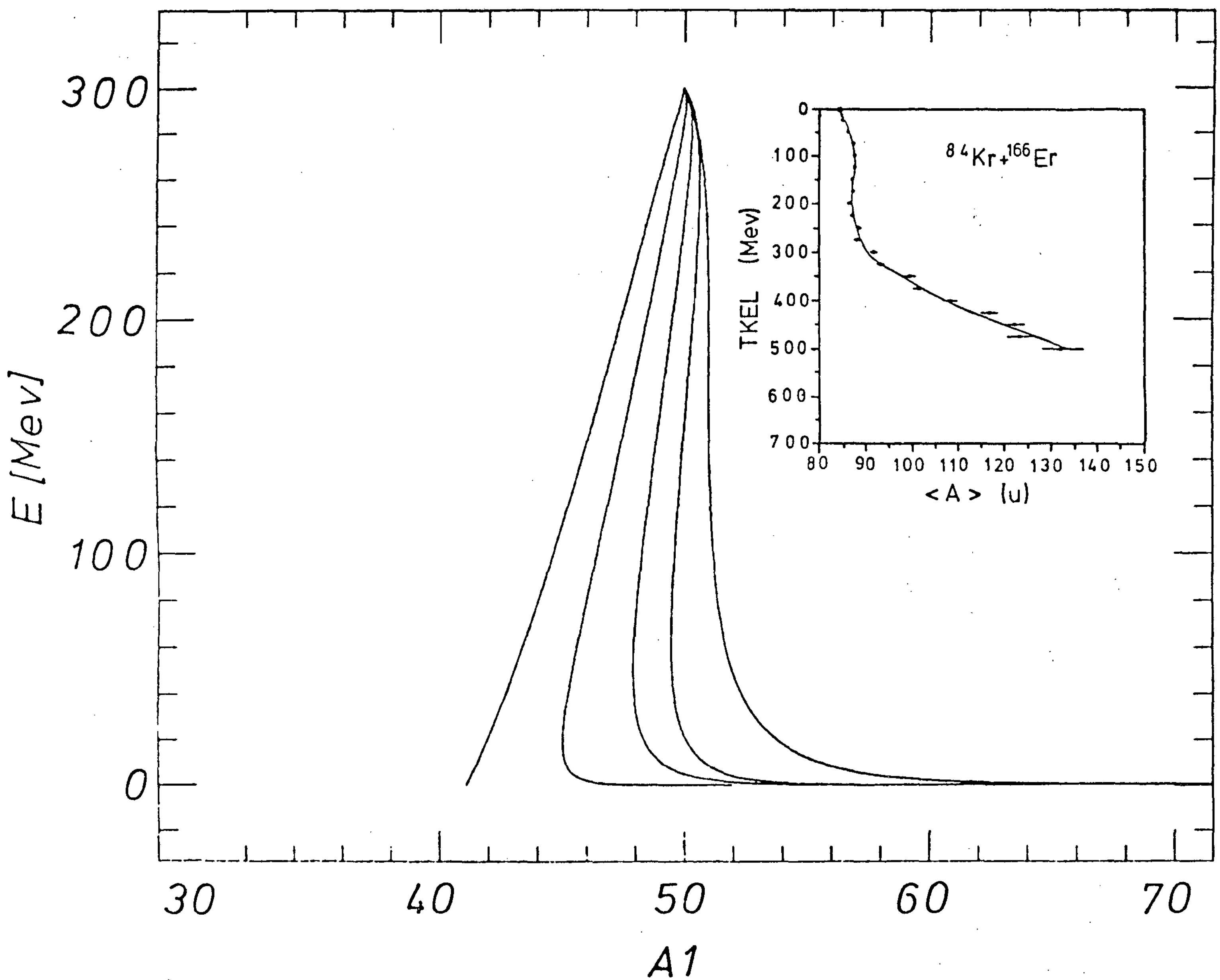

4037-83 MPI H
T1/T2
2.5
2.0
1.5
1.0
0.5
0
100
200
300
E [Mev]
E [Mev]
300
200
100
0
40
45
50
55
60
A1

Fig. 1



4036-83 MPI H

Fig. 2

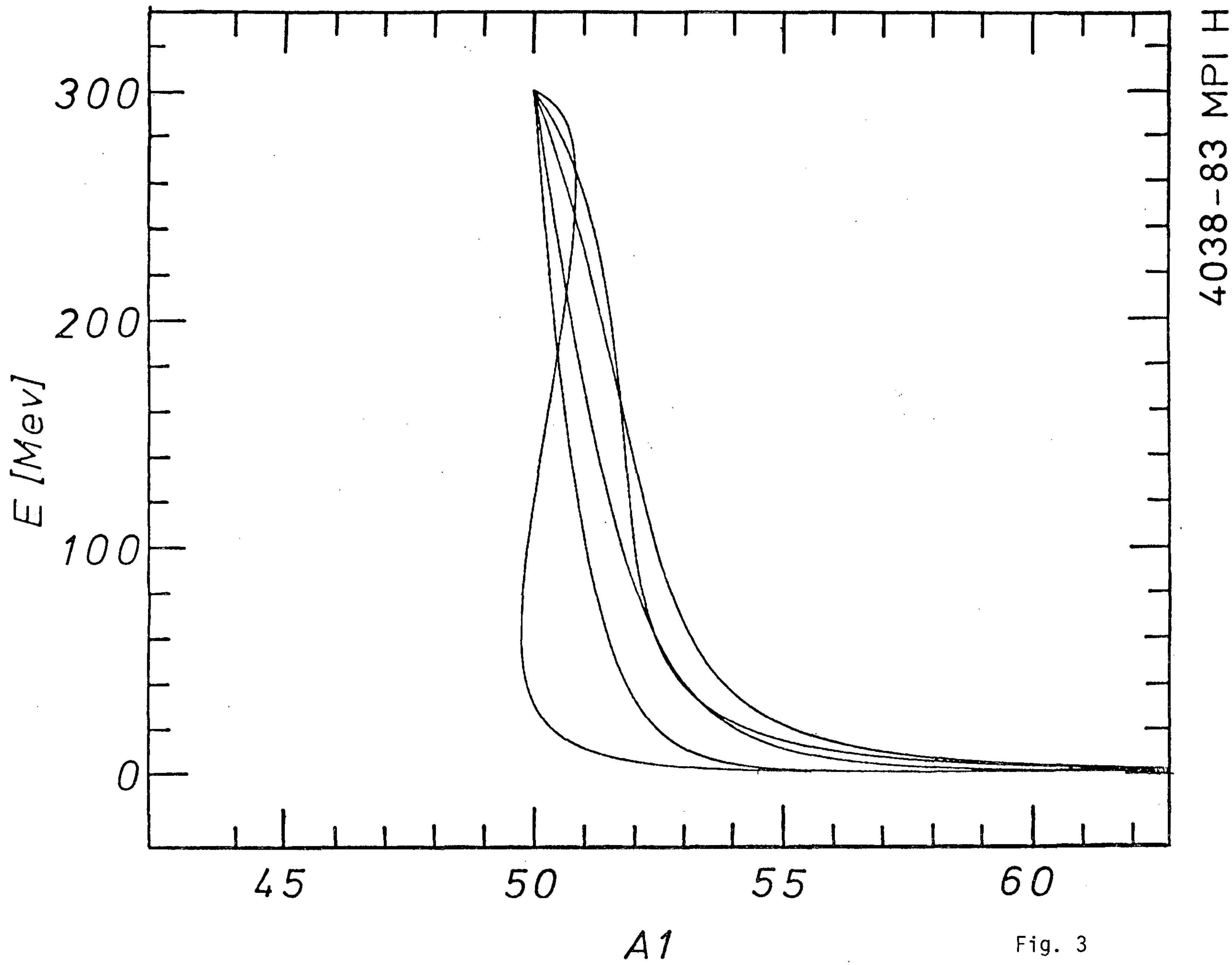


Fig. 3

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