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Absence of saturation in energy deposition in $^{40}Ar + ^{232}Th$ collisions at E = 15 - 115 AMeV

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Abstract

Fission fragment (FF), intermediate mass fragment (IMF), and light charged particle (LCP) production have been measured in ^{40}Ar + ^{232}Th collisions at E = 15 - 115 AMeV with the Michigan State University 4π Array. Trends in IMF and LCP production and in calculated excitation energy indicate there is no saturation in the deposited energy in central collisions of this system in the bombarding energy range studied.

In the ^{40}Ar + ^{232}Th system, and similar asymmetric systems, there has been much discussion about the evolution of the reaction mechanism in central collisions as beam energies are increased to values well above the Coulomb barrier. The decline in the cross section for fusion-fission processes, as evidenced by fission fragment folding angle distributions has received particular attention [1, 2, 3, 4, 5, 6], as has the possibility that there is a limit to the amount of excitation energy that can be deposited in such systems [2, 3, 4, 5, 7, 8, 9, 10]. Several hypotheses have been suggested to explain the phenomenon of the demise of fusion-fission, including the increase in the preequilibrium emission of light charged particles leaving a non-fissionable residue, the increase in the statistical emission of charged particles, and the onset of more complex decay mechanisms such as multifragmentation [1, 2, 3, 4, 5, 6, 11]. However, there is conflicting evidence regarding whether there is a saturation in the energy deposited in the ^{40}Ar + ^{232}Th system at beam energies above ~30 AMeV [2, 3, 5, 7, 8, 9, 12]. This more basic question must first be answered before further speculation about the decay mechanism can be made. In the present analysis, we study the ^{40}Ar + ^{232}Th reaction over a wide range of beam energies (E_{beam} = 15 - 115 AMeV) with nearly 4π detection of fission fragments (FFs), intermediate mass fragments (IMFs), and light charged particles (LCPs). Trends in the average IMF and LCP production and calculations of excitation energy indicate that there is no saturation in energy deposition in central collisions in the energy range studied.

The experiment was performed at the National Superconducting Cyclotron Laboratory at Michigan State University where ^{40}Ar beams accelerated by the K1200 cyclotron bombarded a 1 mg/cm^2 ^{232}Th target. Reaction products of nuclear collisions were detected with the Michigan State University (MSU) 4π Array [13]. At the time these data were taken, the 4π Array consisted of a main ball of 170 phoswich counters covering angles from 18° to 162° and a forward array of 45 phoswich counters covering from 7° to 18° . Mounted in front of the main ball phoswiches were 55 Bragg curve counters (BCCs) which were operated with 125 torr of C_2F_6 gas. In front of the BCCs, 30 position-sensitive low pressure multi-wire proportional counters (MWPCs)[13] were installed and operated with 5 torr of isobutane. The MWPCs have an angular resolution of $\sim 1^\circ$. Together these devices detect particles with Z = 1-18, as well as fission fragments, with the lower energy thresholds for Z=1, 3, 5, and 12 fragments being 17 MeV, 2 AMeV, 3 AMeV, and 4 AMeV respectively. The lower energy threshold for the Forward Array detectors was 17 AMeV. The data presented in this letter were taken with a hardware trigger that required two particles to enter the phoswiches in the main ball. This trigger reduces the contribution of peripheral collisions, which are not of interest in this study.

In Figure 1, we present the inclusive fission fragment folding angle distributions from the ^{40}Ar + ^{232}Th system at 15, 35, 55 and 115 AMeV. In the present work, the folding angle is defined as $\Theta_{ff} = \cos^{-1}(\mathbf{f_1} \cdot \mathbf{f_2})$, where $\mathbf{f_1}$ and $\mathbf{f_2}$ are the directional unit vectors of the two fission fragments. The effect of the hardware trigger as a first order impact parameter filter is made obvious in these distributions, particularly in the 15 AMeV plot. At this energy, the target fission peak that typically appears at approximately 170°, due to low linear momentum transfer (LMT) collisions [1, 2, 3, 14, 15, 16], is almost completely absent as these types of collisions rarely satisfy the hardware trigger. The dominant feature at 15 AMeV is a peak at 115° which, for low beam energies, has been established as being due to central, high LMT collisions that result in incomplete or complete fusion followed by fission. [1, 2, 4, 5, 15]. At all other energies shown, the low LMT component is present but is reduced by the trigger condition. This allows the high LMT component to remain visible even at the highest energy.

Figure 1 clearly shows that, in central collisions in this system at 115 AMeV, there is still a significant contribution from a high LMT process, which results in two fission-like fragments.

However, this process is certainly diminished at this energy, as has also been shown in Ref. [16]. The decrease in the importance of this fission-like process may be caused by an increase in the deposited energy to the point where multifragmentation becomes the dominant process. If this is true, and one assumes that charged particle multiplicity is strongly correlated with deposited energy, one expects to see enhanced production of IMFs and LCPs. It is also interesting to look at the average number of IMFs emitted in the fission-like events that still occur at high energies. The fission-like fragment pairs in this system exhibit a strong non-coplanarity with the beam axis that increases with beam energy and probably cannot be explained by light particle emission alone [5, 16]. Thus, there is a possibility of an increase in mean IMF production in the fission-like events as beam energy increases.

In Figure 2a, we plot the mean IMF multiplicity, $\langle N_{IMF} \rangle$, determined event by event, versus the lab projectile energy E_{beam}. The various symbols represent selection criteria, and are shown in the inset. These were the only criteria used, and no explicit attempt was made to separate preequilibrium and equilibrated sources. The open squares represent $\langle N_{IMF} \rangle$ for the inclusive data set. These data show that, above 35 AMeV, IMF production saturates at a value well below $\langle N_{IMF} \rangle$ = 1.0. The solid circles show $\langle N_{IMF} \rangle$ for central collisions only. Centrality was determined using the total transverse kinetic energy (E_T) of each event, where events with E_T in the top 10% of the inclusive E_T distribution were tagged as central. This cut corresponds to a reduced impact parameter (b/b_{max}) of $\leq$0.3 as calculated through a simple geometric prescription in which b_{max} represents the largest impact parameter leading to a triggering event. If one assumes that b_{max} is equal to the sum of the projectile and target radii, this corresponds to $\sim$10% of the geometric cross-section. In reality b_{max} is somewhat smaller than this due to the trigger condition [17], and 10% may be taken as an upper limit. It was determined that E_T is an appropriate variable to use as a centrality condition for this system in that it was most efficient at suppressing the low LMT component of the fission fragment folding angle distribution. It was determined that E_T does not autocorrelate with N_{IMF}, by using methods similar to those detailed in Ref. [17]. The values of the $\langle N_{IMF} \rangle$ data for these central events are well above the inclusive data points at all energies shown. The excitation function increases steadily with beam energy and shows no sign of saturation.

The open triangles in Figure 2a show $\langle N_{IMF} \rangle$ when the same cut is made on central events with the further requirement that two fission-like fragments are detected in each event. The number of events in this subset varies from ~5% (at 15 AMeV) to ~1% (at 115 AMeV) of the number of all central events. The excitation function for this subset then falls between the excitation functions for the inclusive data and the data with only the E_T cut. The trend of this excitation function is consistent with the previous observation that the fission-like fragments are being emitted increasingly out-of-plane as beam energy increases [5, 16]. The shift of the excitation function to lower values of $\langle N_{IMF} \rangle$ than the those found in the data gated on only E_T occurs because we require a large fraction of the mass to be bound in two large fragments.

In Figure 2b, we plot the mean charge bound in light charged particles, $\langle Z_{LCP} \rangle$, versus beam energy, with the same gates as applied in Figure 2a. As in the above plot, the excitation function from the inclusive data saturates after ~30AMeV while the excitation function from the data selected with only E_T increase steadily. For this system, Jiang et al. [7] measured a saturation in mean LCP production in central collisions – as defined by neutron multiplicities – at beam energies above 30 AMeV, and determine that excitation energy is saturating also. Based on the comparison of the trends of our inclusive and central $\langle N_{IMF} \rangle$ data, we suggest that this previous result was due to the less stringent exclusion of peripheral collisions in the events used to determine mean LCP multiplicity. This conclusion is supported by Utley et al. [12] who measure the excitation energy in this system as being significantly higher than Jiang et al., although both use a similar method. Also apparent in Figure 2b is that there is little difference between the curve gated on E_T and FFs and the curve gated on only E_T. This similarity indicates an insensitivity of LCP production to the formation of fission-like fragments versus IMFs in these data.

The steady increase of the $\langle N_{IMF} \rangle$ and $\langle Z_{LCP} \rangle$ excitation functions gated only on E_T (solid circles) in Figure 2a and 2b suggests that increasing amounts of energy are being deposited in this system in central collisions. The evidence of this increase is contrary to the results of Ref. [7], but in qualitative agreement with Refs. [2] and [3]. This observation leaves open the possibility that a change in the dominant reaction mechanism to multifragmentation could be occurring as beam energy increases. However, it is difficult to determine if this is true from the IMF multiplicities alone. The value of $\langle N_{IMF} \rangle$ reached at 115 AMeV is measured to be less than 2.5, which may seem low if a system of this size is multifragmenting. However, at 115 AMeV, the standard deviation of the IMF probability distribution for central events is quite large ($\sigma_{IMF} = 1.3$), and a significant fraction (~40%) of the central events contains three or more IMFs. Note that all reported values of $\langle N_{IMF} \rangle$ and $\langle Z_{LCP} \rangle$ are not corrected for detector acceptance.

In order to make a quantitative estimate of the energy deposited in the system, we performed a calculation of the average excitation energy, $\langle E^* \rangle$, using a method similar to that described in Ref. [6]. The quantity $\langle E^* \rangle$ is calculated from the average LMT measured in the most central, high LMT, fission-like reactions (the subset marked by the open triangles in Figure 2). The folding angle distribution in this subset is characterized by a single peak at ~100° [16]. Folding angle is converted into LMT event-by-event using the method of Ref. [14], and a gaussian is then fit to the peak of the LMT distribution. The centroid of this gaussian is taken as the mean LMT for central collisions. There is no explicit angular cut on the fission-like fragments in this distribution.

In the $\langle E^* \rangle$ calculation, average fission-like fragment energies were determined using the prescription from Viola [18], and the size of the composite system was extrapolated from measurements made by Conjeaud et al. [2]. The average excitation energies $\langle E^* \rangle$, extracted in this way are 474±4, 710±9, 788±11, 860±13, 884±15, 998±20, 1067±26, 1300±44, and 1693±92 MeV for the beam energies 15, 25, 30, 35, 40, 45, 55, 75, and 115 AMeV respectively. The values we obtained for the energies studied in Ref. [2] and [12] agree well with the values cited in those works.

Figure 3 shows the calculated values of the average excitation energy per nucleon, $\langle \epsilon^* \rangle$, versus beam energy (solid circles). The value of $\langle \epsilon^* \rangle$ increases with beam energy up to ~7.5 AMeV, indicating that there is no saturation in excitation energy in this system. We also extracted excitation energies from a two-stage model [19, 20, 21] which was shown in Ref. [16] to accurately predict the decline of the fusion cross section in the present system. The first stage of this model is hydrodynamical in nature, and begins with the nucleons of the projectile trapped within the potential well of the target. This system then equilibrates through two-body collisions and the emission of light particles, and at the end of this stage, the excitation energy is extracted. As shown in Figure 3, the values of $\langle \epsilon^* \rangle$ extracted from the first stage of the model agree quite well with the calculation based on momentum transfer.

In summary, we have studied fission fragment angular correlations, intermediate mass fragment production, and light charged particle production in ^{40}Ar + ^{232}Th reactions over a broad range of bombarding energies. Evidence that a high LMT, fission-like process diminishes in importance, but is still occurring in this system at 115 AMeV has been presented. The mean values of the N_{IMF} and Z_{LCP} distributions in the most central collisions, are found to increase smoothly with beam energy up to the highest energy measured, indicating that the energy deposited in the system has not saturated. A simple calculation of excitation energy, based on measured average momentum transfer, supports this conclusion. Whether or not this increase in deposited energy has led to a transition of the reaction mechanism to multifragmentation is not clear from the mean IMF multiplicities alone, and is the topic of further work.

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References

[1] V.E. Viola Jr., Nucl. Phys. A502, 531c (1989).

[2] M. Conjeaud *et al.*, Phys. Lett. B159, 244 (1985).

[3] E.C. Pollacco *et al.*, Z. Phys. A346, 63 (1993).

[4] D. Jacquet *et al.*, Phys. Rev. Lett. 53, 2226 (1984).

[5] E. Schwinn *et al.*, Nucl. Phys. A568, 169 (1994).

[6] M. Begemann-Blaich *et al.*, Phys. Rev. C45, 677 (1992).

[7] D.X. Jiang *et al.*, Nucl. Phys. A503, 560 (1989).

[8] J. Galin and U. Jahnke, J. Phys. G20, 1105 (1994).

[9] T. Ethvignot *et al.*, Phys. Rev. C43, R2035 (1991).

[10] S. Bhattacharya *et al.*, Phys. Rev. Lett. 62, 2589 (1989).

[11] B. Jakobsson *et al.*, Nucl. Phys. A509, 195 (1990).

[12] D. Utley *et al.*, Phys. Rev. C49, R1737 (1994).

[13] G.D. Westfall *et al.*, Nuc. Inst. and Meth. A238, 347 (1985).

[14] H.K.W. Leegte *et al.*, Phys. Rev. C46, 991 (1992).

[15] V.E. Viola Jr. *et al.*, Phys. Rev. C26, 178 (1982).

[16] J. Yee, E. Gualtieri *et al.*, Submitted to Phys. Lett. B.

[17] W.J. Llope *et al.*, Phys. Rev. C51, 1325 (1995).

[18] V.E. Viola *et al.*, Phys. Rev. C31, 1550 (1985).

[19] G.D. Harp and J.M. Miller, Phys. Rev. C 3, 1847 (1971).

[20] J. Desbois *et al.*, Z. Phys. A238, 101 (1987).

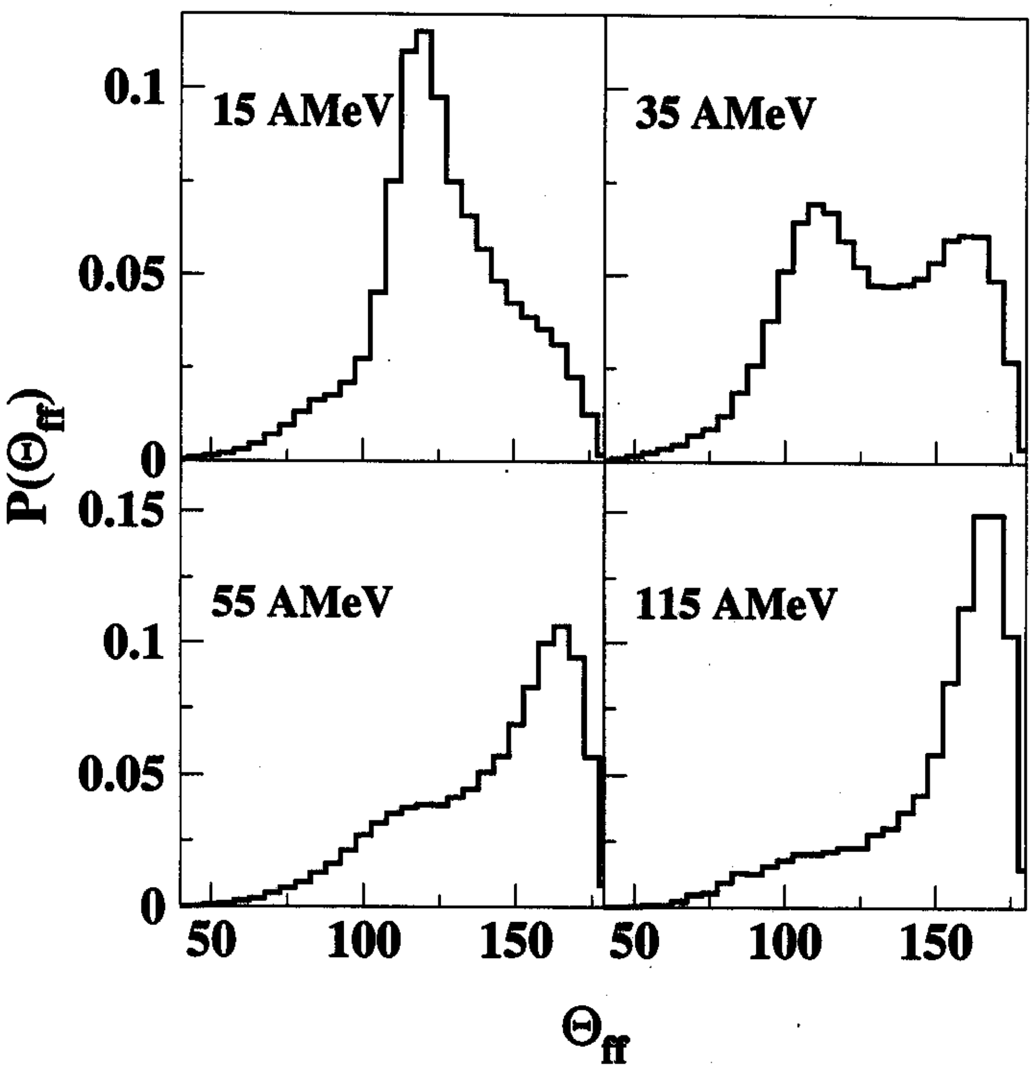
[21] C. Cerruti *et al.*, Nucl. Phys. A492, 322 (1989).

Figure Captions

Figure 1: Probability distributions of the fission fragment folding angles (Θ_{ff}) for the ^{40}Ar + ^{232}Th system.

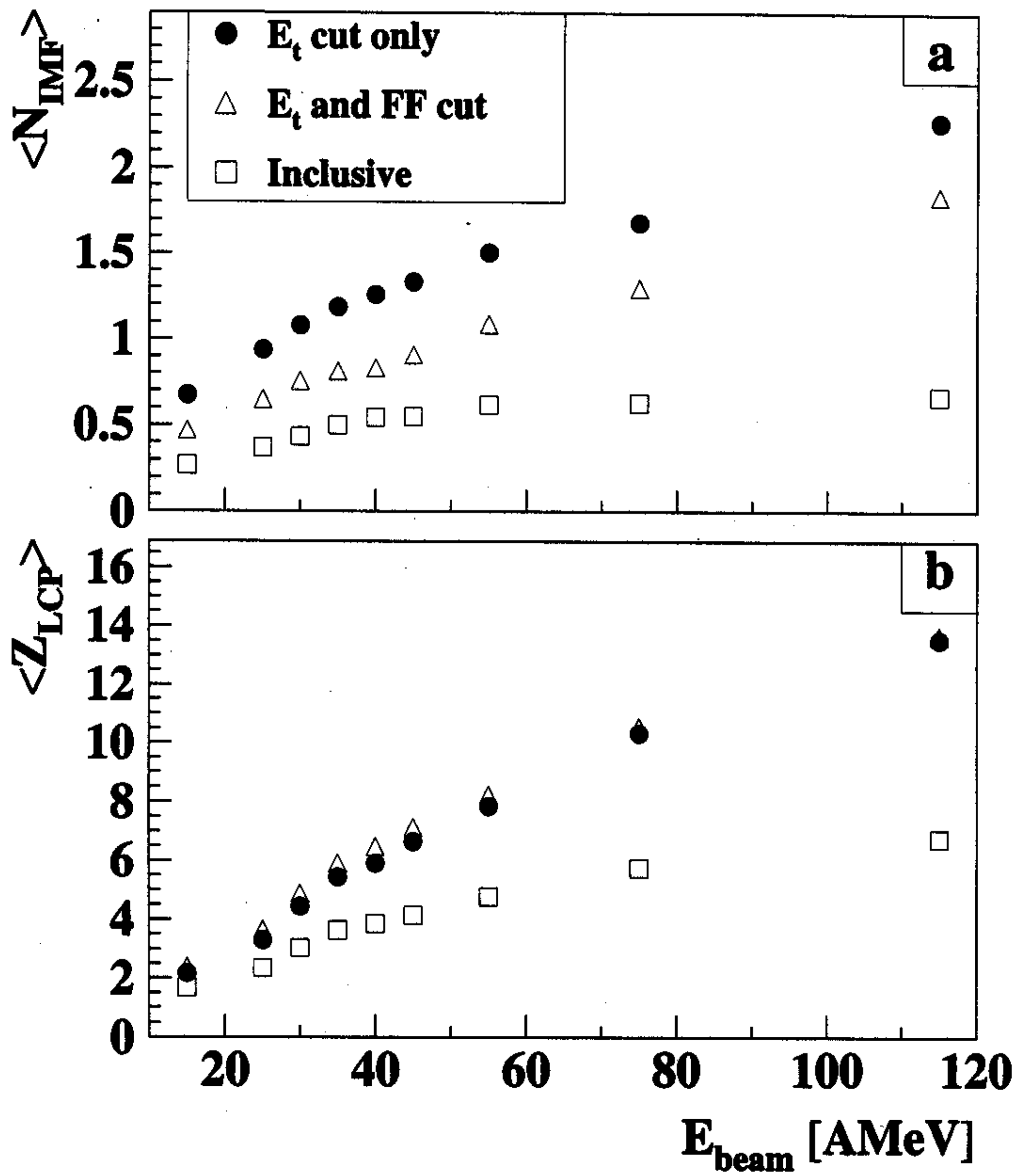
Figure 2: Average values of a) N_{IMF} and b) Z_{LCP} versus the projectile energy per nucleon for ^{40}Ar + ^{232}Th. Symbols representing different gating conditions are as defined in the inset and the text. Values are not corrected for acceptance.

Figure 3: Solid circles represent the average excitation energy per nucleon in the composite system as calculated from the data. Open squares represent average values of excitation energy per nucleon extracted from the first stage of the model.



0.1
0.05
0
0.15
0.1
0.05
0
P(Θ_ff)
15 AMeV
35 AMeV
55 AMeV
115 AMeV
50
100
150
50
100
150
Θ_ff

Figure 1:



$\langle N_{IMF} \rangle$
E_t cut only
E_t and FF cut
Inclusive
a
2.5
2
1.5
1
0.5
0
$\langle Z_{LCP} \rangle$
b
16
14
12
10
8
6
4
2
0
20
40
60
80
100
120
E_{beam} [AMeV]

Figure 2:

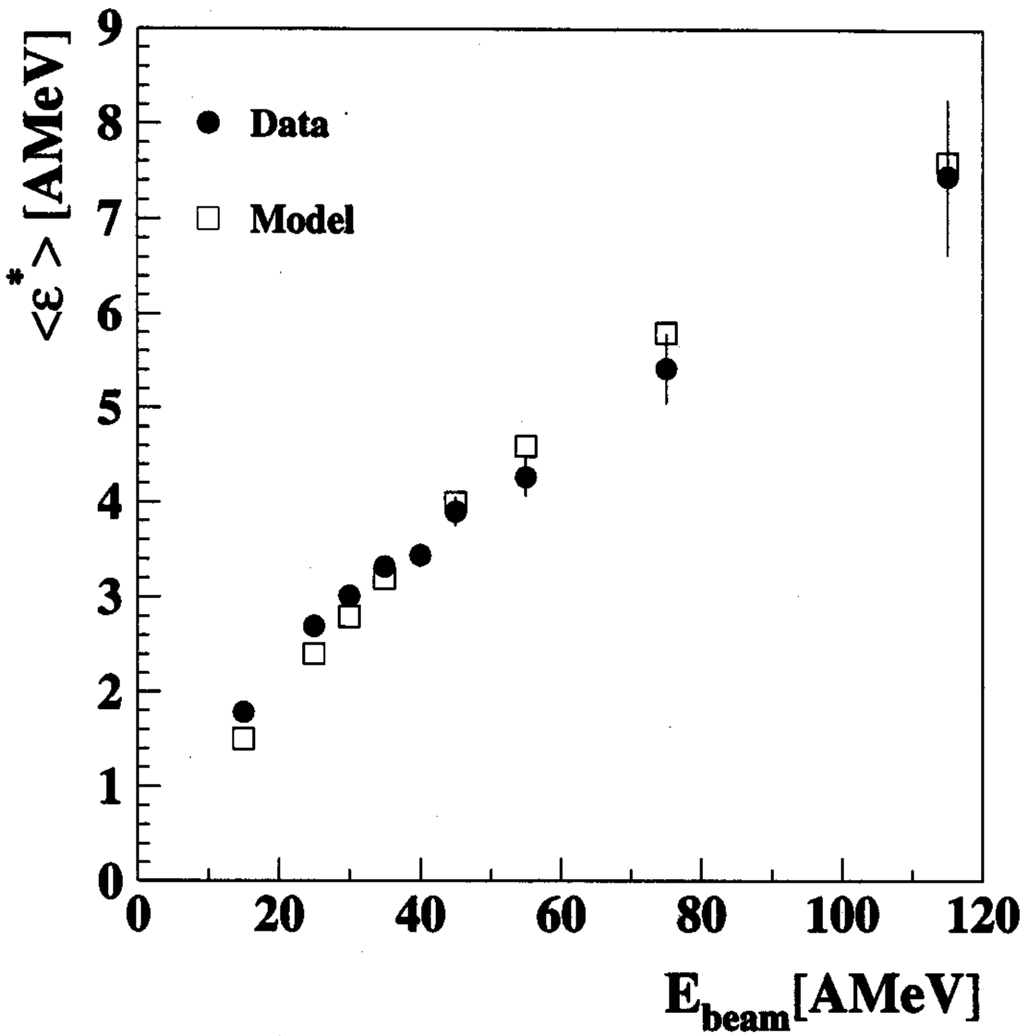


Figure 3: