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*TIME SCALE IN ^{24}Mg PROJECTILE BREAKUP AT 25A AND 35A MeV**

M. Samri[a], G.C. Ball[b], L. Beaulieu[a], B. Djerroud[a †], D. Doré[a ‡], A. Galindo-Uribarri[b], E. Hagberg[b], D. Horn[b], R. Laforest[a §], Y. Larochelle[a], J. Pouliot[a **], R. Roy[a] and C. St-Pierre[a]

[a] *Laboratoire de physique nucléaire, Département de physique, Université Laval, Ste-Foy, Québec G1K 7P4, Canada*

[b] *AECL, Chalk River Laboratories, Chalk River, Ontario K0J 1J0, Canada*

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* Experiments performed at TASCC, Chalk River, Ontario, Canada

† Present address: NSRL, University of Rochester, New York, USA

‡ Present address: Institut de Physique Nucléaire de Lyon, 46 Bd du 11 Novembre 1918, F-69622 Villeurbanne Cedex, France

§ Present address: Laboratoire de Physique Corpusculaire, Bd du Maréchal Juin, F-14050, Caen Cedex, France

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Time scale in ^{24}Mg projectile breakup at 25A and 35A MeV *

M. Samri[a], G.C. Ball[b], L. Beaulieu[a], B. Djerroud[a] †, D. Doré[a] ‡,
A. Galindo-Uribarri[b], E. Hagberg[b], D. Horn[b], R. Laforest[a] §,
Y. Larochelle[a], J. Pouliot[a] **, R. Roy[a], C. St-Pierre[a]

[a] *Laboratoire de physique nucléaire, Département de physique, Université Laval, Québec, Canada G1K 7P4.*

[b] *AECL Research, Chalk River Laboratories, Ontario, Canada K0J 1J0.*

Abstract

The time scale involved in the breakup of ^{24}Mg projectiles into the 6α and the 5αpH channels has been investigated by examining distortions and shifts in the fragment velocity distributions due to the Coulomb field of the target. The deduced time scale decreases with increasing excitation energy.

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†Present address: NSRL, University of Rochester, New York, USA.

‡Present address: Institut de Physique Nucléaire, 91406 Orsay Cedex, France.

§Present address: Laboratoire de Physique Corpusculaire, Bd du Maréchal Juin, F-14050, Caen Cedex, France.

**Present address: Hôtel-Dieu, 1 rue Collins, Québec, Canada, G1R 4J1.

The experimental determination of the time scale involved in intermediate-energy heavy-ion reactions [1–6] may be very helpful in discriminating between the different disassembly mechanisms that occur in such reactions. At low energies, these mechanisms are essentially of a sequential binary-fission nature [7–9] characterized by a long time scale, while towards the high energy limit of the intermediate energy domain, it has been predicted that simultaneous multifragmentation, occurring on a short time scale ($\tau \leq 100$ fm/c), should become the main decay mode [10–13]. Despite the numerous experiments devoted to this question, no clear separation or transition between these two extreme situations has yet been found. In fact, short time scales are sometimes reported in experiments at low bombarding energy [14]. The time information is usually extracted via particle correlation function measurements based on the intensity interferometry method [15]. In projectile fragmentation experiments, alternative methods for the determination of the lifetime of excited nuclei, based on the target proximity effect, have been used in some recent studies [1,2,4]. These methods make use of the influence of the target Coulomb field on the final velocities of the fragments, and allow the time determination with the help of event simulation. In the following, we will apply these methods to extract the lifetime with respect to ^{24}Mg projectile breakup into the six-alpha and the 5αpH channels at 25A and 35A MeV incident beam energy.

The projectiles were excited in peripheral collisions on a gold target at the TASCC facility of Chalk River Laboratories. Charged reaction products were detected by an array of 80 scintillation counters mounted in five beam-centered rings, covering the whole azimuthal domain and located at mean polar angles of 8^0, 13^0, 20^0, 29^0 and 40^0 with respect to the beam direction. The three inner rings are composed of fast-slow ΔE-E phoswich detectors while rings 4 and 5 are made of CsI(Tl) scintillators. The energy threshold ranges from 7.5A MeV for hydrogen and helium to 19.5A MeV for $Z = 12$ ions in the phoswich detectors and is approximately 2A MeV for $Z = 1, 2$ particles in the CsI detectors. Element numbers up to $Z = 12$ were resolved in the phoswich detectors and the CsI scintillators identified up to $Z = 4$. In the 25A MeV experiment, mass resolution for hydrogen isotopes was achieved in the CsI detectors. The data were acquired on an event-by-event basis, with each detector contributing to the trigger. For each event, the measured quantities were the energy, emission angle and charge of the reaction products. Events corresponding to the multiple breakup of the projectile were selected by requiring, in the off-line analysis, that the total detected charge in one event be equal to the charge of the projectile.

The first method [1,2] that we have used to determine the time scale consists of simulating a series of velocity distributions as a function of the lifetime τ of the decaying ^{24}Mg, and using the simulated final fragment velocities to construct a normalized velocity tensor

$$V_{ij} = \frac{1}{MN} \sum_{n=1}^{MN} (v_i^{(n)} - \overline{v}_i)(v_j^{(n)} - \overline{v}_j), \tag{1}$$

where $\overline{v}_i = \sum_{n=1}^{MN} v_i^{(n)}/MN$. N is the total number of events and M is the multiplicity of each event. The ordered ($q_1 \leq q_2 \leq q_3$) and normalized eigenvalues ($Q_i = q_i^2/\sum_{j=1}^{3} q_j^2$) of this tensor yield the total coplanarity given by $C_T = \frac{\sqrt{3}}{2}(Q_2 - Q_1)$ [16]. The evolution of C_T as a function of τ is mapped out by several calculations assuming different values of τ. The experimental lifetime is finally obtained as the intersection of the experimental total coplanarity with the simulated plot C_T vs τ. In the simulations, the initial relative position and momentum of the projectile and the target were calculated with the reaction code Torino [17] which takes account of both a statistical exchange of nucleons between the two colliding nuclei and a deformation term through surface collective excitations. The disintegration of ^{24}Mg is then followed from the time $t = 0$ set at the distance of closest approach until all particles are emitted. This disintegration is assumed to proceed in a purely sequential statistical way, as justified in a preceding study [18,19]. At each stage of the decay chain, the position and the velocity of all particles are generated randomly and in such a way as to conserve the linear momentum and the position of the total center of mass. The angular momentum of the decaying ^{24}Mg nucleus has been calculated by the code Torino which gives a mean value of $6\hbar$ with a variance of $2\hbar$. This value is calculated in a range of impact parameters by giving to each value of angular momentum the experimental weight of the corresponding experimental excitation energy. For each channel, two sets of simulations were performed corresponding to an angular momentum of $4\hbar$ and $8\hbar$ respectively. The program code used in this work is that of Ref. [20]. The simulated events were filtered through the geometrical and energy cuts of the detection apparatus and a value of the total coplanarity is extracted for each value of τ. The excitation energy is obtained by summing the kinetic energies in the center of mass of the fragments and adding the separation energy for the reaction channel. This method has been applied to the 6α at 25A MeV and 35A MeV and 5αpH at 25A MeV channels whose mean excitation energies are 80, 95 and 108 MeV, respectively as shown in Fig. 1. Experimental observations [21] and theoretical calculations [22] have shown that about 90% of the Z = 2 nuclei are ^{4}He. Lacking isotope identification for most helium ions, we therefore treat them all as α particles. In the case of the 5αpH channel, as mass resolution for hydrogens is achieved in the CsI detectors, the analysis is restricted to events where at least one proton is detected in these detectors ($24^0 \leq \theta \leq 46^0$). In this way, we select events (among which 8% are fully mass resolved 5αpp) with high excitation energy, since this quantity is highly correlated with the charged particle multiplicity in the CsI detectors [22]. Moreover, the results for this channel obtained by the fragments' velocity distortion method can be compared to those obtained by the proton velocity shift method. The results for these channels, shown in Fig. 2, display the smooth monotonic decrease of the total coplanarity as a function of the time delay already observed in previous work [1,2]. The time delays corresponding to the experimental total coplanarities are about $(5.1 - 6.8) \times 10^{-22}$ s, $(4.7 - 6.8) \times 10^{-22}$ s and $(3.0 - 5.9) \times 10^{-22}$ s for the 6α channel at 25A MeV and 35A MeV and 5αpH at 25A MeV, respectively .

In the case of the 5αpH channel, it has been shown in Ref. [4] that it is possible to observe post-breakup effects which are characterized by a shift of the longitudinal velocity spectra that is more pronounced for protons than for α particles. We have used the program code of Ref. [4]. The correlated velocity, angle and excitation energy of the primary projectile are taken as input to generate projectile fragmentation events filtered by the geometry and energy cuts of the detection apparatus. In a first step the projectile and the target are followed along peripheral collision trajectories until a given separation r is reached, then the trajectories of the projectile fragments are calculated under the target Coulomb field.

The proton velocity spectra are constructed in the center of mass frame of all fragments, with the z-axis parallel to the quasiprojectile vector and the x-axis in the reaction plane determined by the beam axis and the quasiprojectile vector. The spectra corresponding to the z-component of the proton velocity are shown in Fig. 3 for three breakup distances, corresponding to average proton emission times of 2×10^{-22} s, 3×10^{-22} s and 15×10^{-22} s. For the longest simulated times (where no shift should be observed as the breakup occurs far away from the target Coulomb field), the z-component of the proton velocity is centered around zero showing no shift with respect to the center of mass of all fragments. The observed shift in the experimental data for this velocity component is best reproduced by assuming an average proton emission time of $\approx 3 \times 10^{-22}$ s. These different results are given in Table I as a function of the excitation energy per nucleon of the corresponding channel.

The time scale deduced in the case of the 6α channel indicates a long delay, characteristic of sequential particle emission. It corroborates the results obtained with the relative-angle and the event-shape analysis of a preceding study [18]. For the 5αpH channel, the deduced time scale derived by the second method is shorter than that derived by the first one. This might be due to the fact that in the second case only protons are considered, while in the first one all particles in the event are considered. Moreover, although the present experiment is performed at a relatively low beam energy, the deduced proton emission time is of the same order of magnitude as the time reported in Ref. [4] for the same target-projectile combination and the same breakup channel but at 60A MeV incident energy. This may be understood in terms of excitation energy, since in our case, the analysis is restricted to protons detected at angles greater than 24^0 and in such a case the average excitation energies are 15 MeV higher than when only particles detected between 6^0 and 24^0 are considered. The reported time approaches typical thermalization times [23,24] and is faster than that of the alpha particle in the 6α channel.

The observed decrease in the time scale is correlated with the increase of excitation energy per nucleon as it increases from 3.4A MeV for the six-alpha channel up to 4.5A MeV for the 5αpH channel. For the same range of excitation energy per nucleon, a decrease of fragment emission time was also observed in the reaction $^{40}Ar + ^{197}Au$ at 30 and 60A MeV [3] in studies of correlation functions for fragment velocities. One possibility is to correlate this trend with a change in the reaction mechanism from sequential to "instantaneous" breakup. For example, in a study of the Ni + Al system at 15.8A MeV [25], only a small fraction of the observed multifragmentation events was classified as fast sequential decays. In contrast, however, the breakup of 94A MeV ^{16}O into four alpha-particles [2] and the fragmentation of Ar + Ni into three heavy fragments [14] are both in good agreement with a sequential decay mechanism despite their short (2×10^{-22} s or less) time scales. It therefore appears that the observation of short timescales is not, in itself, sufficient to signal a change in the reaction mechanism and distinguish between "instantaneous" and fast sequential breakup.

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TABLES

TABLE I. Deduced fragment emission times for the 6α and 5αpH channels in the reaction ^{24}Mg + ^{197}Au at 25A MeV and 35A MeV as a function of the channels' excitation energy per nucleon. The method labelled 1 refers to the velocity distortion method (Ref. [1]), while label 2 refers to the velocity shift method (Ref. [4]).

FIGURES

FIG. 1. Reconstructed excitation energy spectra for the six-alpha channel at 25A MeV (top), at 35A MeV (middle) and the 5αpH channel at 25A MeV (bottom) in the reaction ^{24}Mg + ^{197}Au. Left arrows indicate the channels separation energies (28.5 and 48.3 MeV). Right arrows indicate the channels mean excitation energies (80, 95 and 108 MeV).

FIG. 2. The curves represent the simulated total coplanarity values as a function of the time delay in the breakup of ^{24}Mg into six alpha particles at 25A MeV (top), at 35A MeV (middle) and into $5\alpha + p + H$ particles at 25A MeV (bottom). The full and dashed curves correspond to values of angular momentum of 4 $\hbar$ and 8 $\hbar$ of the decaying ^{24}Mg nucleus, respectively. The experimental coplanarity values for each channel are also indicated with horizontal bars.

FIG. 3. Experimental (dot symbols) and simulated (solid line) proton velocity spectra in the reaction ^{197}Au(^{24}Mg,5αpH) at 25A MeV. Only events in which at least one proton registers in the CsI detectors are considered. The solid curves give the results of filtered simulated events for the various emission times indicated in the figure.

Channel	Method	ϵ^* (A MeV)	τ (s)
6α at 25A MeV	(1)	3.4	$(5.1 - 6.8) \times 10^{-22}$
6α at 35A MeV	(1)	4.0	$(4.7 - 6.8) \times 10^{-22}$
5αpH at 25A MeV	(1)	4.5	$(3.0 - 5.9) \times 10^{-22}$
5αpH at 25A MeV	(2)	4.5	3×10^{-22}

TABLE I M.Samri et al.

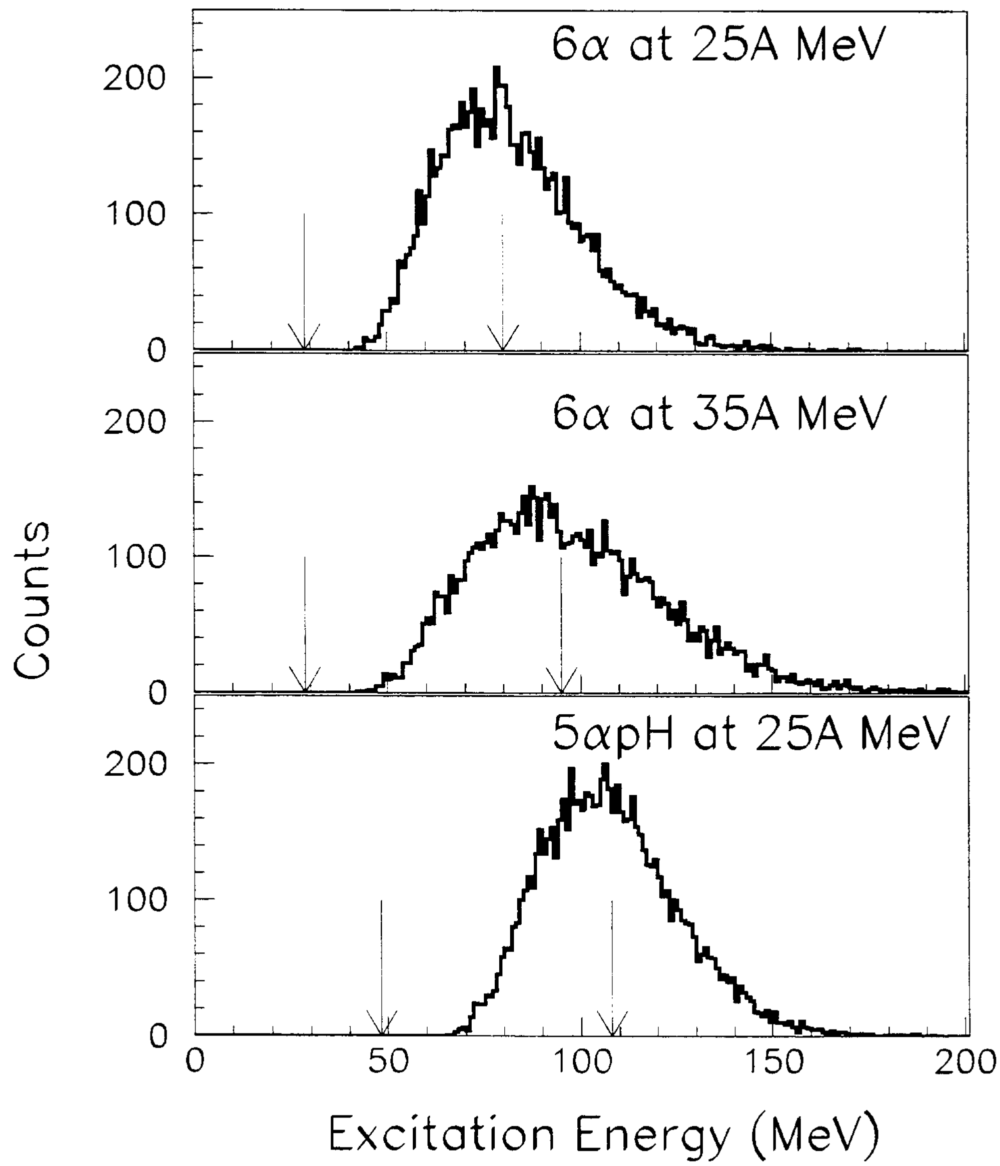

FIG. 1. M. Samri et al.

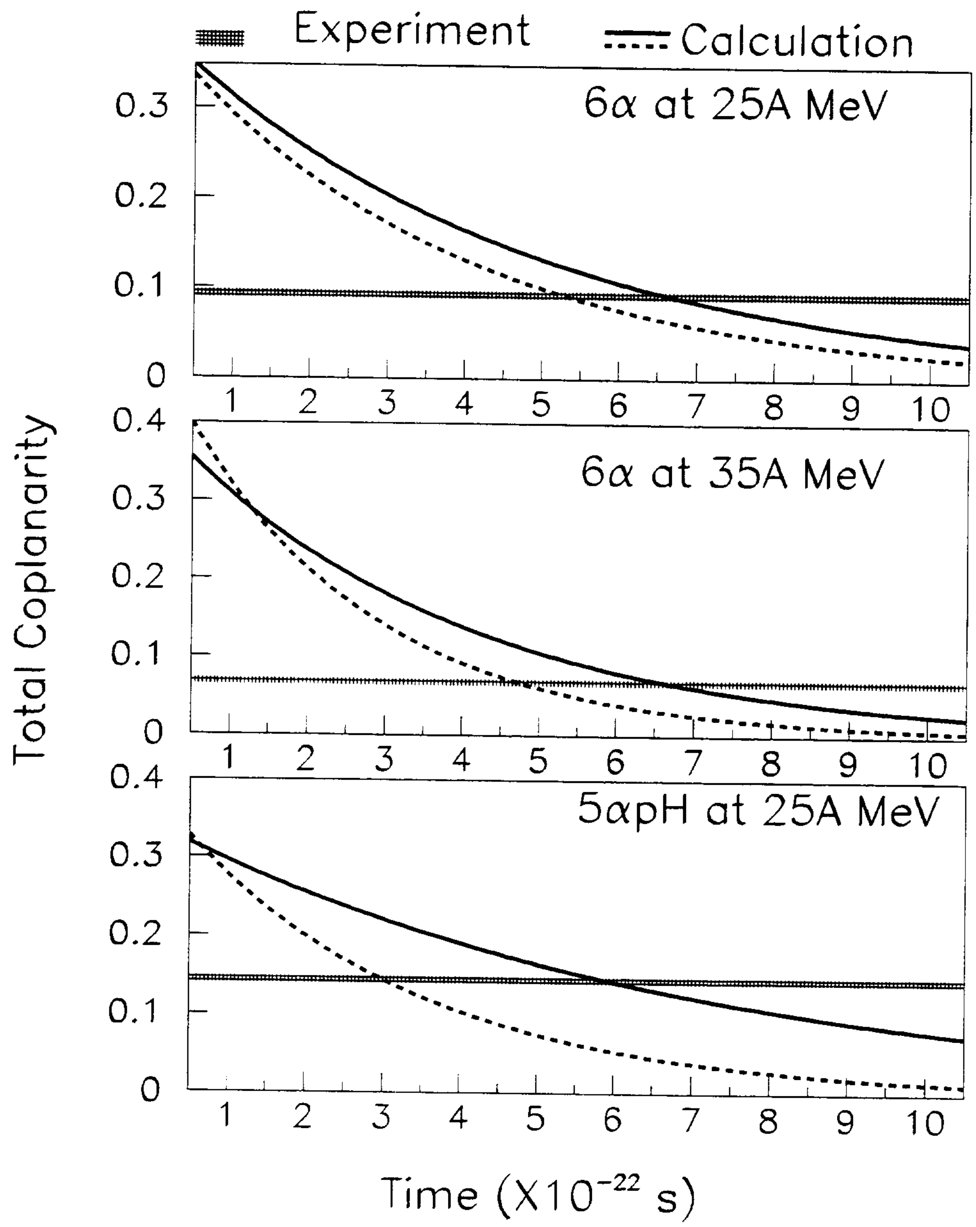

FIG. 2. M. Samri et al.

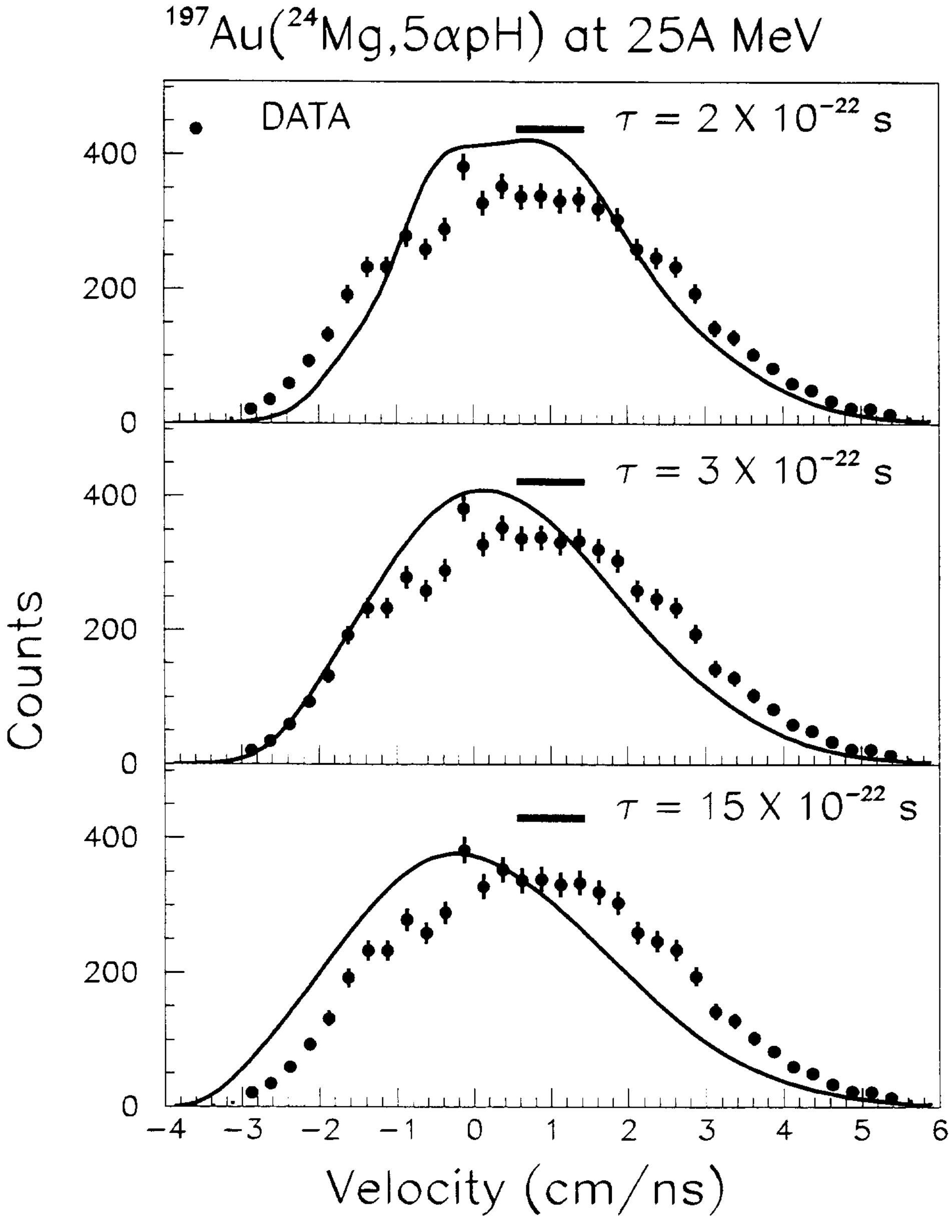

FIG. 3. M. Samri et al.