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Dominant two-step process in nuclear fragmentation at high energies

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Definitive measurements of negative $\langle p_L \rangle$ in the projectile rest frame are carried out for isotopes produced by fragmentation of relativistic ^{16}O and ^{12}C nucleus projectiles. They are analyzed for the evidence of the dominant two-step diffractive excitation processes during the fragmentation. Average energies in the range of 100 MeV or less are explored and the decays of the excited states with lifetimes longer than 10^{-21} s are investigated.

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I. INTRODUCTION

The recent development of accelerator technology with relativistic heavy ions such as Bevalac at Lawrence Berkeley Laboratory (~ 1 GeV/nucleon), the Alternating Gradient Synchrotron (AGS) at BNL (~ 14.6 GeV/nucleon), the Super Proton Synchrotron (SPS) at CERN (~ 200 GeV/nucleon), and the Relativistic Heavy Ion Collider (RHIC) at BNL (~ 100 GeV/nucleon in the near future), enables us to study collisions of complex systems of projectile and target nuclei both for the "hard" process of multipheripheral particle production and for the "soft" process of diffractive excitation (DE) for low-p_T physics [1]. The aim of the former high-energy heavy-ion accelerator programs is largely in the study of the quark-gluon plasma (QGP), a new form of matter, under conditions of extremely high densities and temperatures [2].

The latter two-step DE process becomes evident as the Lorentz factor of the projectile nuclei in laboratory system (LS) energy $E_b = m_b \gamma_b$ becomes large. The incident projectile and the target nuclei of masses m_b and m_t are frequently excited to high-mass states of long lifetimes ($\gtrsim 10^{-21}$ s) with masses m_{b^*} and m_{t^*}, respectively. These large impact-parameter collisions at the first stage seem to be mainly due to Coulomb interactions, and the high-mass states decay into fragments and mesons at the second stage, long after the collision [3].

In this paper we use the data from the classical paper by Greiner *et al.* [4] to search for independent evidence of scenarios for the above two-step, large impact-parameter collision process and we find that dominance of the DE mechanism of Ref. [3] is consistent with the data of the fragmentation of nuclei in high-energy collisions.

In Ref. [4], the first definitive measurements of the momentum distributions for isotopes produced by the fragmentation of projectile heavy-ion beams at Bevalac, LBL, have been reported for 1.05 and 2.1 GeV/nucleon ^{12}C and 2.1 GeV/nucleon ^{16}O nuclei. The fragment longitudinal momentum distributions in the projectile rest frame (PRF) are typically Gaussian, narrow, and isotropic, and they depend only on the fragment and the projectile, having no significant correlation with the target mass or the beam energy. This is consistent with the spirit of limiting fragmentation [5,6].

Using a Gaussian-shaped recursion formula, Greiner *et al.* have found good fits to the observed longitudinal momentum (p_L) spectra for all isotopes (except hydrogen) regardless of the projectile material, beam energy, or target material. However, the average longitudinal momentum $\langle p_L \rangle$ is found to be slightly negative in the PRF which is of order of -30 MeV/c. The negative $\langle p_L \rangle$ in the PRF [or target reference system (TRF) in the target DE events] indicates that after the collision the fragments of the projectile nucleus remember the direction from which the projectile was hit. This paper interprets the negativeness of $\langle p_L \rangle$ mainly on the basis of the following derivation from the two-step DE model of Ref. [3]:

$$\Delta y = y_b - y_{b^*} \simeq \ln(m_{b^*}/m_b) \; . \tag{1}$$

Equation (1) states that the absolute difference Δy of the primary LS rapidity of the projectile, y_b, and that of the excited state b^*, y_{b^*}, is approximately equal to the logarithm of the ratio of the mass of the excited state m_{b^*} and that of the projectile m_b (see also Sec. II). The rapidity of a particle, y, is defined as [7]

$$y = \operatorname{arctanh}(\beta \cos\theta) = \operatorname{arctanh}(\beta_L) \; . \tag{2}$$

This accommodates the negativeness of $p_L = m\gamma\beta_L$ in the evaluation of the masses of m_{b^*} for proof of the two-step process dominance in nuclear fragmentation. Here, for each secondary particle the Lorentz factor may be approximated as $\gamma \cong \gamma_b$ since the projectile fragments at LS are of the same speed as that of the beam particle [4].

There are two important factors concerning the advantage of using nuclear particles of ~ 1 GeV/nucleon to observe in the LS the process of nuclear "fragmentations" which are produced in collisions in detectors such as nuclear emulsions (the data of Ref. [4] were not from the nuclear emulsion technique). First, the charges, momenta, and masses of heavy fragments with low velocity, easily distinguishable from relativistic shower particles (mainly mesons), are nevertheless difficult to be measured accurately and identified in the LS due to their high ionization and short track lengths. By virtue of the relativistic heavy ions available, however, this difficulty may be overcome if an inverse reaction kinematics is used, i.e., the target nucleus and the projectile nucleus interchange their respective roles. The target-like reaction fragments from the collisions in the PRF are emitted at forward angles with high energies, which simplifies the particle identification procedure for secondary fragments in the LS [8]. Second, this identification procedure becomes more difficult as the momenta of the fragments become larger than 10 GeV/nucleon, mainly due to limitations on the magnitude and the size of the magnetic field available for the spectrometer. Thus, it is hoped that, because of limiting fragmentation [5,6], the analysis of the process of fragmentation at ~ 1 GeV/nucleon in the present paper may be in large part applicable at the energies of the AGS, the SPS, and the RHIC as far as most large impact-parameter soft collisions in fragmentation are concerned. These two facts led us to the analysis of the data of Ref. [4].

In this paper, the theoretical basis of our method is described in Sec. II. The distribution of the masses of the excited states, m_{b^*}, at the first stage of production at the site of the collision is obtained from fairly accurate data measured with a single-focusing magnetic spectrometer as explained in Ref. [4] and Sec. III. Finally, the results and a discussion are presented in Sec. IV.

II. THE THEORETICAL BASIS OF OUR MODEL

In the first stage of the quasi-two-body DE interaction, the incident beam particle b with LS primary energy $E_b = m_b \cosh y_b$ is excited to b^*

$$b + A_t \to b^* + A_t \ , \tag{3}$$

where A_t stands for the stationary target nucleus of mass number A_t. The LS energy of the high-mass state b^* becomes $E_{b^*} = (m_{b^*}^2 + q_T^2)^{1/2} \cosh y_{b^*} \simeq m_{b^*} \cosh y_{b^*}$, since q_T is negligibly small. The diffractive condition (or equivalently, the uncertainty relation) of the process of Eq. (3) is

$$q_T R \simeq 1 \ , \tag{4}$$

where q_T is the transverse momentum transfer to the target nucleus A_t and R is the interaction radius of the nucleus with the incident and target nuclei considered as one entity. Thus, we may assume $R \sim (A_b^{1/3} + A_t^{1/3})/m_\pi$ $(1/m_\pi \simeq 1.42 \text{ fm})$ and $q_T^2/2A_t m_N < 1$ MeV.

From the energy conservation for this process, we have

$$E_b + A_t m_N = E_{b^*} + (A_t m_N + T_A) \ , \tag{5}$$

which, to a good approximation, is equivalent to

$$m_b \cosh y_b \simeq m_{b^*} \cosh y_{b^*} \tag{6}$$

in the DE process since the nuclear recoil kinetic energy $T_A = q^2/2A_T m_N < 1$ MeV is also negligibly small [3]. For interactions of $E_b \gtrsim 1$ GeV/nucleon, Eq. (6) may be well approximated by $m_b(\exp y_b)/2 \simeq m_{b^*}(\exp y_{b^*})/2$ as indicated in Eq. (1), $\Delta y = y_b - y_{b^*} \simeq \ln(m_{b^*}/m_b)$.

From the conservation of longitudinal momenta for the process of Eq. (3), we have

$$p_b = p_{b^*L} + q_L \ , \tag{7}$$

which is equivalent to

$$\begin{aligned} m_b \sinh y_b &= (m_{b^*}^2 + q_T^2)^{1/2} \sinh y_{b^*} + q_L \\ &\simeq m_{b^*} \sinh y_{b^*} + q_L \ . \end{aligned} \tag{8}$$

From Eqs. (6) and (8), we obtain

$$m_b + q_L \sinh y_b = m_{b^*} \cosh(-\Delta y) \tag{9}$$

and

$$q_L \cosh y_b \simeq m_b \sinh(\Delta y) \ . \tag{10}$$

Finally, from Eqs. (9) and (10), we have a formula for m_{b^*}

$$m_{b^*} \simeq m_b (1 - q_L^2/m_b^2 + 2q_L \sinh y_b / m_b)^{1/2} \ . \tag{11}$$

In our picture of the DE process at high energy, a large mass m_{b^*} can be generated from a projectile of mass m_b without transferring large energy to the target nucleus because of the intrinsic wave nature of the incident and the diffracted beams. The diffractive condition of Eq. (4), $q_T R \simeq 1$, implies a deviation angle of $\theta_{b^*} (\neq 0)$ for b^* since $q_T = q \sin\theta_{b^*}$. From Eq. (4) and $y_{b^*} = \operatorname{arctanh}(\beta_{b^*} \cos\theta_{b^*})$ [7], $\cos\theta_{b^*} < 1$ (and $\beta_{b^*} \simeq 1$ due to the expected projectile's relativistic velocity in the LS) assures $y_{b^*} < y_b$ [equivalently $\Delta y = y_b - y_{b^*} \simeq \ln(m_{b^*}/m_b) > 0$ from Eq. (1)] and, consequently, $m_{b^*} > m_b$; i.e., $\Delta m \equiv m_{b^*} - m_b > 0$.

Therefore, we claim that the increased mass of m_{b^*} (easily up as much as to $m_{b^*} \simeq 10 m_b$ at the RHIC energy) comes from the intrinsic wave nature due to the opaque on semi-opaque disk represented by the target nucleus. In other words, the relativistic effect plays the cardinal role of increasing the rest mass of the projectile nucleus. Thus this large mass excitation with small momentum transfer (or energy transfer) to the target in our picture, i.e., $\Delta m \gg \Delta E$ where $\Delta E \equiv E_{b^*} - E_b$, may imply that the prevailing calculation of electromagnetic dissociation [9] is at fault, especially at large $\sinh y_b (\simeq \gamma_b)$, because the authors of Ref. [9] have assumed $\Delta m \sim \Delta E$ and universally invoked the mechanism of a giant dipole resonance.

As stated in Sec. I, the projectile DE may be regarded as a dominant two-step process. At the first stage, the excited state b^* is created in the collisions of the beam particle b with the stationary target particle t, i.e., $b + t \to b^* + t$, and then at the second stage, b^* decays into several hadrons and fragments,

$$b^* \to N_1 + N_2 + \cdots + \pi + \pi + \cdots \ . \tag{12}$$

In this process, the decay lifetime is typically $\gamma_b \tau \sim 10^{-21}$ s, and energy-momentum conservation must be applied separately for the second stage. This condition can be represented by

TABLE I. $\Delta m = m_{b^*} - m_b$ (in MeV/c^2), energy widths Γ (in MeV), and lifetimes τ (in 10^{-21} s).

Beam energy	Z_F	A_F	Secondary Δm (MeV/c^2)	Γ^a (MeV)	τ (10^{-21} s)
^{16}O	1	1[b]	16±79	5.4±0.9	0.77±0.02
2.10 GeV/nucleon	1	2	184±15	9.6±0.4	0.43±0.006
	1	3	219±25	8.0±0.3	0.52±0.007
	2	3	203±15	8.6±0.2	0.48±0.01
	2	4	108±12	4.6±0.1	0.90±0.01
	2	6	107±26	4.9±1.2	0.83±0.02
	3	6	88±18	3.5±0.4	1.2±0.01
	3	7	105±13	4.0±0.2	1.0±0.01
	3	8	48±23	3.8±0.6	1.1±0.01
	3	9	112±53	4.2±0.7	0.99±0.01
	4	7	103±20	4.2±0.1	0.99±0.02
	4	9	84±12	3.3±0.1	1.3±0.02
	4	10	104±9	2.7±0.2	1.5±0.01
	4	11	106±38	3.8±0.8	1.1±0.01
	5	8	114±21	4.1±1.0	1.0±0.01
	5	10	64±11	3.3±0.3	1.3±0.01
	5	11	77±4	2.5±0.1	1.7±0.02
	5	12	79±13	2.4±0.2	1.8±0.02
	5	13	83±27	2.3±0.3	1.8±0.02
	6	10	51±24	3.8±0.4	1.1±0.01
	6	11	66±18	2.5±0.2	1.6±0.02
	6	12	33±8	1.3±0.1	3.2±0.05
	6	13	41±8	1.4±0.1	3.0±0.05
	6	14	44±8	1.2±0.1	3.5±0.06
	6	15	141±26	1.1±0.3	3.7±0.06
	7	12	65±36	2.1±0.3	2.0±0.03
	7	13	43±5	1.5±0	2.8±0.04
	7	14	31±3	0.95±0.05	4.3±0.08
	7	15	22±6	0.64±0.04	6.4±0.14
	7	16	100±15	0.19±0.08	21±0.79
	8	13	70±31	1.7±0.3	2.5±0.03
	8	14	35±8	0.75±0.09	5.5±0.11
	8	15	25±3	0.63±0.04	6.6±0.14
^{12}C	1	1[b]	0±36	4.8±0.7	0.86±0.03
2.10 GeV/nucleon	1	2	162±17	9.6±0.6	0.43±0.006
	1	3	193±15	6.8±0.5	0.61±0.009
	2	3	124±15	7.5±0.8	0.55±0.008
	2	4	75±12	4.4±0.1	0.93±0.01
	2	6	58±29	3.3±0.3	1.3±0.02
	3	6	66±19	2.9±0.3	1.4±0.02
	3	7	69±12	3.2±0.1	1.3±0.02
	3	8	65±17	3.4±0.3	1.2±0.02
	3	9	47±22	3.1±0.3	1.3±0.02
	4	7	84±10	3.2±0.1	1.3±0.02
	4	9	51±12	2.1±0.1	2.0±0.03
	4	10	36±9	1.8±0.1	2.3±0.04
	4	11	112±86	2.3±1.2	1.8±0.02
	5	8	59±17	3.0±0.6	1.4±0.02
	5	10	42±8	1.9±0.1	2.2±0.03
	5	11	25±10	1.1±0.1	3.8±0.07
	5	12	96±13	0.35±0.11	12±0.4
	6	9	57±39	2.6±0.7	1.6±0.02
	6	10	50±13	1.6±0.2	2.7±0.04
	6	11	44±10	1.0±0.1	4.0±0.08
	7	12	100±11	0.28±0.18	15±0.5
^{12}C	1	1[b]	−158±47	4.2±0.5	0.98±0.03
1.05 GeV/nucleon	1	2	78±69	6.8±1.3	0.61±0.01
	1	3	100±50	9.3±1.6	0.44±0.005
	2	3	128±8	6.2±1.3	0.67±0.01

TABLE I. (*Continued*).

Beam energy	Z_F	A_F	Secondary Δm (MeV/c^2)	Γ^a (MeV)	τ (10^{-21} s)
	2	4	81±6	4.2±0.2	0.99±0.02
	2	6	44±27	3.6±1.0	1.2±0.02
	3	6	56±14	2.6±0.4	1.6±0.02
	3	7	76±7	3.1±0.3	1.3±0.03
	3	8	53±20	3.4±1.1	1.2±0.02
	3	9	57±26	2.3±0.6	1.8±0.03
	4	7	91±8	3.0±0.3	1.4±0.02
	4	9	47±6	2.0±0.3	2.0±0.03
	4	10	44±6	1.7±0.3	2.5±0.04
	4	11	114±45	1.0±0.7	4.0±0.08
	5	8	92±29	2.6±0.4	1.6±0.02
	5	10	42±9	1.9±0.3	2.1±0.03
	5	11	33±4	1.0±0.2	4.1±0.08
	5	12	112±30	0.69±0.27	6.0±0.14
	6	9	37±22	2.6±1.0	1.6±0.02
	6	10	55±6	1.7±0.2	2.4±0.04
	6	11	47±43	1.1±0.2	3.9±0.07
	7	12	55±18	0.16±0.14	25±1.2

[a]The FWHM Γ is evaluated from the formula $\Gamma \approx 2(\sigma_L^2/2A_F m_N)$, where the values of σ_L are from Table I of Ref. [4], assuming that there is a single level in a secondary fragment; thus, the widths listed here must be taken as the highest values (the lowest values) for Γ (for τ).
[b]Non-Gaussian distribution.

$$\langle y \rangle = \langle \bar{y} + y_{b^*} \rangle \simeq y_{b^*} , \tag{13}$$

where $y_{b^*} = y_b - \Delta y$ with $\Delta y \simeq \ln(m_{b^*}/m_b)$, $\bar{y}$ is the rapidity in the rest frame of b^*, and $\langle \bar{y} \rangle \approx 0$. In other words, energy-momentum conservation is satisfied in each stage, which enables us effectively to measure the lifetimes of the excited states b^* to be of the order of $10^{-22} \sim 10^{-20}$ s.

Because of this relation [10]

$$q_L \simeq (m_{b^*}^2 - m_b^2)/2E_b \simeq \Delta m \gamma_b , \tag{14}$$

our investigation of the distribution of Δm provide us the average q_L distribution.

III. EXPERIMENTAL DATA AND THE RESULTS OF OUR ANALYSIS

Using a single-focusing magnetic spectrometer with a half-angle acceptance of 12.5 mrad around the forward direction, Greiner *et al.* [4] have measured the first definitive measurements of the momentum distributions and cross sections for the secondary isotopes produced by the fragmentation of heavy-ion beams at Bevalac, LBL. The targets were Be, CH_2, C, Al, Cu, Ag, and Pb. The charges and masses of the fragments were obtained by measuring their rigidities (pc/Ze), energy losses in solid-state detectors, and time of flight as detailed in Ref. [4] and the references quoted therein. Their final results for the average of the longitudinal momenta $\langle p_L \rangle$ (in MeV/c) in the PRF and for the standard deviations σ_L are tabulated in Table I of Ref. [4] according to the charge, Z_F, and the mass, A_F, of each secondary fragment.

Since the LS velocities of the projectile fragments are near the beam velocity, the longitudinal velocity $\langle \beta_L \rangle$ can be obtained from the $\langle p_L \rangle$ of Ref. [4] by using the Lorentz factor of the beam as stated in Sec. I. The results of our calculation of $\Delta m = m_{b^*} - m_b$ using Eq. (1) are tabulated in Table I and displayed in Figs. 1(a)–1(c) for secondaries from a 2.10 GeV/nucleon ^{16}O beam, a 2.10 GeV/nucleon ^{12}C beam, and a 1.05 GeV/nucleon ^{12}C beam, respectively. (In the data concerning the ^1H, e.g., those of 1.05 GeV/nucleon ^{12}C, we find deviation from the general trend, as shown by $\langle p_L \rangle > 0$.)

The full width at half maximum (FWHM) Γ and lifetime τ are evaluated from the formula

$$\Gamma \approx 2 \frac{\sigma_L^2}{2 A_F m_N} \tag{15}$$

and the uncertainty relation

$$\Gamma \tau \sim 1 . \tag{16}$$

The results are listed in Table I and the distributions of τ are plotted in Figs. 2(a)–2(c). Here, as stressed in Ref. [4], with a keen awareness of the isotropy of the decay isotopes in mind [4], the contributions of the measuring instruments to Γ are neglected, and the level of each isotope is assumed to be a single level of b^*.

IV. DISCUSSIONS AND CONCLUSIONS

It is conjectured theoretically in Ref. [3] that, in DE, even with the energy transfer $\Delta E = E_{b^*} - E_b$ in the first stage as small as 1 (in MeV), an excited state of mass $m_{b^*} = m_b + \gtrsim 0.1$ (in GeV/c^2) may be reached as the primary rapidity y_b becomes large. Moreover, our mass

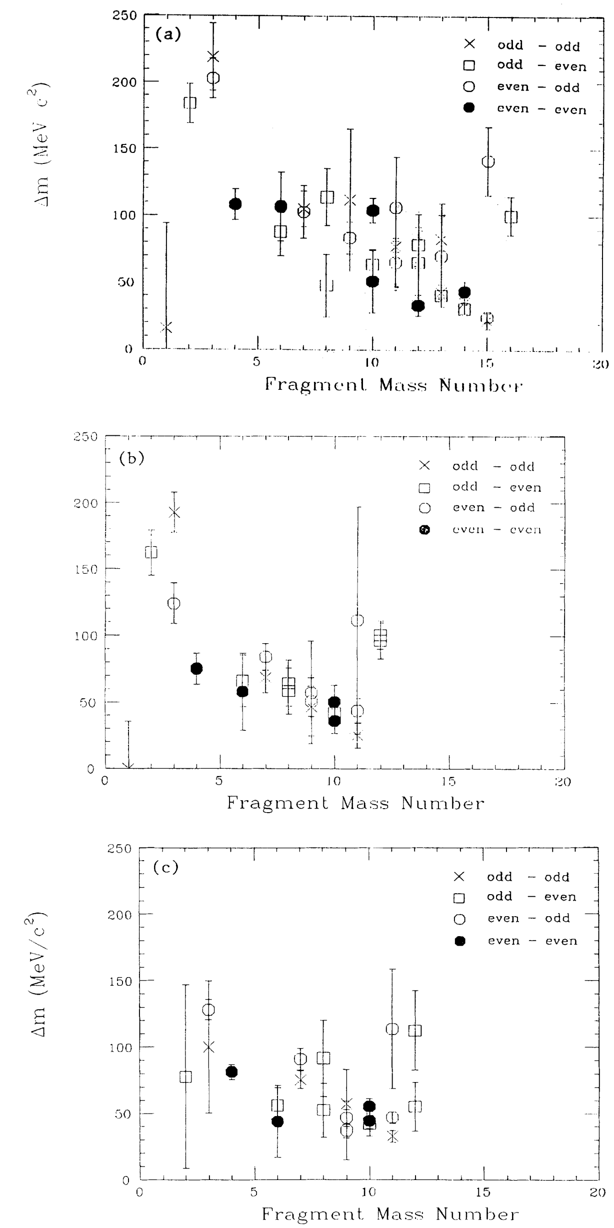

FIG. 1. (a) The mass difference $\Delta m = m_{b^*} - m_b$ for each projectile fragment from a 2.10 GeV/nucleon ^{16}O beam. (b) The mass difference $\Delta m = m_{b^*} - m_b$ for each projectile fragment from a 2.10 GeV/nucleon ^{12}C beam. (c) The mass difference $\Delta m = m_{b^*} - m_b$ for each projectile fragment from a 1.05 GeV/nucleon ^{12}C beam.

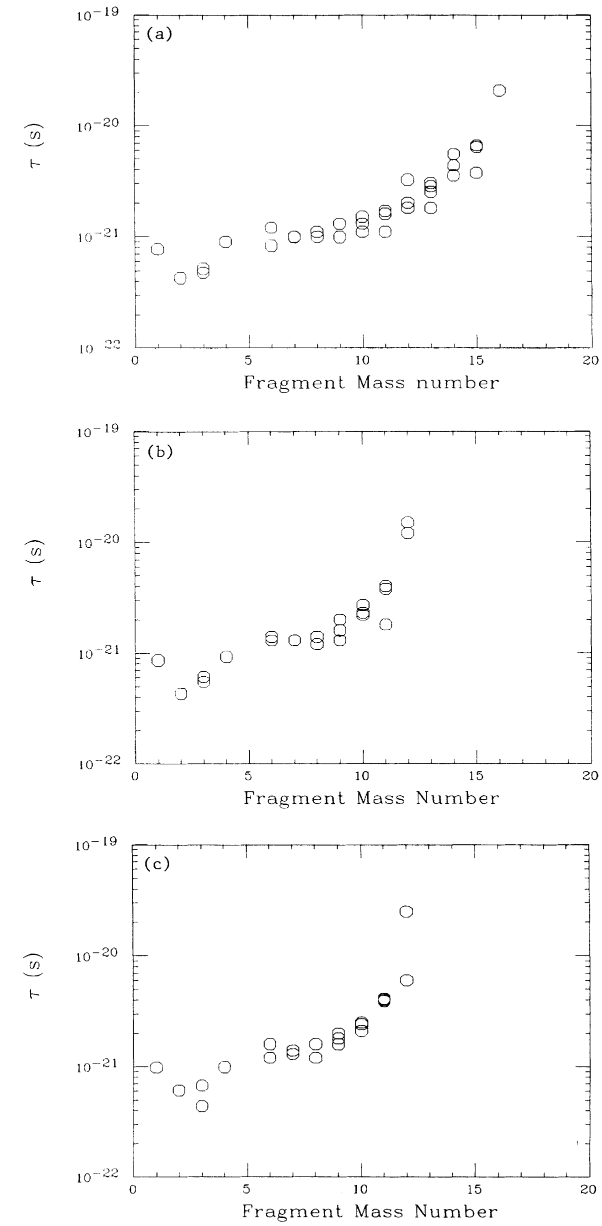

FIG. 2. (a) The lifetime of b^* for each projectile fragment from a 2.10 GeV/nucleon ^{16}O beam. (b) The lifetime of b^* for each projectile fragment from a 2.10 GeV/nucleon ^{12}C beam. (c) The lifetime of b^* for each projectile fragment from a 1.05 GeV/nucleon ^{12}C beam. In (a)–(c), the errors are smaller than the sizes of the circles.

differences, Δm, are typically ~ 0.1 GeV/c^2, which agrees well with the results of Ref. [3]. This agreement is excellent when we consider the fact that the present data are not confined to such DE interactions as identified in Ref. [3]. Thus, we are led to propose that the very process of fragmentation is largely due to the DE process as envisaged by Serber as early as in 1947 [11].

Besides the overall evidence of $\Delta m \lesssim 100$ MeV/c^2, we have observed the following trends in Table I and Figs. 1(a)–1(c): (i) The two-body decay fragmentations,

$$ {}^{A}Z^* \rightarrow p + {}^{A-1}(Z-1) \,, \tag{17} $$

$$ ({}^{A}Z^* \rightarrow n + {}^{A-1}Z) \,, \tag{18} $$

and

$$ {}^{A}Z^* \rightarrow \alpha + {}^{A-4}(Z-2) \,, \tag{19} $$

which are found to constitute about 90% of the whole DE process in Ref. [3], also exhibit small $\Delta m \lesssim 30$ MeV/c^2, judging from the heavier fragment sides of these processes, i.e., from ${}^{A-1}(Z-1)$, ${}^{A-1}Z$, ${}^{A-4}(Z-2)$. It must be kept in mind that, in comparing Δm in the present paper with the Δm distributions in Ref. [3], the latter did not take the kinetic energies of the p (d or t) and the α fragments in the PRF into account so that Δm in the former can be a little larger than that in Ref. [3]. (ii) The projectile fragments, ^{2}H, ^{3}He, and ^{4}He, show relatively large $\Delta m \gtrsim 100$ MeV/c^2, indicating that many other possible mechanisms other than DE (such as the direct knock-on process) are at work. Likewise, the production of ^{1}H comes largely from DE, but other processes may come into play, which must be the reason why a Gaussian-shaped recursion formula could not fit the data for the hydrogen fragments [12]. (iii) Excluding the above two ranges, i.e., in the middle range of A and Z, $\Delta m \approx 50 \sim 60$ MeV/c^2. (iv) The lifetimes obtained are indeed within 10^{-22}–10^{-20} s, indicating that the decays occur long after leaving the site of the interaction as we have claimed.

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[12] For instance, for one particular reaction, ${}^{12}\mathrm{C} \to {}^{11}\mathrm{B} + p$, the exclusive case has been studied with the result about 20% of the cross section is due to DE. [See M. L. Webb *et al.*, Phys. Rev. C **36**, 193 (1987).]