Interpretation of Anomalous Mean Free Paths of Projectile Fragments from Relativistic Heavy-Ion Collisions

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(Received 26 March 1982)

The anomaly associated with mean free paths of projectile fragments observed in relativistic heavy-ion collisions is interpreted in terms of nuclear size, isotope, and structure effects. This interpretation relies upon the existence of quasibound quasimolecular states, predicted by many nuclear-structure calculations.

PACS numbers: 25.70.Ba, 21.10.Ft, 25.70.Hi

Several analyses[1] of high-energy cosmic-ray tracks in nuclear emulsions have indicated that the mean free paths (mfp) λ_s of projectile fragments (PF, i.e., secondary nuclei) near the points of origin are shorter than the mfp λ_p of the corresponding primary nuclei. Recent experimental results[2,3] obtained with use of the Lawrence Berkeley Laboratory Bevalac with primary beams of kinetic energies near 2 GeV/nucleon have confirmed that a statistically significant difference does exist.

The presence of anomalous behavior (sometimes referred to as "anomalons") has also been ascertained by a careful reanalysis of cosmic-ray data by Barber, Freier, and Waddington.[4] In Fig. 1, we show their results for the mfp of primary and secondary nuclei (measured over the first centimeter of track from the points of origin), together with two $Z=3$, ^{6}Li primary points obtained from a recent Bevalac measurement.[5,6] Using the results for $Z=2$ and $Z\geqslant 6$, Barber, Freier, and Waddington found that a power-law relation, introduced in Refs. 2 and 3, of the form (dashed line)

$$\lambda_p(Z)=\Lambda Z^{-b} \qquad (1)$$

with $\Lambda=25.1\pm 1.7$ cm and $b=0.34\pm 0.03$ can be fitted to their primary data quite well.

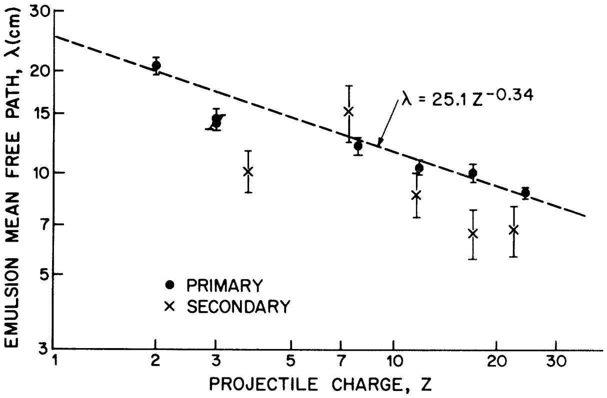

FIG. 1. Mean free paths λ_p and λ_s. The dashed line represents a power-law fit to the primary data of Ref. 4. Experimental points shown are those of Refs. 4–6.

The salient features contained in Fig. 1 are as follows: (i) The λ_s point for the charge group with $Z=3-5$ lies appreciably below the dashed line. (ii) For the charge group with $Z=6-9$, the values of λ_p and λ_s are statistically consistent with each other. (iii) The value of λ_s starts to be marginally smaller than that of λ_p for the charge group with $Z=10-14$. On the other hand, λ_s is significantly smaller than λ_p for the groups with $Z\geqslant 15$.

We now show that, for an interpretation of these features, it is important to consider the nuclear size, isotope, and structure effects.

(A) Size and isotope effects.—It is well known that very light nuclei do not follow the systematic behavior based upon observed properties of heavier nuclear systems. This can be clearly seen from Table I, where we list some values of the rms matter radius R_0,[7] the radius parameter $r_0=R_0/A^{1/3}$, and the binding energy per nucleon E_0. Here one sees that the nuclei with $Z=3-5$ are weakly bound and have rather large radii which cannot be adequately characterized by an $A^{1/3}$ law. For example, the values of R_0 for ^{6}Li, ^{9}Be, and ^{10}B are close to the values for ^{14}N, ^{16}O, and ^{12}C, respectively. At relativistic energies, reaction cross sections depend mainly on the geometrical sizes of the nuclei involved[8]; therefore, one would expect the λ_p values for Li and Be to be considerably smaller than estimates based on systematics as expressed by Eq. (1), obtained from data on ^{4}He and $Z\geqslant 6$ nuclei.

As an illustration of the importance of the size effect, consider the nucleus ^{6}Li. Since the reaction cross section is close to the geometrical limit, one should be able to estimate the value of λ_p

TABLE I. Root mean square matter radius R_0, radius parameter r_0, and binding energy per nucleon E_0 for various nuclei.

Nucleus	R_0 (fm)	r_0 (fm)	E_0 (MeV/nucleon)
^{4}He	1.47	0.93	7.1
^{6}Li	2.42	1.33	5.3
^{7}Li	2.37	1.24	5.6
^{9}Be	2.61	1.25	6.5
^{10}B	2.27	1.06	6.5
^{12}C	2.31	1.01	7.7
^{14}N	2.42	1.01	7.5
^{16}O	2.60	1.03	8.0
^{28}Si	3.00	0.99	8.5
^{32}S	3.15	0.99	8.5
^{40}Ca	3.37	0.98	8.6
^{58}Ni	3.72	0.96	8.7

for ^{6}Li by setting $Z = 7$ (corresponding to ^{14}N) in Eq. (1) while correcting, at the same time, for the fact that the nucleus ^{6}Li is somewhat surface transparent to the hydrogen component in the emulsion.[9] The result is

$$\lambda_p(^6\text{Li}) = 13.7 \pm 1.2\ \text{cm}, \qquad (2)$$

which compares quite well with the preliminary results of recent measurements (i.e., 14.5 ± 1.0 cm from Ref. 5 and 14.1 ± 0.7 cm from Ref. 6; see also Fig. 1), and is much smaller than the value of 17.3 cm calculated by using Eq. (1) with $Z = 3$.

In addition to nuclei within the valley of stability, there may also appear in PF long-lived neutron-rich isotopes such as ^{9}Li, ^{16}C, and so on. Because of anticipated low abundances, the effect on mfp arising from the presence of such isotopes is not expected to be of major significance, especially when the Z value under consideration is not too small.[10] For example, in the $Z = 3$ case, an assumption of a 10% population for each of these isotopes (^{8}Li, ^{9}Li, and ^{11}Li) will lead to only a small decrease of around 0.3 cm for the mfp.

With size and isotope effects taken into account, the estimated mfp in the $Z = 3$ case is $\lambda_s \approx 13.4 \pm 1.2$ cm. Proceeding in the same way, we can estimate the λ_s values for Be and B. The result, obtained by averaging over the observed distribution of $Z = 3-5$ in Ref. 4, is

$$\lambda_s(Z = 3-5) \approx 13.2 \pm 1.2\ \text{cm}, \qquad (3)$$

a value which is not inconsistent with the measured value[4] of $\lambda_s = 10.1 \pm 1.5$ cm.

Variation of λ_s with distance D from the point of origin (local-mfp effect) has also been reported.[2-4] Within our considerations, this effect will be rather weak for mixed-Z and mixed-A light fragments. The difference in λ_s values computed for D less and greater than 2.5 cm is estimated to be only a few tenths of a centimeter, in apparent variance with the observations discussed in Refs. 2 and 3. It should be pointed out, however, that the existing sample sizes are fairly small, and the data of Friedlander *et al.*[2] show, in particular, a somewhat weaker effect for the low-charge group than for the higher-charge groups. In addition, it is worth remarking that the latest experimental results[11] for $Z = 2$ show no local-mfp effect and the data of Barber, Freier, and Waddington[4] for $Z = 6-9$ show no significant difference between λ_p and λ_s. Thus, in our view, an important task would be to obtain accurate experimental values of λ_p and λ_s for the lighter nuclei so that comparisons for individual-Z fragments may be made.

(B) Structure effect.—For higher-Z fragments, the anomaly seems to begin with the charge group $Z = 10-14$ and becomes more evident for larger Z values. This Z dependence suggests that the explanation for this anomaly lies in the structures of the nuclei involved. We propose now that the PF with anomalously short mfp or anomalons are, in fact, shape isomers or quasibound quasimolecular resonances (QMR) of rather low angular momentum. As has been found in many theoretical studies,[12] such long-lived ($> 10^{-10}$ sec proper time) resonances are expected to exist in nuclear systems with $Z \geq 12$ and $A \geq 24$. In the following, we shall specifically consider the nucleus ^{32}S as an example, since this particular nucleus has received detailed attention from many research groups.

Resonating-group[13] or generator-coordinate[14] studies, constrained Hartree-Fock (HF) calculations,[15,16] and the microscopic α-cluster model[17] have all indicated that there should exist in ^{32}S cluster states which are structurally very different from the ground state. This is schematically illustrated in Fig. 2 for a HF calculation constrained with respect to the c.m. separation distance. Here one notes that there are two minima for the intrinsic energy, which support class-I and class-II states of distinctly different structure. The ground 0^+ state, being a class-I state, possesses little clustering correlations and is only slightly prolate deformed. The class-II states, related to the second minimum in the en-

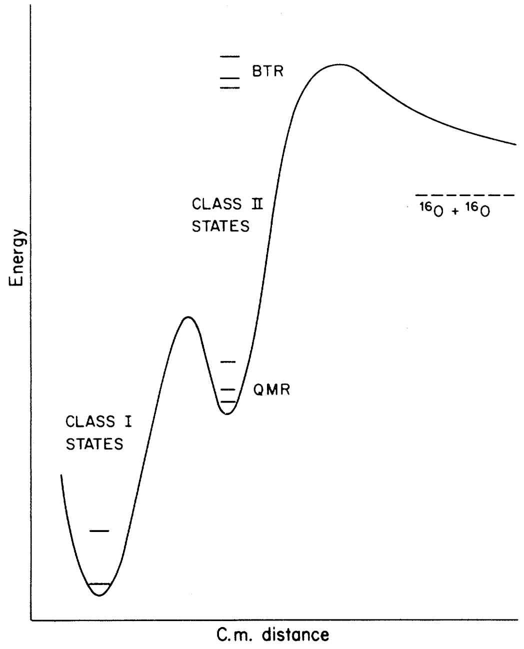

FIG. 2. Schematic diagram for the ^{32}S intrinsic energy as a function of the c.m. distance.

ergy curve, consist of two types of resonances, both with strong clustering features. The barrier-top resonances[18] (BTR) (sometimes also known as orbiting or surface-wave resonances) have short lifetimes and are responsible for the gross structures in the excitation functions and back-angle oscillations in the angular distributions. The quasimolecular resonances[19] (QMR) lie deep in the energy pocket and constitute well-formed rotational bands with large moments of inertia.

At present, the best quantitative study seems to be that of Schultheis and Schultheis,[17] utilizing the microscopic α-cluster model. These authors have performed an elaborate calculation with variation after projection. The results they obtained show a QMR band with the bandhead at an excitation energy of 7.5 MeV and a rotational constant of 77.7 keV. By studying the experimental energy spectrum of ^{32}S, they have tentatively identified the QMR 0^+, 2^+, and 4^+ states as the states determined experimentally[20] with excitation energies of 8.507, 9.065, and 10.276 MeV, respectively. In addition, it was found that the intrinsic state has a strong degree of $^{16}O + ^{16}O$ clustering, with the density distribution showing a necked-in configuration. The intrinsic quadrupole moment was calculated to have a very large value of 208 fm^2, corresponding to that of a classical uniformly charged spheriod of axis ratio 2.3. The overlap between the intrinsic states for the QMR band and the ground-state band turned out to be very small, being only equal to 4×10^{-9}.

It is our belief that the QMR 0^+ state is likely to be found in the 7–10-MeV excitation-energy region. This implies that the QMR states are stable against fission but are unstable against γ decay and light-ion emission. The lifetimes should, however, be very long, since the light-ion processes have to proceed below the Coulomb and centrifugal barriers and all the transitions (except transitions among class-II states which are not of interest here) are additionally inhibited because of the very small overlap between class-I and class-II intrinsic states.

The necked-in density distribution and large intrinsic quadrupole moment indicate that the radius of the ^{32}S anomalon could be nearly equal to twice the radius of an ^{16}O nucleus in its ground state. In other words, this anomalon could behave as if it were as large as a rare-earth nucleus. Using again the geometrical argument for the reaction cross section, one can then make a crude estimate as to the fraction of anomalons needed in order to explain the experimental findings of Barber, Freier, and Waddington[4] for the charge groups with $Z \geq 15$.[21] The result turns out to be about 25%, which is not a small fraction, but is by no means unreasonable.

Finally, we briefly discuss a possible mechanism for populating the low-angular-momentum QMR states in relativistic collisions. With the knockout of a few nucleon clusters, a projectile fragment, say ^{32}S, remains. Let us now view the peripheral interaction between this nucleus and an emulsion target in the Lorentz frame of the ^{32}S nucleus. As the target nucleus moves by with relativistic speed, the nucleons in the near side of ^{32}S will experience, on the average, a substantial transverse impulse. The result will be that these nucleons acquire an appreciable transverse linear momentum, but the amount of angular momentum transferred to ^{32}S perpendicular to the reaction plane will be quite small. On the other hand, because of the short range of nuclear forces, the nucleons in the far side of ^{32}S will be much less affected. As a consequence, one expects that there should be an appreciable probability for the excitation of highly deformed, low-angular-momentum cluster states, such as the QMR states.

Other attempts[22-26] to explain the anomalous mfp have involved quark phenomena, or the existence of an exotic nuclear species with an almost toroidal spatial configuration. However, we suggest here that, for $Z \leq 12$, the observed behavior of the mfp can be understood in terms of known properties of the nuclei involved. For higher values of Z, we believe that the anomalons provide the first experimental evidence for the existence of highly deformed quasibound states in light nuclei, states whose existence has been predicted on strong theoretical grounds. Further support of our explanation will require a quantitative study of the production probability. Also, it would be especially interesting to find other experimental evidence for the existence of these states, such as the detection of delayed γ transitions between them and the class-I states.[27]

We are grateful to Professor P. S. Freier and Professor C. J. Waddington for valuable discussion and for introducing us to this fascinating subject. Also, we wish to thank Professor H. H. Heckman and Dr. B. Judek for allowing us to quote their preliminary results prior to publication.

This work was supported in part by the U. S. Department of Energy under Contract No. DOE/DE-AC02-79 ER 10364.

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[1] B. Judek, Can. J. Phys. 50, 2082 (1972), and references contained therein.

[2] E. M. Friedlander, R. W. Gimpel, H. H. Heckman, Y. J. Karant, B. Judek, and E. Ganssauge, Phys. Rev. Lett. 45, 1084 (1980).

[3] P. L. Jain and G. Das, Phys. Rev. Lett. 48, 305 (1982).

[4] H. B. Barber, P. S. Freier, and C. J. Waddington, Phys. Rev. Lett. 48, 856 (1982), private communication.

[5] H. H. Heckman, private communication.

[6] B. Judek, private communication.

[7] G. R. Satchler and W. G. Love, Phys. Rep. 55, 183 (1979).

[8] P. J. Karol, Phys. Rev. C 11, 1203 (1975).

[9] This correction is relatively minor and has been made by using measured reaction cross sections for protons of about 550 MeV incident on a variety of target nuclei [P. U. Renberg *et al.*, Nucl. Phys. A183, 81 (1972)].

[10] The isotope effect will be important in the $Z = 2$ case, if a significant fraction of PF happens to be ^{6}He.

[11] P. L. Jain, M. M. Aggarwal, G. Das, and K. B. Bhalla, Phys. Rev. C 25, 3216 (1982).

[12] D. Baye, in Proceedings of the International Conference on the Resonant Behavior of Heavy-Ion Systems, Aegean Sea, Greece, 1980 (to be published), and references contained therein.

[13] T. Ando, K. Ikeda, and A. Tohsaki-Suzuki, Prog. Theor. Phys. 64, 1608 (1980).

[14] D. Baye and G. Reidemeister, Nucl. Phys. A258, 157 (1976).

[15] P. G. Zint and U. Mosel, Phys. Rev. C 14, 1488 (1976).

[16] S. J. Krieger and C. Y. Wong, Phys. Rev. Lett. 28, 690 (1972).

[17] H. Schultheis and R. Schultheis, Phys. Rev. C 25, 2126 (1982).

[18] W. A. Friedman and C. J. Goebel, Ann. Phys. (N.Y.) 104, 145 (1977).

[19] The BTR has sometimes been referred to also as the QMR. We believe that the name QMR should be reserved for the quasibound states we refer to here.

[20] P. M. Endt and C. van der Leun, Nucl. Phys. A310, 1 (1978).

[21] For this estimate, we assume that the fraction of anomalons is independent of Z for $Z \geq 15$.

[22] W. J. Romo and P. I. Watson, Phys. Lett. 88B, 354 (1979).

[23] H. Stöcker, G. Graebner, J. A. Maruhn, and W. Greiner, Phys. Lett. 95B, 192 (1980).

[24] S. Fredriksson and M. Jändel, Phys. Rev. Lett. 48, 14 (1982).

[25] G. F. Chapline, to be published.

[26] J. Boguta, in Proceedings of the Workshop on Anomalons, Berkeley, California, 1982 (unpublished).

[27] As has been suggested in Ref. 17, the best way to populate the QMR states seems to be by ^{16}O + ^{16}O radiative capture through the BTR states.